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Advanced temperature control of high carbon steel for hot strip mills †

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Abstract

In this paper, an advanced temperature control for the high carbon steel is proposed to obtain the desirable temperature and property of a steel on the run-out table (ROT) process. The temperature model based on the nonlinear heat transfer equation is described to predict the temperature of the steel at each position of the ROT. A cooling stop temperature (CST) concept is proposed to increase the volume fraction of the transformed phase for the high carbon steel. The concept is derived from a time-temperature transformation (TTT) diagram which is measured from the dilatometric experiment. The simulator using the temperature model is developed to achieve the desired temperature, and the effectiveness of the proposed control is also analyzed from the simulation. It is shown through the field test of the hot strip mill of POSCO that the performance with respect to the temperature and the property of the steel is greatly improved by the proposed control technology.

Keywords: Hot strip mill; Temperature control; High carbon steel; Run-out table; Cooling stop temperature; Structure and property

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1. Introduction

As the customers' demands for the property of the high strength steel become strict, the cooling control in a hot strip mill becomes more important. The run-out table (ROT) is the next process of the hot strip finishing mill, and it is a very important process where the structure and the property of the steel are determined. The temperature control on the ROT is the technology which controls the temperature by the radiation and the cooling water and the phase transformation by the property prediction of the steel. Since the uniform shape and the property of the strip are related to the temperature of the steel, the temperature control is the core technology to determine the quality of the product [1, 2].

The high carbon steel out of the high strength steel contains above 0.8 wt. (%) of the carbon, and it is used for parts of an automobile, a machine which demand a high strength. It is not easy to produce the high carbon steel with the uniform structure and property because of the high strength [3]. Especially, the temperature control has some difficulties due to the exothermal reaction during the pearlite transformation when it is cooled on the ROT process: First, the edge part along the lateral direction of the steel can be led to the edge crack by the bainite structure which is produced by the lower temperature than the pearlite structure of the middle part. Since it is easier to transfer the heat at the edge part than the middle part, the edge part produces the bainite structure. The edge crack can reduce the productivity of the hot strip mill. Second, the collapsed coil which is collapsed with the egg shape is produced by the transformation plasticity during the phase transformation on the ROT process [4]. Third, the prediction model of the phase transformation has been developed to control the temperature of the high carbon steel. However, it is not easy to control the temperature since the precision of the model is deteriorated.

There have been some works on the temperature control on the ROT process. The heat transfer model for the history of the thermodynamic energy was developed instead of the conventional control for the temperature history [5, 6]. From the model, the precision of the temperature control can be improved without operator intervention. The feedforward temperature controller was proposed from the relation between the desired temperature of the exit of the ROT and desired water flux [7, 8]. The feedback controller was also proposed by modeling simply with 1st delay system for the ROT process which was expressed by the nonlinear differential equation [9]. Recently the model of the ROT process and the optimal control [10-14] such as a model predictive control (MPC), a multivariable adaptive control [15, 16] have been proposed to obtain the uniform temperature by regulating the cooling speed. The partial differential equation with two-point boundary condition was applied to develop the more exact tempera-

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ture model [17]. Moreover since there exist disturbances for the temperature control such as the abnormality of the pyrometer, valve, cooling water, and so on, there have been some works on the optimization of facilities [18, 19]. The aforementioned works on the ROT process have focus on the temperature control for the steel which doesn't consider the carbon quantity. The temperature and property control of the high carbon steel need the new control concept.

In this paper, the temperature models based on the nonlinear heat transfer equation are described to predict the longitudinal temperature of the strip. The models are composed of the heat loss model by the water cooling and the radiation. The concept of an advanced temperature control using a cooling stop temperature (CST) is proposed to settle the aforementioned problems of the high carbon steel. The concept is analyzed from the time-temperature transformation (TTT) diagram of the steel. The cooling pattern on the ROT should be controlled based on CST, not the coiling temperature in order to increase the fraction of the transformation before coiling. The control concept can prevent the edge crack, the collapsed coil, and so on. The simulator based on the temperature prediction models is developed to achieve the desired temperature. The optimal cooling pattern can be also obtained to control the CST by using the simulator. The proposed control concept is applied and verified to the hot strip mill of POSCO. The key idea is that an advanced temperature control using CST concept can achieve the desirable transformation phase and settle the problems of the high carbon steel.

This paper is organized as follows: Section 2 gives a brief description of the ROT process and the temperature models. In Section 3, the concept of CST and the cooling pattern of the high carbon steel are described. In Section 4, the effectiveness of the proposed concept is analyzed from the simulation. In Section 5, it is shown through the field test of the hot strip mill of POSCO that the control performance is greatly improved by the proposed control. Conclusions are presented in Section 6.

2. Process description and temperature control models

2.1 ROT process

Fig. 1 shows a layout of the ROT cooling system for hot strip mills. The ROT has three pyrometers to measure the temperature: the finishing delivery temperature (FDT), the intermediate temperature (MT) installed between 8th and 9th bank, and the coiling temperature (CT). The feedforward and the feedback bank have 14 banks (no.1-no.14) and 2 banks (no.15-no.16), respectively. Moreover, they consist 6 and 12 heads at the upper and bottom bank, respectively.

There are 4 control modes for the coiling temperature control. The first is the preset mode which determines the control parameters and the numbers of the cooling banks, head, and so on when the strip arrives at the 3rd stand of the finishing mill. The second is the feedforward control mode. The temperature model predicts the temperature drop from the measured FDT, the rolling speed, and the target CT when the strip arrives at the ROT. The third is the feedback control mode. This mode controls the differences between the target CT and the measured CT by using the feedback banks with the PI controller. The fourth is the learning mode. The compensation of the model parameters can be achieved by the measured temperature data of the longitudinal and lateral direction of the strip.

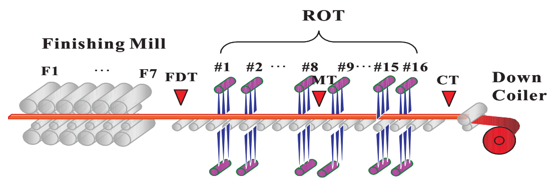

Fig. 1. Configuration of ROT cooling system.

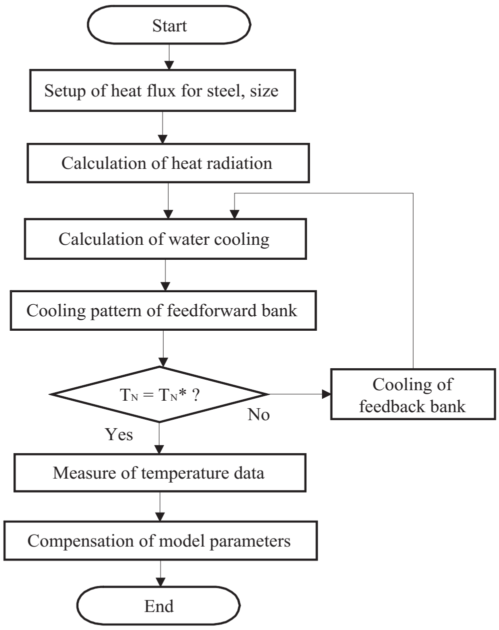

Fig. 2. Flowchart of the temperature control model.

2.2 Temperature control models

Fig. 2 shows the flowchart of the temperature control models, where T_N is a measured CT and T_N^* a target CT, respectively.

Fig. 3 shows the temperature representation of the ROT process, where T_0 is the FDT, ΔT_d the heat loss by a water cooling, ΔT_r the heat loss by a radiation, respectively. The strip temperature of the ROT process is dropped by the water cooling from the water jets and the radiation losses to the surrounding air before and after the water cooling as follows [20]:

$$T_N = T_0 - \Delta T_d - \Delta T_r. \tag{1}$$

In this section, we describe the temperature models (ΔT_d, ΔT_r) by the water cooling and the radiation as below.

The nonlinear heat transfer equation that governs the cool-

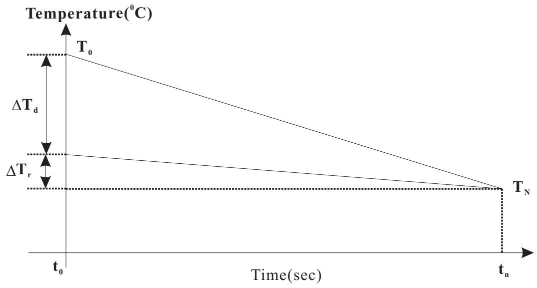

Fig. 3. Temperature representation of the ROT process.

ing process of the ROT can be represented as follows [12]:

$$\rho c\frac{\partial T}{\partial t}-\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)-\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)=0, \tag{2}$$

where x, y are the longitudinal and the thickness direction of the strip, respectively, T the temperature, ρ the density, c the specific heat, k the heat conductivity.

1) Heat loss model by the water cooling

The heat loss rate by the water cooling (dq_w/dt) for the strip length (Δl) on the ROT process can be expressed as follows [11]:

$$dq_w = 2kwf\,\Delta l(T-T_w)\left(\frac{t_w}{\pi a}\right)^{0.5} dt, \tag{3}$$

where w is the strip width, f the heat flux coefficient, T_w the water temperature, t_w the time ($t_w=\Delta l/v$), v the rolling speed, a the heat diffusivity, respectively. The heat loss is expressed as a function of the temperature deviation.

$$dq_m = \rho(T)\ c(T)\ V\ dt, \tag{4}$$

where V is the strip volume and

$$V = w\ h\ \Delta l, \tag{5}$$

where h is the strip thickness. Substituting Eqs. (3) and (4) into the heat balance condition ($dq_w=dq_m$), and integrating the time (0~t_w), the heat loss by the water cooling (ΔT_d) can be obtained as follows:

$$\Delta T_d = \frac{2kf}{\rho(T)c(T)h}(T-T_w)\left(\frac{\Delta l}{\pi av}\right)^{0.5} t_w. \tag{6}$$

2) Heat loss model by the radiation

The heat loss rate by the radiation (dq_r/dt) on the ROT process can be expressed as follows [11]:

$$dq_r = s\xi A_r[(T+460)^4 - (T_a+460)^4]\,dt, \tag{7}$$

where s is the Stefan Boltzman constant, ξ the emissivity, A_r the surface area, T the material temperature in degrees F (Fahrenheit), T_a the environment temperature in degrees F, respectively. Similarly, the heat loss by the radiation (ΔT_r) by using the heat balance condition can be obtained as follows:

$$\Delta T_r = \frac{s\xi A_r}{\rho(T)c(T)V}[(T+460)^4-(T_a+460)^4]t_r. \tag{8}$$

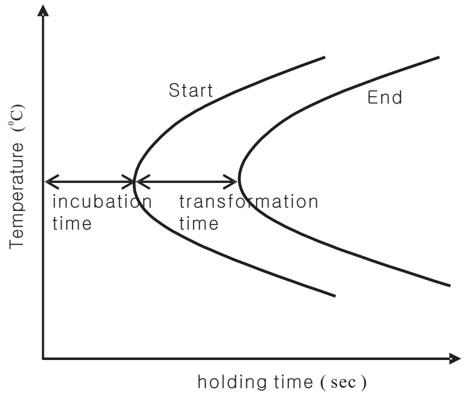

Fig. 4. Schematic diagram showing time-temperature transformation of high carbon steel.

3. CST control of high carbon steel

Fig. 4 shows a schematic TTT diagram of the high carbon steel. In general, the isothermal transformation is delayed as carbon concentration increases, that is, the high carbon steel shows a long incubation time and a long transformation time for the isothermal transformation. It is not easy to produce the high carbon steel for these reasons. If the high carbon steel is processed at the low cooling rate to the coiling temperature, the steel has the low transformation fraction of the pearlite phase on the ROT process before coiling. The residual austenite transforms to pearlite during and after coiling of the hot strip. This additional transformation of austenite to pearlite during and after coiling makes the temperature of hot strip increase due to the exothermal reaction during transformation. It can lead to ununiform microstructures and mechanical properties of the high carbon steel and occasionally result in collapsed coils. In order to settle difficulties on the process to make the high carbon steel, the cooling pattern should be controlled based on FDT and CST on the ROT, not CT in order to increase the fraction of the transformation before coiling. Therefore, the cooling pattern for the high carbon steel should be designed to maximize the fraction of transformation to pearlite on the ROT as follows: 1) cooling down from FDT to CST as fast as possible, 2) holding time at CST as long as possible. The process conditions of the high carbon steel were determined from an experimental TTT diagram.

3.1 Experimental procedure

The experimental procedure of this work is as follows:

• *Step* 1: Test material

The alloy used in this paper was SK85 steel in Japanese industrial standards, which contains 0.85 wt. (%) carbon and 0.7

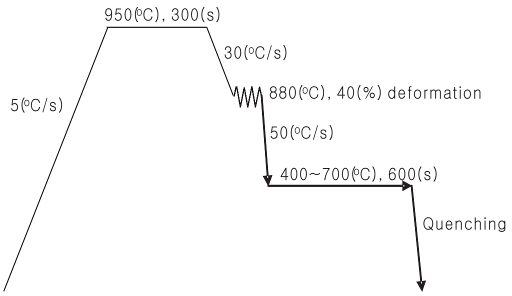

Fig. 5. Schematic diagram showing the thermo-mechanical process.

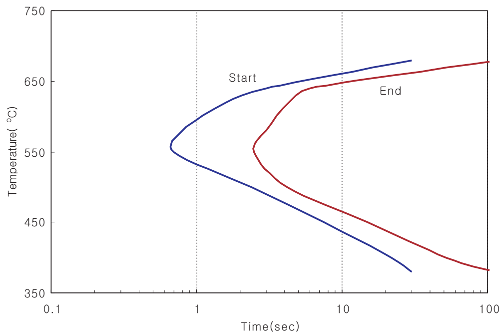

Fig. 6. Measured TTT of the test alloy.

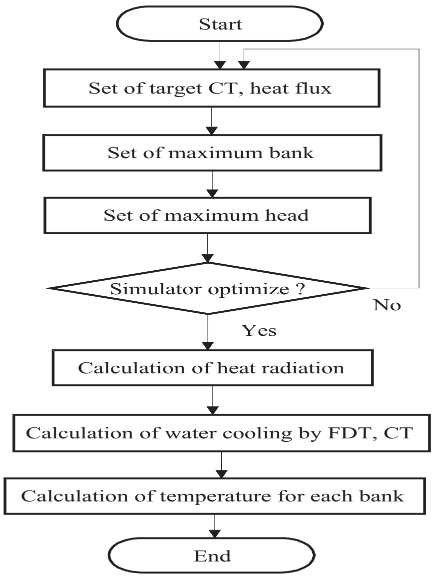

Fig. 7. Flowchart of the temperature simulator.

wt. (%) manganese. The alloy was prepared from slab and rolled to a 25 (mm) thickness plate. Cylindrical samples of 3.2 (mm) diameter and 6 (mm) length were machined from the plate for the dilatometric machine (thermo-mechanical simulator), which can control the temperature of the sample and the uniaxial load strain.

• *Step 2*: Thermo-mechanical processing

Fig. 5 illustrates the thermo-mechanical cycles used in the experiments. A Pt-Pt/Rh thermocouple was spot-welded at the point of half way along the longitudinal of the specimen to measure the temperature and to provide feedback to the simulator electronics. The cooling between the various isothermal steps was achieved by using a computer-controlled nitrogen jet directed at the specimen.

Specimens were austenitized at 950 (°C) for 5 (min) and cooled to 880 (°C) at the cooling rate of 30 (°C/s). After cooling to 880 (°C), the samples were 40 (%)-deformed. The deformed specimen were cooled to the various isothermal temperatures and finally isothermally transformed to pearlite and bainite at these temperatures for 10 (min).

• *Step 3*: Microscopy

The samples were characterized by using optical, scanning electron microscopy. Samples for optical and scanning electron microscopy were etched by using 2 (%) nital solution.

3.2 Transformation behavior

Fig. 6 shows a measured TTT diagram for the experimental alloy. The nose of C-curve of the isothermal transformation exists between 500 (°C) and 600 (°C), and the isothermal temperature increases or decreases from the range 500~600 (°C), the kinetics of the isothermal transformation of austenite gets slow drastically. The isothermal transformation at the nose of C-curve begins after incubation time of about 1 second. The transformation lasts for about 3 seconds after beginning. SK85 steel shows the delay of the isothermal transformation as expected.

3.3 Process conditions of the high carbon steel

As mentioned above, the cooling pattern on the ROT for the high carbon steel should be controlled by using FDT and CST because of the delay of the isothermal transformation kinetics. The cooling rate from FDT to CST should be as fast as possible and the time at CST be as long as possible to increase the volume fraction of the transformed product. In other words, we want to avoid some problems which result from the late transformation kinetics of high carbon steel. Based on Fig. 6, process conditions to produce the high carbon steel can be described as follows: 1) CST should be determined between 500 (°C) and 600 (°C) where the nose of C-curve for the isothermal transformation of SK85 steel exists, 2) the running speed of the hot strip on the ROT should be controlled between 750 and 850 (mpm) to guarantee at least 4 seconds at CST after cooling in order to increase the volume fraction of the transformed phase before coiling.

4. Simulation of cooling control

Authors developed the temperature simulator by using the temperature models (Eqs. (2)-(8)) [21]. The simulator can determine the number of the maximum banks and heads in order to guarantee at least 4 seconds at CST on the ROT. Fig. 7 shows the flowchart of the temperature simulator. The heat flux is the important parameter to determine the cooling performance. Before simulating the cooling pattern, we have to

Table 1. Cooling parameters to optimize the simulator.

Parameter	Value	Parameter	Value
Thick. (mm)	2.0	T_N (°C)	620-660
Width (mm)	1,100	Speed (mpm)	750-850
T_0 (°C)	880	Heat flux (W/m^2 °C)	2.0-3.0

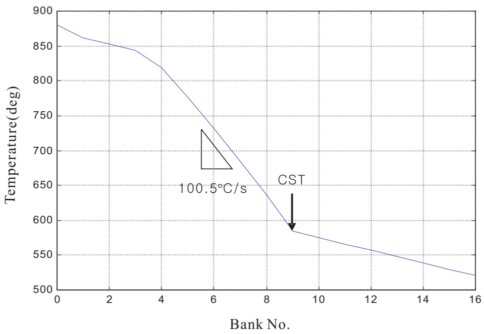

Fig. 8. Simulator optimization of high carbon steel.

optimize the simulator by reducing the difference between the estimated temperature by the simulator and the measured temperature in the field as shown in Fig. 8. The simulator can be optimized by regulating the heat flux coefficient in Eq. (6) under the same conditions as the field.

Fig. 8 shows the result of the simulator optimization under the product thickness 2.0 (mm), the carbon 0.85 wt. (%). We can obtain the parameters of the simulator, such as the heat flux coefficient and the model constants and so on, from the simulator optimization. Table 1 is the cooling conditions to optimize the simulator. We can calculate the rolling speed 750-850 (mpm), heat flux 2.0~3.0 (W/m^2 °C) in order to obtain the CST 500~600 (°C) within 4 (sec) as shown in Fig. 8 and Table 1. The optimization parameters can be calculated by the transformation time and the distance between two banks. The cooling speed at the continuous cooling zone can be obtained by 100.5 (°C) in Fig. 8.

Fig. 9 shows the simulation result of the cooling pattern by the optimized simulator in order to produce the high carbon steel in the field. The cooling conditions of the simulation are the same as the Table 1 except for the thickness. If the number of maximum head sets up 33, 30, 27 in case that the heat flux is 2.9 in Table 1, then CST can be obtained 517, 545, 582 (°C), respectively. In this paper, the optimal cooling pattern sets up the maximum head 27 and the maximum 8 bank.

5. Field test results

In this section, it is shown that the performance of the temperature control is improved by the proposed CST control. Fig. 10 shows the result of the field test for T_0, T_N as the pulse of the strip. The targets of T_0, T_N, rolling speed are 880 (°C), 650 (°C), 800 (mpm), respectively. The x-axis is a control period, which is called a pulse, and 1 pulse is 11.52 (m). The tail temperature of the strip in case of T_0 is decreased, because its radiation time is longer than the head of strip. The target tem-

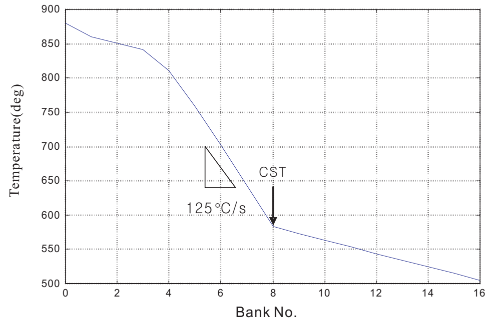

Fig. 9. Simulation result of cooling pattern.

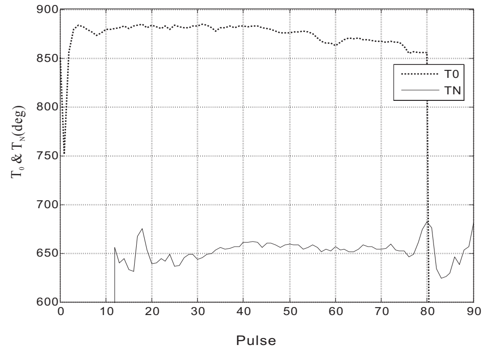

Fig. 10. Field test result of T_0 and T_N with CST control.

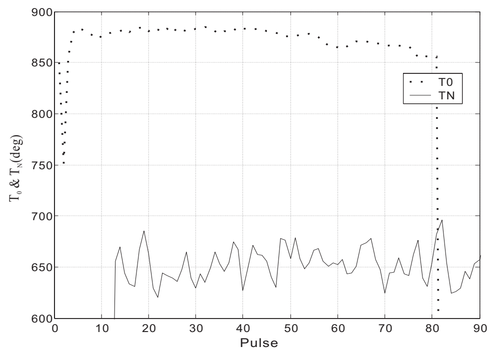

Fig. 11. Field test result of T_0 and T_N without CST control.

peratures of the head and tail are increased by 20 (°C), respectively, in order to easy to wind the strip. The standard deviation of T_N with CST control is improved by 10 (°C) compared with 16.8 (°C) without CST control as shown in Fig. 11.

Fig. 12 shows the middle temperature of the strip. The middle temperature can be measured between 8 and 9 bank. 'A' period of the figure is the step control as shown in Fig. 10. Since maximum 8 bank is watered as the rolling speed increases, 'C' is a temperature fluctuation period due to the cooling water on the strip. However, the temperature of the 'B' period is reliable since the cooling water has not an effect on this period. The maximum bank is 5 in this period. We can obtain the desirable CST from the field test because the measured temperature of 'B' period is 580 (°C).

Fig. 13 shows the microstructures of the tested strip along the longitudinal direction. Fig. 13(a), (b) and (c) are the micro-

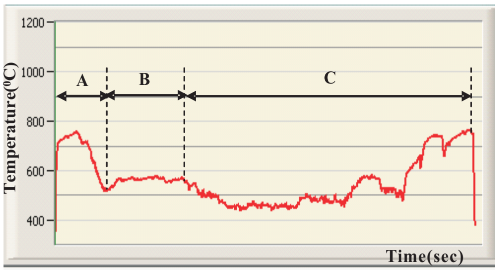

Fig. 12. Field test result of middle temperature.

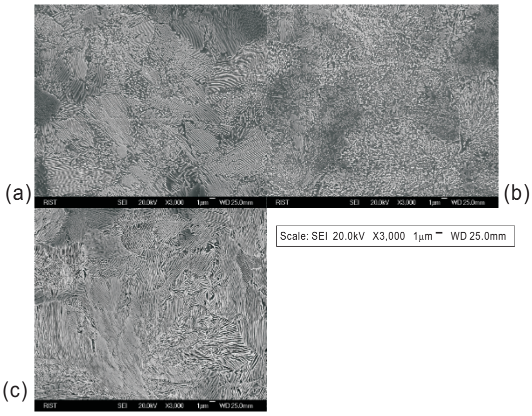

Fig. 13. Scanning electron micrographs showing fine pearlite (a), (c) and spherodized pearlite by self-annealing (b): (a) head part of tested strip, (b) middle part of tested strip, (c) tail part of tested strip.

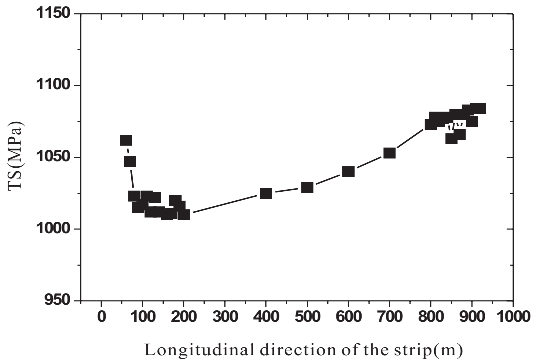

Fig. 14. Tensile strength (TS) of the tested strip.

structures in the head, middle, tail part of the strip, respectively. The microstructures of the tested strip along the longitudinal direction are the uniform fine pearlite as shown in (a) and (c). They don't show the coarse pearlite transformed at relatively elevated temperature due to exothermal reaction during transformation austenite to pearlite after coiling. The spherodized pearlite microstructure is shown in the middle of the strip, because the slow cooling rate after coiling anneals the pearlite microstructure, which results in the spherodized pearlite microstructure in Fig. 13(b). It means that the temperature of the tested strip along the longitudinal direction is cooled to CST on the ROT and most parts of the tested strip are transformed to pearlite on the ROT before coiling by the new cooling pattern.

Fig. 14 shows the tensile strength (TS) of the tested strip along the longitudinal direction. The TS of the tested strip is 1040 (MPa), and the difference between minimum TS and maximum TS in the strip is about 70 (MPa). This deviation of TS in the strip controlled with CST is much improved, compared with the strip controlled with CT. TS in the head part of the tested strip is about 1060 (MPa). TS decreases to about 1010 (MPa) up to 100 (m) ahead from the head part of the strip and increases again to 1080 (MPa) along the longitudinal direction. TS in the middle of the strip is lower than that of the other parts because of self-annealing in the middle part. The temperature in the head and tail drops relatively fast after coiling and the decrease of the temperature in the middle of the strip is slower. This results in self-annealing in the middle part of the strip. It can be confirmed in Fig. 13(b).

From the on-line field test for 3 months, the ratio of the pearlite transformation is increased from 50 (%) to 93 (%), and the temperature deviation is decreased by 18.2 (%). Moreover the coil numbers of the collapsed and the edge crack are decreased due to the fully transformation.

6. Conclusions

The temperature control of the high carbon steel with CST concept is developed and applied to the hot strip mill of POSCO in order to obtain fully transformed steel on the ROT.

The temperature prediction model with the radiation and the water cooling is described from the heat transfer governing equation. The phase transformation is analyzed by the TTT curve from the dilatometric experiment. CST control concept is proposed to obtain the fully transformation phase for the high carbon steel. The temperature simulator is developed to achieve the desired temperature by using the rolling speed, cooling pattern, and so on.

The results of the field test have shown that the ratio of the pearlite transformation has greatly increased by 43 (%) from 50 (%) to 93 (%), and the temperature deviation is decreased by 18.2 (%), respectively. It is believed that the proposed control is very effective in obtaining the uniform quality of the material along the longitudinal direction of the strip.

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References

[1] M. Phaniraj, S. Shamasundar and A. K. Lahiri, Relevance of ROT control for hot rolled low carbon steels, *Steel Res.*, 72 (5) (2001) 221-224.

[2] W. Timm, K. Weinzierl, A. Leipertz, H. Zieger and G. Zouhar, Modelling of heat transfer in hot strip mill runout table cooling, *Steel Res.*, 73 (3) (2002) 97-104.

[3] M. Suehiro, T. Oda, T. Senuma and S. Konishi, Development of mathematical model for predicting transformation of high-carbon steel during cooling on runout table and its application to on-line temperature control of hot strip mill, *Nippon Steel Technical Report*, 67 (1995) 49-56.

[4] R. Xu, J. Liu, Y. Zhang, R. Guo and W. Liu, Transformation-induced plasticity of expandable tubulars materials, *Materials Science and Eng. A 438-440 (SPEC. ISS.)*, (2006) 459-463.

[5] T. Oda, Y. Kondo, S. Konishi, H. Murakami, M. Suehiro and T. Yabuta, Development of accurate temperature control in hot strip mill, *The Iron and Steel Institute of Japan*, 81 (3) (1995) 35-40.

[6] N. S. Samaras, Novel control structure for runout table coiling temperature control, *AISE Steel Tech.*, (2001) 55-59.

[7] A. G. Groch, R. Gubernat and E. R. Birstein, Automatic control of laminar flow cooling in continuous and reversing hot strip mills, *Iron and Steel Eng.*, 67 (9) (1990) 16-20.

[8] R. W. Moffat, M. C. Moore, M. J. Robinson and J. D. Ashton, Computer control of hot strip cooling temperature with variable flow laminar sprays, *Iron and Steel Eng.*, 62 (11) (1985) 21-28.

[9] G. V. Ditzhuijzen, The controlled cooling of hot rolled strip: A combination of physical modeling, control problems and practical adaption, *IEEE Trans. on Automatic Control*, 38 (7) (1993) 1060-1065.

[10] M. D. Leltholf and J. R. Dahm, Model reference control of runout table cooling at LTV, *Iron and Steel Eng.*, 66 (8) (1989) 31-35.

[11] N. S. Samaras and M. A. Simaan, Water-cooled end-point boundary temperature control of hot strip via dynamic programming, *IEEE Transactions on Industry Applications*, 34 (6) (1998) 1335-1341.

[12] N. S. Samaras and M. A. Simaan, Optimized trajectory tracking control of multistage dynamic metal-cooling processes, *IEEE Transactions on Industry Applications*, 37 (3) (2001) 920-927.

[13] S. K. Biswas, S. Chen and A. Satyanarayana, Optimal temperature tracking for accelerated cooling processes in hot rolling of steel, *Dynamics and Control*, 7 (1997) 327-340.

[14] T. Harakawa and T. Kawaguchi, Digital control in iron and steel-making processes, *Automatica*, 20 (5) (1993) 1185-1202.

[15] R. K. Kumar, S. K. Sinha and A. K. Lahiri, An on-line parallel control for the runout table of hot strip mills, *IEEE Transactions on Control Systems Technology*, 9 (6) (2001) 821-830.

[16] S. Guan, H. X. Li and S. K. Tso, Multivariable fuzzy supervisory control for the laminar cooling process of hot rolled slab, *IEEE Transactions on Control Systems Technology*, 9 (2) (2001) 348-356.

[17] N. Hatta and H. Osakabe, Numerical modeling for cooling process of a moving hot plate by a laminar water curtain, *The Iron and Steel Institute of Japan*, 29 (11) (1989) 919-925.

[18] D. Auzinger and F. Parzer, Process optimization for laminar cooling, *MPT International*, 5 (1996) 68-75.

[19] E. N. Hinrichsen and G. P. Petrus, Hot strip mill runout table cooling-A system view of control, operation and equipment, *Iron and Steel Eng.*, 53 (10) (1976) 29-34.

[20] K. Yanagi, Prediction of strip temperature for hot strip mills, *The Iron and Steel Institute of Japan*, 16 (1) (1976) 11-19.

[21] H. Yoshida, A. Yorifuji, S. Koseki and M. Saeki, An integrated mathematical simulation of temperatures, rolling loads and metallurgical properties in hot strip mills, *The Iron and Steel Institute of Japan*, 31 (6) (1991) 571-576.

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