Analysis and Process Control of Induction Heater in Hot Strip Mill

Toshihito Shimotani[1], Masayasu Sekimoto[1], Sho Ito[1], Kohji Dohjoh[1], Takahiro Mitsui[1]

[1]TMEIC Corporation
3-1-1 Kyobashi, Chuo-ku, Tokyo, Japan. 104-0031
Phone:+81-3-3277-4940
Email:SHIMOTANI.toshihito@tmeic.co.jp, SEKIMOTO.masayasu@tmeic.co.jp, ITO.sho@tmeic.co.jp
DOHJOH.kohji@tmeic.co.jp, MITSUI.takahiro@tmeic.co.jp

ABSTRACT

Induction heating (IH) is installed in hot strip mills to improve strip temperature control. IH has relatively higher heating efficiency and responsiveness compared to other heating methods, while emitting less carbon dioxide. To heat the strip effectively using IH, the induction heaters should be optimally controlled. In this paper we introduce analysis and online control functions for IH to achieve the required temperature distribution in both the length and width axes. The mathematical model for this control is constructed based on the results of analysis by electromagnetic finite element method. Furthermore, an optimization calculation to determine the widthwise heating pattern by the combination of multiple IHs is introduced.

Keywords: Induction heating, Bar heater, Edge heater, Process control, Temperature control, Hot strip mill, Finite element method, Genetic algorithm

INTRODUCTION

In hot rolling, improvement of product quality and operational stability have been long-standing issues. To address these issues, temperature control of the strip during rolling is crucial, as mechanical characteristics such as hardness are highly dependent on temperature. It is necessary to control the temperature not only in the lengthwise (rolling direction) but also widthwise. However, controlling the ideal temperature distribution in the width axis is particularly challenging due to the limitations of the actuators used for temperature control.

Electromagnetic Induction heating (IH) is an effective method of strip heating. IH for hot rolling is normally installed between the roughing mill (RM) and the finishing mill (FM) (Figure 1). The steel strip being processed in this region is called a “bar”. IH has significant merits for hot rolling. For example, heating to reduce lengthwise and widthwise temperature unevenness can improve the product quality. Heating the head end of the strip can improve the stability of threading in FM. Heating the tail end can reduce the risk of tail chew.

In addition, in recent years, carbon neutrality targets have led to requirements to reduce CO2 emissions and a shift to electrification in the steel industry. In this aspect, IH has a significant advantage because it uses electrical power for heating and has high heating efficiency.

Due to the above reasons, IH has been installed in many hot rolling facilities[1]. However, the IH must be controlled correctly to heat the strip effectively. In particular, for widthwise temperature control, combining heating by several heaters is effective. This requires a highly accurate control model for IH.

In this paper, at first, heating theory and IH characteristics are described. Then, the technique used to analyze heating characteristics correctly - computational simulation by 3-dimensional finite element method (FEM) - is described. Then, online control functions for induction bar heaters (BH) and edge heaters (EH) are described. These functions calculate the optimal heating amount based on strip temperature predicted by a 2-dimensional (thickness and width axes) temperature model. The calculation to determine the optimal widthwise heating pattern using several IH’s is also described.

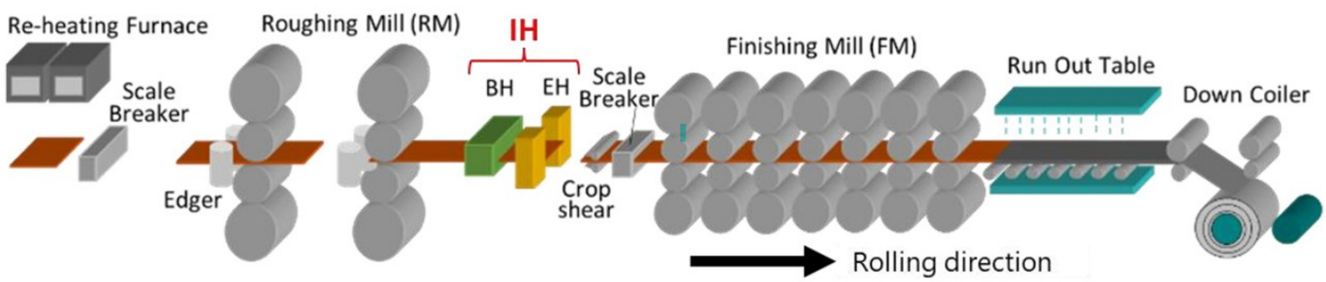


Figure 1. Heater equipment layout in the Hot Strip Mill

THEORY OF INDUCTION HEATING

IH heats up the strip by eddy currents induced by alternating magnetic flux through the strip. Eddy current flows in a cross section which is vertical to the magnetic flux. The distribution of the induced magnetic flux is determined by mechanical and electrical characteristics. The mechanical characteristics are the shape of the heating coil and iron core. The electrical characteristic is the skin depth of the eddy current, which depends on the electrical frequency, the electrical resistivity and the magnetic permeability of the strip.

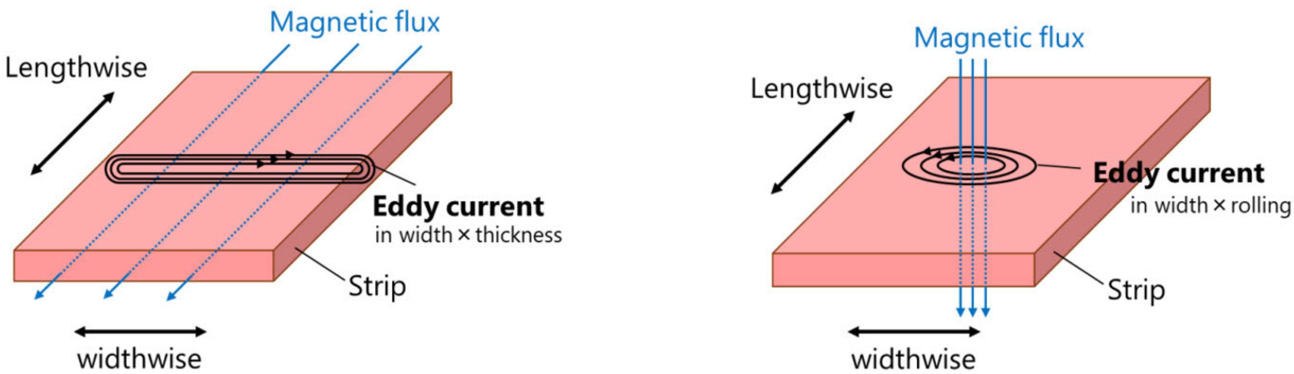


Figure 2. Physical principle of Solenoid/Transverse type IH

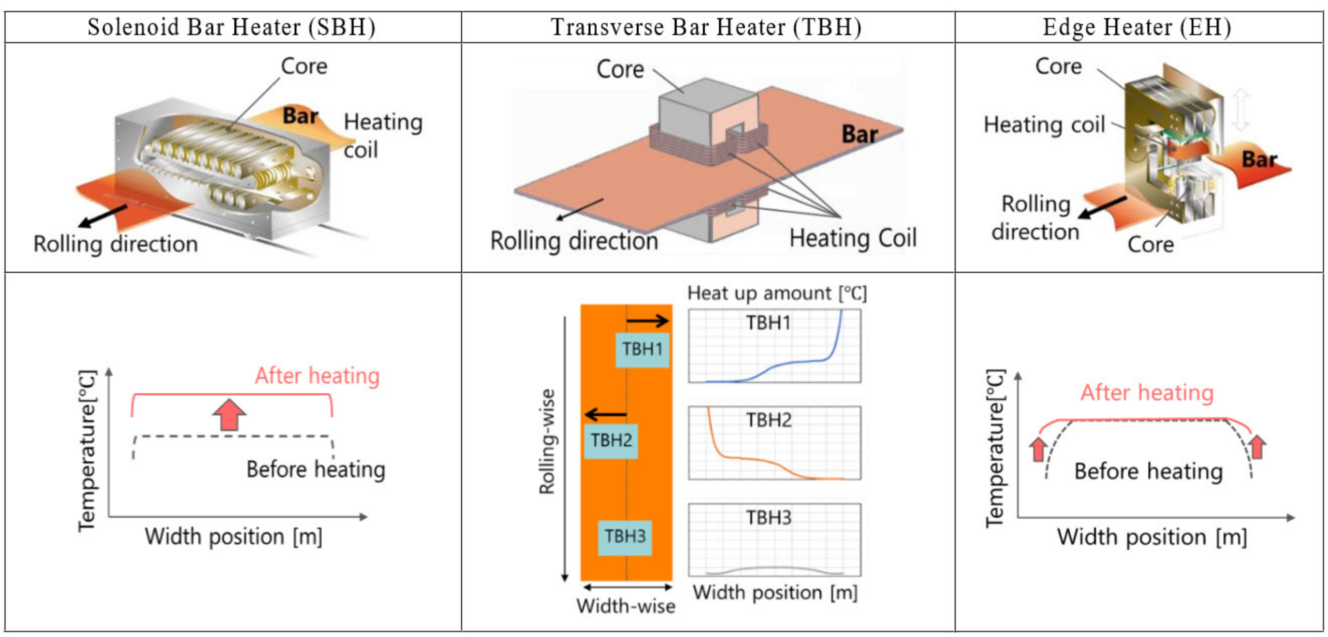


Figure 3. Comparison of each Heater equipment

IH for hot rolling can be divided into two types – "solenoid type" and "transverse type" as shown in Figure 2. The two types are distinguished by the direction of the alternating magnetic flux through the strip as follows:

Solenoid type
In the solenoid type IH, magnetic flux parallel to the length axis of the strip is generated by a heating coil wound around the strip. In this case, eddy current flows through the thickness-width cross section of the strip. Normally, the solenoid type can heat the strip uniformly across its width.

Transverse type
In the transverse type IH, the heating coil and iron core are designed to generate magnetic flux parallel to the thickness axis of the strip. Eddy current flows through the width-length cross section of the strip. The eddy current distribution and the resultant heating across the strip width are non-uniform and depend on the mechanical design of the heater and its position across the strip width. In particular, the IH can be designed and positioned to provide higher eddy current density at the edge of the strip, to heat the edge more than the rest of the strip.

In addition to the above division (solenoid/transverse), IH can be divided into "bar heater" (BH) and "edge heater" (EH) types based on the purpose of the heating. BH is mainly used to heat the strip across its entire width. EH is mainly used to heat up the (width axis) edges. Figure 3 shows the example of IH equipment. A solenoid bar heater (SBH) can heat the strip uniformly across its width. Transverse bar heater (TBH) can be designed and positioned on the width axis to provide a specific width distribution of heating. EH can locally heat the edges.

COMPUTATIONAL SIMULATION OF HEATING CHARACTERISTICS

This section describes the computational simulation of IH by 3-dimensional FEM. FEM is useful for detailed analysis of the heating characteristics of IH. Electromagnetic analysis using the FEM model allows calculation of distributions such as magnetic flux and eddy current at each part of the heater and strip. The FEM model is also used to estimate the heat amount by IH. Equations for electromagnetic analysis are described as follows:

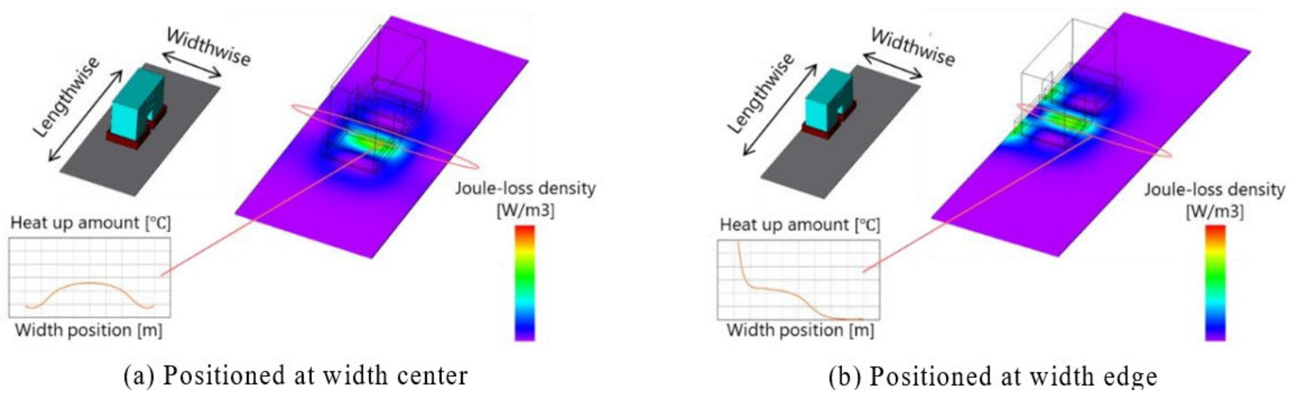


Figure 4. Electromagnetic FEM for TBH

Equation for Electromagnetic Analysis
Ampere-Maxwell law in frequency domain is as follows.

$$\mathrm{rot}\boldsymbol{H} = \mathrm{j}\omega\boldsymbol{D} + \boldsymbol{J} \tag{1}$$

where $\boldsymbol{H}$, ω, $\boldsymbol{D}$ and $\boldsymbol{J}$ are magnetic field, angular frequency, electric flux density and current density, respectively. can be expressed as follows.

$$\boldsymbol{D} = \epsilon\boldsymbol{E} \tag{2}$$

where $\boldsymbol{E}$ and ϵ are electric field and permittivity. Here, current density $\boldsymbol{J}$ can be expressed as follows.

$$\boldsymbol{J} = \boldsymbol{J}_{\mathrm{o}} + \sigma\boldsymbol{E} \tag{3}$$

(3) where $\boldsymbol{J}_{\mathrm{o}}$ and σ are source current density and electric conductivity, respectively. $\boldsymbol{H}$ can be expressed as follows.

$$\boldsymbol{H} = \gamma \boldsymbol{B} \tag{4}$$

where γ and $\boldsymbol{B}$ are magnetic resistivity and magnetic flux density, respectively. γ can be expressed as follows.

$$\gamma = 1/\mu \tag{5}$$

where μ is magnetic permeability. Gauss's law for magnetism is as follows.

$$\mathrm{div}\boldsymbol{B} = 0 \tag{6}$$

From eq(4), because rotation of divergence is 0, $\boldsymbol{B}$ can be expressed using rotation.

$$\boldsymbol{B} = \mathrm{rot}\boldsymbol{A} \tag{7}$$

where $\boldsymbol{A}$ is magnetic vector potential. By substituting eq(3), (4) and (7) into equation (1), and if we assume in (1) that D is small and can be ignored, the following equation is obtained:

$$\mathrm{rot}\gamma\mathrm{rot}\boldsymbol{A} = \boldsymbol{J}_{\mathrm{o}} + \sigma\boldsymbol{E} \tag{8}$$

Faraday's law is as follows:

$$\mathrm{rot}\boldsymbol{E} = -\mathrm{j}\omega\boldsymbol{B} \tag{9}$$

Considering eq(7) and (9), since the rotation of the gradient of a scalar field is identically zero, $\boldsymbol{E}$ can be expressed as follows.

$$\boldsymbol{E} = -\,\mathrm{j}\omega\boldsymbol{A} - \mathrm{grad}\varphi \tag{10}$$

where φ is electric scalar potential. By substituting eq(10) into eq(8), the following equation is obtained.

$$\mathrm{rot}\gamma\mathrm{rot}\boldsymbol{A} + \sigma(\mathrm{j}\omega\boldsymbol{A} + \mathrm{grad}\varphi) = \boldsymbol{J}_{\mathrm{o}} \tag{11}$$

By taking divergence of equation (11), the following equation is obtained.

$$\mathrm{div}\sigma(\mathrm{j}\omega\boldsymbol{A} + \mathrm{grad}\varphi) = 0 \tag{12}$$

After discretizing eq(11) and (12), by solving simultaneous equation of them considering boundary condition in FEM, distribution of magnetic field in analysis region can be obtained. In this study, we used JMAG-Designer, produced by JSOL Corporation, a Japanese company, for FEM analysis.

Example of FEM Analysis

An example of FEM analysis for TBH is shown in Figure 4. Heating data for various strip sizes and steel grades can be obtained through FEM analysis. From these results, a highly accurate mathematical model for the online-control function described in the next section can be constructed. Additionally, many heating patterns can be easily evaluated without experimentation.

IH ONLINE CONTROL FUNCTION

This section describes the IH online BH control function and EH control function[2].

BH Control Function

The BH control function shown in Figure 5 consists of the following sub-functions: "Initial setup", "Feedforward control", "Feedback control", and "Model learning". In each sub-function, the temperature distribution in the thickness-width cross-section for each segment along the bar length is predicted by a 2D-temperature model[3].

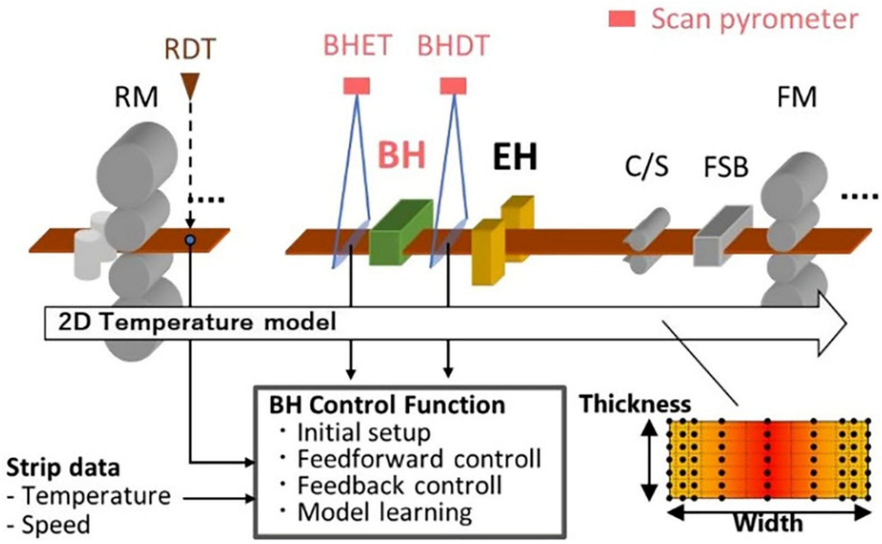


Figure 5. BH control system

Initial Setup

BH output power and position (lateral shift, in the case of TBH) are calculated to achieve the target temperature at BH exit (BHDT) based on the measured roughing mill delivery temperature (RDT), actual strip speed, steel grade, strip size and so on.

Feedforward Control

Based on the temperature measured at the BH entry (BHET), BH output power for measured point is dynamically compensated before heating.

Feedback Control

Based on the deviation between the measured and target temperature at the BH exit (BHDT), BH output power is dynamically compensated during heating. The delay time due to the distance from BH to BHDT can be compensated using the Smith method.

Model Learning

Based on the heating results of the strip, the mathematical model for BH heating is automatically adapted.

Lengthwise and widthwise temperature control by BH is described below.

(1) Lengthwise Temperature Control

There are two control mode for lengthwise temperature control. One is heat up pattern control and another one is target temperature control.

(1-1) Heat Up Pattern Control

Heat up pattern control consists of four heat up patterns which are open loop controls, as shown in Figure 6. 4 . Patterns can be selected and combined to implement a specific temperature increase as a function of length. Mode A is constant heat up. This is the simplest heat up pattern. Mode B is slope heat up. This pattern is applied to reduce thermal run down in the rolling direction, especially for thin strips. Mode C is head/tail heat up. This pattern is applied to reduce instability during threading and tail drop-out. Mode D is used to reduce temperature deviation caused by skid marks, which are periodic temperature deviations resulting from heat transfer from the strip to the skids in a reheating furnace. Reference power to compensate for skid marks is calculated based on the measured RDT.

The above four patterns can be combined for heating purposes. Figure 7 shows an example of a combined heat up pattern using modes A, B, and D.

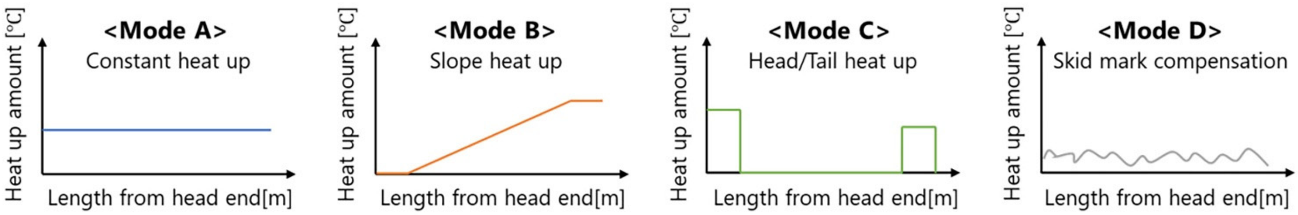


Figure 6. BH heat up pattern

(1-2) Target Temperature Control

Target temperature control is a closed-loop control designed to achieve the target BHDT for the entire strip length. If a constant target BHDT is given, and the required BH heat up amount is smaller than the maximum BH heating capacity, which is mainly determined by maximum power and strip speed, the target BHDT is achievable for the entire length. However, if the required BH heat up power is larger than the maximum BH power, the target BHDT is not achievable due to power limitations. Because the maximum heat up amount reduces as strip speed increases, an increase in strip speed could result in the heat up amount reaching its limit, the BHDT reducing, and skid marks remaining because of lack of capacity to remove them, as shown in Figure 8 (a). To avoid the above issue, the target BHDT can be modified by considering the maximum heat amount predicted by speed pattern prediction. As a result, the BHDT is not equal to the original constant target, but is smoother than the previous case, as shown in Figure 8 (b).

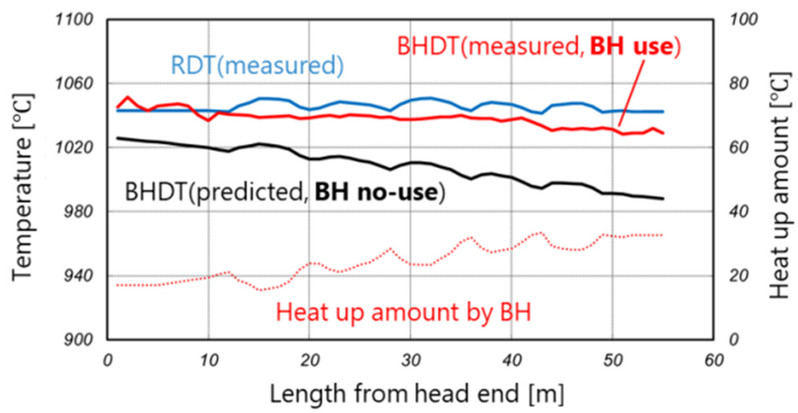
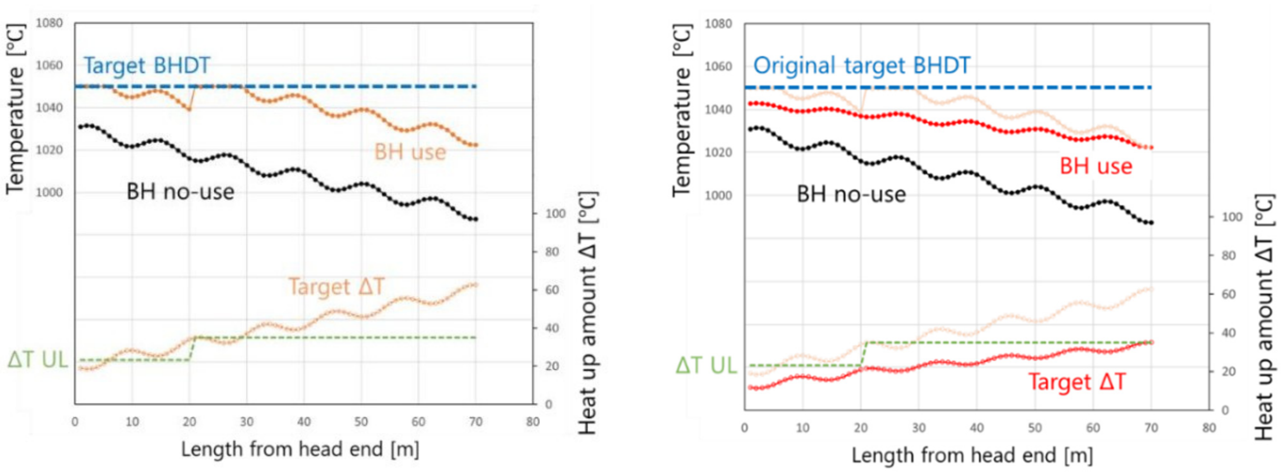


Figure 7. Example of heat up pattern control (Mode A+B+D)



(a) Without considering power limit

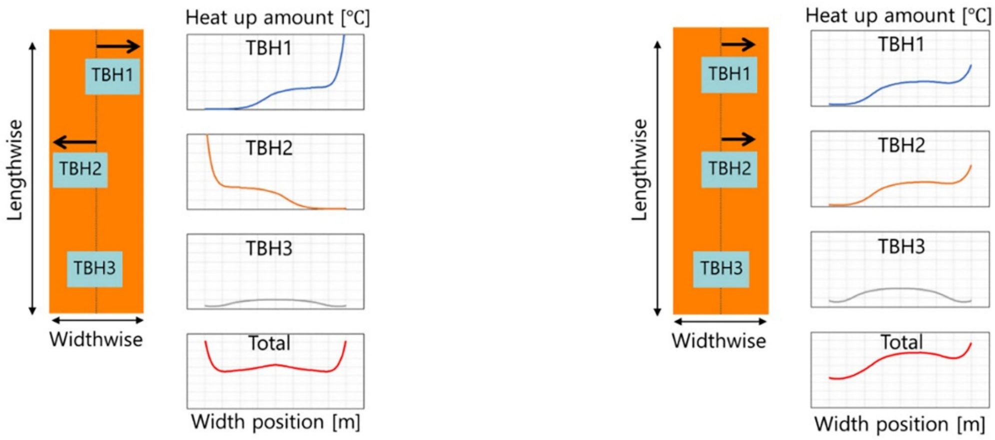
(b) With considering power limit

Figure 8. Example of finishing entry temperature control

(2) Widthwise Temperature Control

SBH uniformly heats the strip temperature across the width. On the other hand, the heat up distribution by TBH depends on the heater position across the width. For example, when TBH is located closer to the width edge, the heat up amount at the width edge increases due to more eddy currents through the edge.

In a typical configuration, three TBHs are installed along the mill length. The widthwise temperature distribution at the TBH delivery is determined by the total heat amount of each TBH. Therefore, the position across the width and the output power of each TBH should be determined according to the heating conditions, which consist of strip size, temperature distribution at the BH entry, and target temperature distribution at the BH delivery. Typical heat up patterns by TBH, (a) edge heat up and (b) asymmetrical heat up, are shown in Figure 9.



(a) Edge heat up

(b) Asymmetrical heat up

Figure 9. Example of widthwise heat up by TBH

EH Control Function

The EH control function shown in Figure 10 consists of the following sub-functions, similar to the BH control function. In each sub-function, the temperature distribution in the thickness-width cross-section is predicted by a 2D-temperature model.

Initial Setup

The EH control function sets the EH output power to achieve the target temperature at EH exit (EHDT) based on the measured roughing mill delivery temperature (RDT), actual strip speed, steel grade , strip size and so on.

Feedforward Control

Based on the temperature measured at the EH entry (BHDT), EH output power for the measured point is dynamically compensated before heating.

Feedback Control

Based on the deviation between the measured and target temperature at the EH exit (EHDT), EH output power is dynamically compensated during heating. The delay time due to the distance from EH to the EHDT can be compensated using the Smith method.

Model Learning

Based on the heating results of the strip, the mathematical model for EH heating is automatically adapted.

The target temperature in EH control is defined at a point 25mm from the edges. For example, it is the increased temperature from the EH entry (BHDT) to the EH delivery (EHDT).

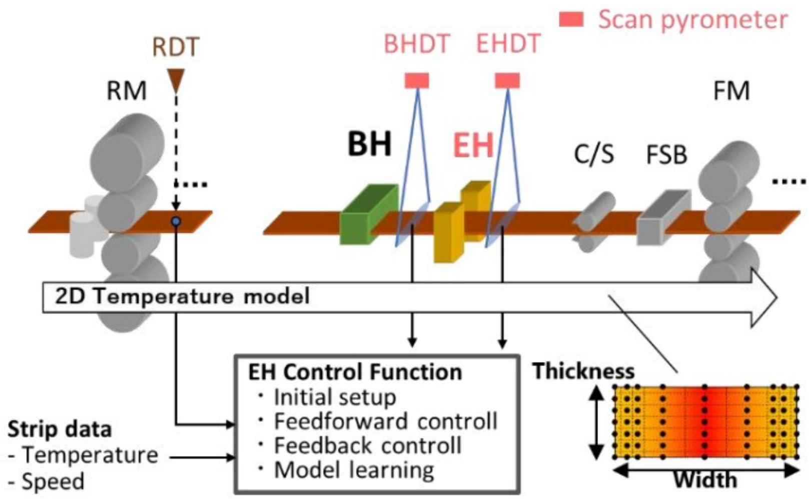


Figure 10. EH control system

OPTIMIZATION CALCULATION

This section describes the optimization calculation for widthwise heating of the strip. The target widthwise temperature distribution can be approximated by optimal heating, which sets output power and width position (shift) of each IH. It is necessary to set the output power and position of each IH according to the strip size, temperature distribution at IH entry, and the target temperature distribution at IH delivery.

Optimization Method

Here, an example of applying the genetic algorithm (GA) [4] as the optimization method is introduced. In GA, we start with an initial population of possible parameter sets. Optimal parameters are found by repeating crossover, selection, mutation, and evaluation, as shown in Figure 11. GA is well known to be effective for nonlinear problems and large-scale problems. The setting conditions of GA for this study are summarized in Table 1.

Table 1. Condition of GA

Number of individuals	200
Selection method	Tournament selection
Cross over model	Two-point crossover
Convergence condition	If objective function does not change for 200 consecutive generations.

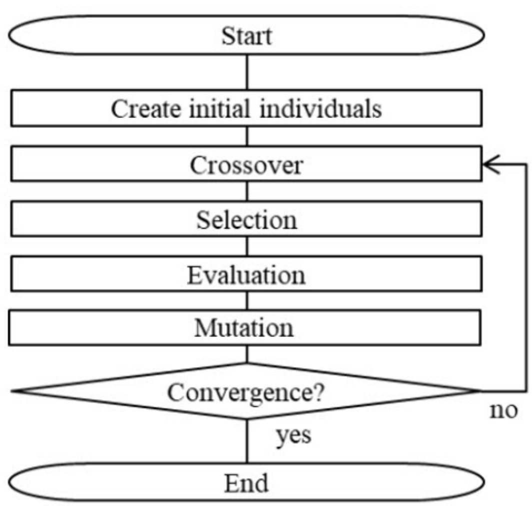


Figure 11. Calculation flow GA

Objective Function

The objective function J is defined for the optimization as follows.

$$\min. \quad J = \frac{1}{N_{node}} \sum^{N_{node}} \left(T^{tgt} - T_i^{cal}\right)^2 \tag{11}$$

where N_{node}, T^{tgt}, T_i^{cal} are number of the width nodes, target temperature at IH exit and calculated temperature of node i, respectively. T_i^{cal} is calculated by following equation. Here, target temperature T^{tgt} is common for all nodes.

$$T_i^{cal} = T_i^{init} + \Delta T_i \tag{12}$$

$$\Delta T_i = \frac{P_i}{\rho c_p H B_i v} \tag{13}$$

where T_i^{init}, ΔT_i, P_i, ρ, c_p, H, B_i and v are entry temperature of node i, node i temperature increase due to IH, IH heating power (total power of each unit) into node i, strip density, strip specific heat, strip thickness, width of node i and strip speed, respectively. P_i is calculated using mathematical model base on the FEM results for each heater. Note that, in the case of TBH, P depends on the width shift position.

Simulation Results

Simulation results of the optimization are shown below. Two cases are implemented. Case 1 assumes that the widthwise entry temperature distribution is asymmetrical and SBH (1 unit) and TBH (3 units) are installed. Case 2 assumes that the widthwise entry temperature has periodic deviation and EH (1 unit) and TBH (3 units) are installed. A summary of the conditions of each case is shown in Table1.

Table 1. Optimization condition

Units	Strip thickness / width	Exit target temperature
case1: SBH(1unit) + TBH(3unit) case2: EH(1unit) + TBH(3unit)	40mm / 1000mm	1070℃

For simplicity, IH entry temperature ("Ent_Temp") is artificially created by a mathematical formula.

The results of simulated temperature in case 1 are shown in Figure 12. IH exit temperature ("Exit_Temp") is close to the target temperature ("Tgt_Temp"). The shift position of each TBH is properly determined to reduce the asymmetry of entry temperature. Temperature drop at the width edge is also reduced by edge heating by TBH.

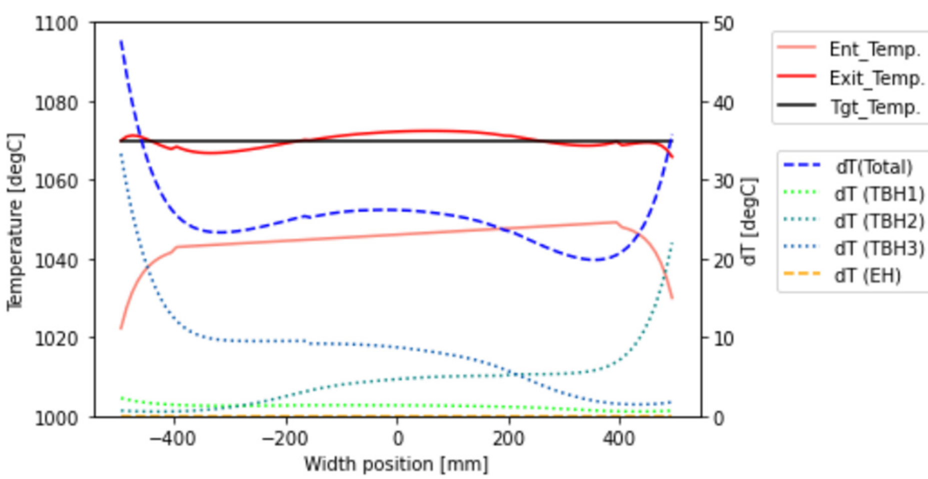


Figure 12. Result of an optimization calculation (case1)

The results of simulated temperature in Case 2 are shown in Figure 13. IH exit temperature is close to the target temperature. The shift position of each TBH is properly determined to reduce the unevenness of entry temperature. Temperature drop at the edge is also reduced by EH.

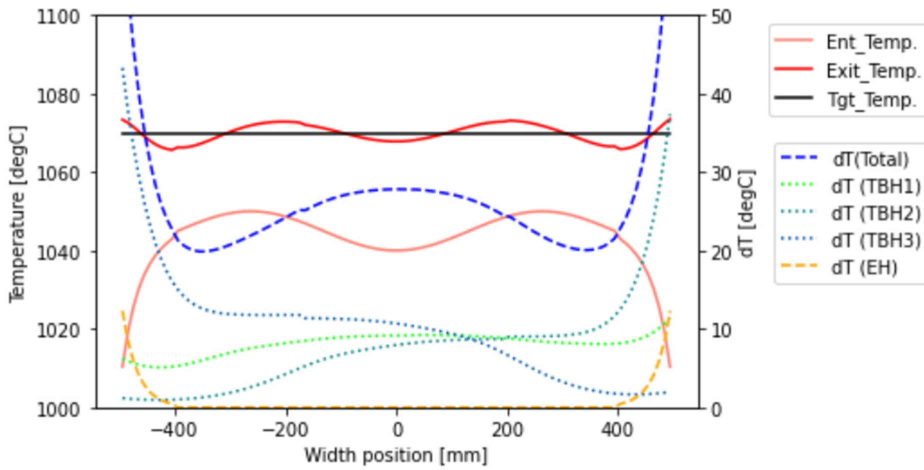


Figure 13. Result of an optimization calculation (case2)

The history of the best objective function of each generation in Case 2 is shown in Figure 14. From the first generation, the objective function is small value (≈0.4), because initially a large number of individuals (=200) are prepared. Then, it gradually improved until about 500 generations. After that, there is very little improvement.

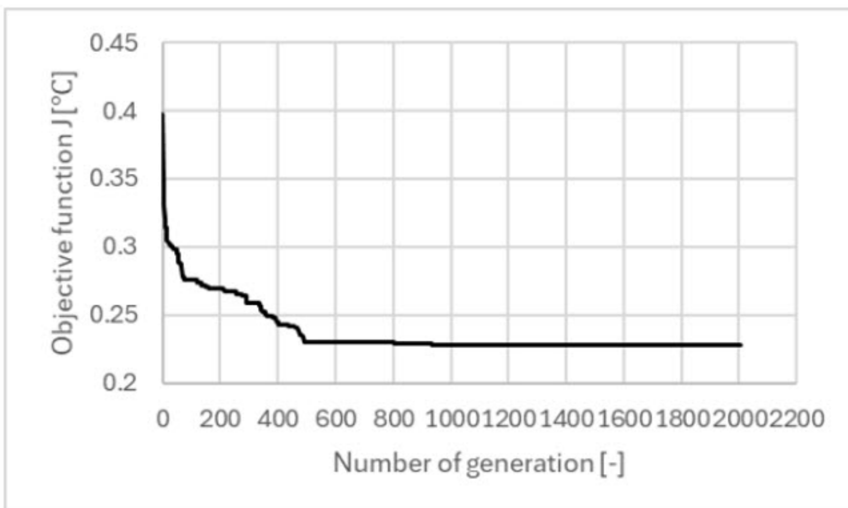


Figure 14. History of best objective function in case2

CONCLUSIONS

In this paper, principles of the IH, computational simulation, online-control function and optimization calculation are described. In computational simulation, 3D-FEM is performed to analyze the heating characteristics of IH in detail. Heating data for various strip sizes and steel grades can be obtained through FEM analysis. From these results, a comprehensive mathematical model for the online-control function can be constructed. Online BH/EH functions consist of initial setup, feedforward , feedback, and model learning. These functions can achieve optimal lengthwise and widthwise temperature distribution. Furthermore, by optimization calculation using GA, power and position settings for each IH can be obtained to minimize widthwise temperature deviation. The optimization has been verified by simulation under simple conditions.

IH not only enhances the stability and product quality of hot rolling but also plays a significant role in advancing towards carbon neutrality. The development of highly accurate IH control leads the hot rolling process to the next stage.

REFERENCES

1. Lucia , O.; Maussion, P.; Burdio, D. E. J. "Induction Heating Technology and its Applications: Past developments, current technology, and future challenges," IEEE Trans. Ind. Electron., 61-5 (2014).
2. Gepitulan, G.; Imanari, H.; Hashimoto, E.; Doizaki, T. "Induction Bar and Edge Heating Technology in the Hot Strip Mill," AISTech 2019 - Proceedings of the Iron & Steel Technology Conference, (2019), P. 1579-1585.
3. Shimoda, N.; Imanari, H.; Suzuki, A.; Sano, M.; Ohara, K. "Advanced Technologies of Process Control to Hot Strip Rolling Mill." Proceedings of the ESTAD2019, (2019).
4. Shimotani, T, "Study on numerical analysis and control model of induction heater in hot strip rolling", PhD thesis, Hokkaido university, (2020).
5. T. Shimotani, T. Mitsui, M. Sekimoto, H. Imanari, T. Hihara, "Recent Technologies of Optimal Induction Heating for Hot Strip Mill", Proceedings of the ESTAD2023, (2023).

