Abridged version

KAWASAKI STEEL TECHNICAL REPORT
No.9 (March 1984)

Optimized Operation System in Hot Strip Rolling

Nariharu Kitao, Masamitsu Obashi, Kiyoshi Takagi, Masayasu Fukui, Ichiro Toda, Kozo Ishikawa, sumihiko Iro

---

Synopsis :
Optimized operation system from furnaces to coilers has been developed at the hot strip mill of Mizushima Works. This system consists of furnace combustion control, mill pacing control and direct digital control from delay table to coilers and is well combined with various rolling techniques. By introducing the system, the accuracy of the temperature calculation model of slab and sheet bar is greatly improved, i.e., $1\sigma = 12$℃, and sheet bar temperatures at the exit of roughing train can be controlled so as to follow closely changeable target values. Furthermore, the rolling interval time at No.1 finishing mill has been shortened to 5 seconds from previous 12 seconds, when the setting of finisher rolling speed is changed.

The body can be viewed from the next page.

Optimized Operation System in Hot Strip Rolling*

Nariharu KITAO ** Masamitsu OBASHI ** Kiyoshi TAKAGI **
Masayasu FUKUI ** Ichiro TODA ** Kozo ISHIKAWA **
Sumihiko ITO **

Optimized operation system from furnaces to coilers has been developed at the hot strip mill of Mizushima Works.

This system consists of furnace combustion control, mill pacing control and direct digital control from delay table to coilers and is well combined with various rolling techniques.

By introducing the system, the accuracy of the temperature calculation model of slab and sheet bar is greatly improved, i.e., $1\sigma = 12°C$, and sheet bar temperatures at the exit of roughing train can be controlled so as to follow closely changeable target values. Furthermore, the rolling interval time at No. 1 finishing mill has been shortened to 5 seconds from previous 12 seconds, when the setting of finisher rolling speed is changed.

1 Introduction

Since its start in January 1970, the hot strip mill plant[1] of Mizushima Works has added rolling stands and reheating furnaces to boost its annual production capacity to 4.6 million tons today. Promoted over these years were active construction and improvement of rolling mills, efficiency increase in the slab reheating furnaces[2,3,4], advancement of hot charging and low-temperature discharging[5], and development of sophisticated operational techniques.

On the other hand, the recent trend of permeation of the automated rolling process is amazing. Up until today, certain levels of automatization and systems development were made in hot strip mill plants of various steel companies. Good examples were the application of direct digital control to the reheating furnace combustion phase and to the electric and instrumentation phase of rolling, as well as the systems developed by interrelating existing controls.

Taking into consideration the following various requirements from many users, the Hot Strip Mill Plant of Mizushima Works not only applied computer control to various existing techniques such as reheating furnace combustion control, tracking schedule calculation, and mill pacing control, but also developed an optimum operation system which has organically combined all these automated control measures:

(1) To meet needs for high quality steels which require the most severe heating temperature control
(2) To cope with complicated furnace operation such as low temperature discharging, hot charging, and furnace operation with heat patterns oriented toward energy saving
(3) To promote efficiency in software for reheating furnace operation
(4) To achieve rolling at an optimum temperature that satisfies both requirements for energy saving and high product quality
(5) To realize proper mill pacing control that can meet various rolling conditions
(6) To establish an operation technique that organically interrelate individual existing techniques
(7) To establish operation system which minimizes an overall line cost

The mainstay of the new system consists of:

(1) Reheating furnace combustion control
(2) Mill pacing control
(3) Direct digital control

The above-mentioned control system was advanced into an on-line system in July 1982. An outline of the system and its operation results are reported below.

2 System Outline

2.1 Basic Principles and System Features

The key point to fundamental policies of the system lies not only in forming a computer control system of

* Originally published in *Kawasaki Steel Giho*, **15** (1983) 4, pp. 273–279
** Mizushima Works

the reheating furnace alone, but in establishing an integrated system including the rolling line. Problems that occurred during operation in the past are cited below.

(1) Insufficient trackability of combustion control against complicated material kinds and variation in the target discharge temperature
(2) Limitation in production efficiency improvement when discharge pitch is determined by operator's judgement
(3) Low reliability in speed setting at various equipment in the rolling line

Therefore, the new system is aimed at satisfying all the above requirements and establishing an integrated cost minimum at the hot strip mill plant. **Figure 1** shows the configuration of the computer control system in the hot strip mill plant; **Table 1** shows the specifications of the rolling line.

This system features a function for optimized determination of target discharge temperature and mill pacing, so that valuation functions can be optimized depending upon the required levels of quality, cost and productivity. In concrete terms, the system gives the valuation functions for optimization in the following four modes:

(1) Rolling efficiency designating mode
(2) Rolling efficiency maximizing mode
(3) Fuel consumption minimizing mode
(4) Cost minimizing mode

Furthermore, for the objective parameters of optimization, the target discharge temperature and rolling pitch are determined by the following equation:

$$Z = F(Y_1, Y_2)$$
$$Y_1, Y_2 = G(W_i, \ldots, X_i, \ldots)$$
$$Y_{1\,\mathrm{opt}}, Y_{2\,\mathrm{opt}} = f(Z_{\mathrm{opt}})$$
$$X_i = g(Y_{1\,\mathrm{opt}}, Y_{2\,\mathrm{opt}}) \quad \cdots\cdots (1)$$

Z: Valuation function of optimization (rolling efficiency, fuel consumption, and cost)
Y: Target parameter (aimed discharge temperature and rolling pitch)
X: Operation parameter (outlet target discharge temperature of each slab at each

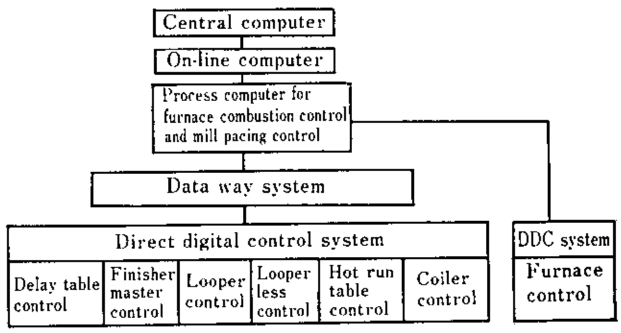
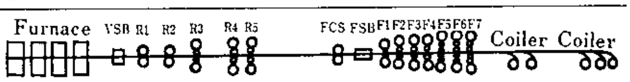


Fig. 1 Configuration and functions of computer and DDC system

Table 1 Basic specification of the facilities

Facilities	Number	Type and capacity
Slab reheating furnace	4	6-zone pusher type, Effective hearth length : 32.0 m, Hearth width : 12.9 m, Nominal capacity : 325 t/h, Type of fuel : oil and mixed gas
Vertical scale breaker	1	Overhead driven type Max. reduction : 75 mm at t = 305 mm
Roughing train	5	R1 : 2 high reversible type, R2 : 2 high non-reversible type, R3, R4, R5 : 4 high non-reversible type, tandem rolling between R4 and R5
Flying crop shear	1	2 cut inner stand type, Max. cutting thickness : 60 mm at sheet bar width of 1 500 mm
Finishing scale breaker	1	Pinch roll and high pressure water spray type Pressure : 150 kgf/cm^2
Finishing train	7	F1, F2, F3, F4 : 4 high type, F5, F6, F7 : 6 high type
Thin gage coiler	2	4 blocker roll type down coiler, Thickness of strip : 1.2 8.0 mm, Coil diameter : max. 2 300 mm Main motor : D.C. 280 kW×2
Thick gage coiler	2	No. 1, 2 : 4 blocker roll type down coiler, Thickness of strip : 1.2-13.0 mm, Coil diameter : max. 2 300 mm, Main motor : D.C. 280 kW×2
	1	No. 3 : 4 blocker roll type down coiler with bending roll, Thickness of strip : 2.3-32.0 mm, Coil diameter : max. 2 300 mm, Main motor : D.C. 500 kW×2



zone and furnace temperature set value for slab group in each zone)

W: Operation parameter (discharge temperature for each slab obtained from the quality conditions and temperature holding conditions)

First, the aimed discharge temperature is determined, at the time of charging into the furnace, by the tracking schedule calculation and the calculation of the slab temperature drop in the rolling line, taking into consideration the discharge temperature required for the sake of quality and that which is required for maintaining the specified rolling temperature.

The rolling pitch is determined and corrected, as rolling progresses, according to the modes set forth in items (1)–(4) above, by the tracking calculation as well as by the shortest rolling pitch calculation, necessary in-furnace time calculation and discharge pitch calculation or specified pitch calculation in furnace combustion control. By following this up-to-date rolling pitch, automatic discharge from the furnace is performed.

2.2 Reheating Furnace Combustion Control System

2.2.1 Outline of control model

Figure 2 shows the flow of reheating furnace combustion control. The control consists of five models shown below.

(1) Aimed discharge temperature determination
The aimed discharge temperature (thickness direction mean temperature at a skid portion) and aimed skid mark quantity (slab temperature difference between an on-skid portion and an off-skid portion) can be determined at the time of charging to the reheating furnace, by taking into consideration the discharge temperature required in respect of quality and that which is required for maintaining the prescribed rolling.

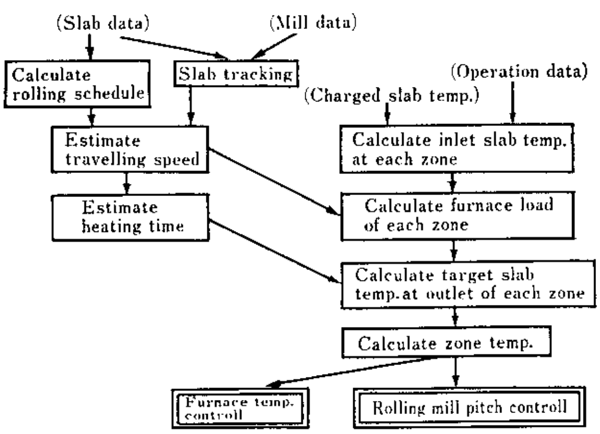


Fig. 2 Furnace combustion control

(2) Slab temperature calculation
Off-skid and on-skid thickness direction mean temperatures and top and bottom surface temperatures can be calculated from the charging temperature and furnace operation records by using a calculation formula which has been approximated to the heat calculation model[6]. In the calculation of the skid temperature, the coefficient of over all heat transmission at a skid portion by heat transfer analysis is quantized and incorporated into the model. The calculation formula of the thickness-direction mean temperature is given below.

$$\theta_O = \theta_g(\theta_g - \theta_S)\exp(-\alpha\cdot t/D) \quad \cdots\cdots\cdots (2)$$

θ_O: Zone outlet slab temperature (°C)
θ_S: Zone inlet slab temperature (°C)
θ_g: Furnace temperature (°C)
α: Heat transfer coefficient (m/h)
t: Time in furnace (h)
D: Slab thickness (m)

(3) Discharge pitch control
For each slab charged, a discharge pitch is set up, which can satisfy mill capacity, reheating furnace capacity and current operating pattern. The discharge pitch is properly corrected on the basis of actual rolling pitch and heating records.

(4) Slab load calculation
Slab load (t/h) can be calculated from the size and weight of the slab in each control zone and slab transfer speed obtainable from the discharge pitch.

(5) Furnace temperature control
Slab in the combustion zone is divided into the entry-side slab group Ⓐ and delivery-side slab group Ⓑ as shown in **Fig. 3**. Furnace temperature Ⓗ$_A$ at zone Ⓐ is obtained from combustion zone slab load, zone inlet actual slab temperature and zone outlet aimed slab temperature. Furnace temperature Ⓗ$_B$ at Zone Ⓑ is obtained from heating

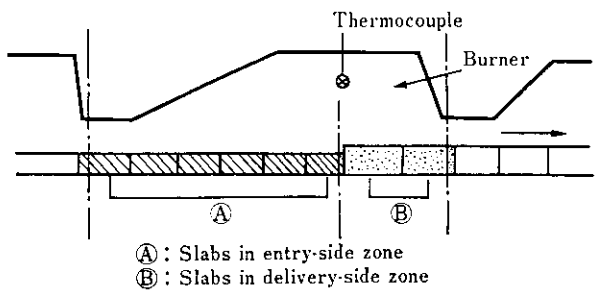


Fig. 3 Schema of delivery temperature control of slabs of each zone

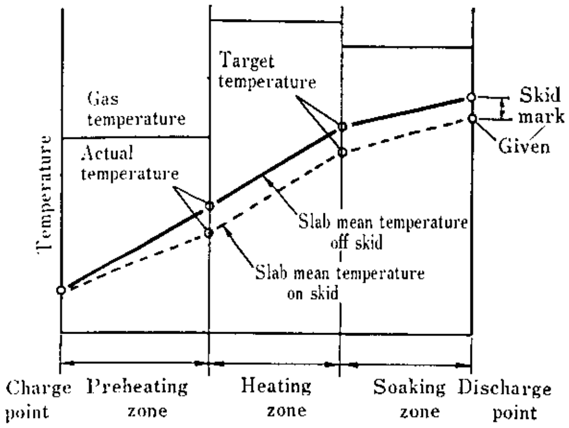


Fig. 4 Calculation of slab temperature (at heating zone)

records, residual time in furnace, zone outlet target slab temperature. The weighted mean value of Ⓗ$_A$ and Ⓗ$_B$ is taken as a set-point furnace temperature. The furnace temperature calculation formula is given below.

$$Ⓗ_A = f_1 (M, \theta_{SI}, \theta_{SO}) \quad \cdots\cdots (3)$$

$$Ⓗ_B = f_2 (t_r, \theta_{SA}, \theta_{SO}) \quad \cdots\cdots (4)$$

Ⓗ$_A$, Ⓗ$_B$: Respective temperatures of Ⓐ and Ⓑ (°C)
M: Combustion zone slab load (t/h)
θ_{SI}: Actual slab temperature at zone inlet (°C)
θ_{SO}: Aimed slab temperature at zone outlet (°C)
t_r: Residual time in furnace (h)
θ_{SA}: Actual slab temperature at Ⓑ inlet (°C)

As shown in **Fig. 4**, out of heat patterns which satisfy the aimed discharge temperature and residual time in furnace, a pattern on the lowest temperature side, which can satisfy the restrictive conditions of the skid mark quantity is selected for each zone, and the temperature at each zone's outlet of the patterns is determined as aimed temperature of each zone's outlet.

2.2.2 Slab and sheet bar temperature model at roughing mill

Slab and sheet bar temperature model during rolling at a roughing mill has been developed in order to obtain correspondence between the discharge temperature and the delivery temperature at rougher under various rolling conditions. This model consists of the following:

① Slab and sheet bar temperature model from the reheating furnace delivery side to rougher delivery side which treats plate-thickness direction mean temperatures.

② Heat regenerative model expressing the relation between surface temperature at the rougher delivery side and plate-thickness direction mean temperature.

Both the models are shown below.

(1) Slab and sheet bar temperature model formula
Temperature drop in the roll bite is given below.

$$T_m - T_{mo} = a_1 \Delta T_c + a_2 \Delta T_w + a_3 \Delta T_f \quad \cdots (5)$$

Temperature drop by air cooling is given below.

$$\left(\frac{1\,000}{T_m + 273}\right)^3 - \left(\frac{1\,000}{T_{mo} + 273}\right)^3 = \frac{t_a}{10^4} \times \left\{\frac{(a_4 E_m + a_5 \alpha_{conv})}{H} + a_6 + a_7 H\right\} \quad \cdots\cdots (6)$$

Temperature drop by water cooling is given below.

$$T_m - T_{mo} = \frac{a_8 \alpha_l (T_{mo} - T_m) t_w}{H} \quad \cdots\cdots (7)$$

T_m: Mean plate temperature (°C)
T_{mo}: Initial mean plate temperature (°C)
ΔT_c: Heat transfer to roll (°C)
ΔT_w: Heat generation by working (°C)
ΔT_f: Heat generation by friction (°C)
t_a: Air cooling time (s)
t_w: Water cooling time (s)
E_m: Emissivity
α_{conv}: Convection heat transfer coefficient (kcal/m²·h·°C)
α_l: Descaling coolant heat transfer coefficient (kcal/m²·h·°C)
H: Slab or sheet bar thickness (mm)
a_i: Coefficient

(2) Heat regenerative model at rougher delivery side

$$T_{so} - T_m = T_m - \frac{H}{6\lambda}[E_m \sigma\{(T_m + 273)^4 - (T_a + 273)^4\} + \alpha_{conv}(T_m - T_a)] \times \frac{1}{1 + (H/6\lambda)\{4\sigma(T_m + 273)^3 + \alpha_{conv}\}} \quad \cdots (8)$$

$$T_s = T_{so} - (A + BT_{so}) \exp\{-B(t - 2)\} \quad \cdots (9)$$

T_s: Sheet bar surface temperature (°C)
T_{so}: Quasi-stationary plate surface temperature (°C)
λ: Heat transfer coefficient of plate (kcal/m²·h·°C)

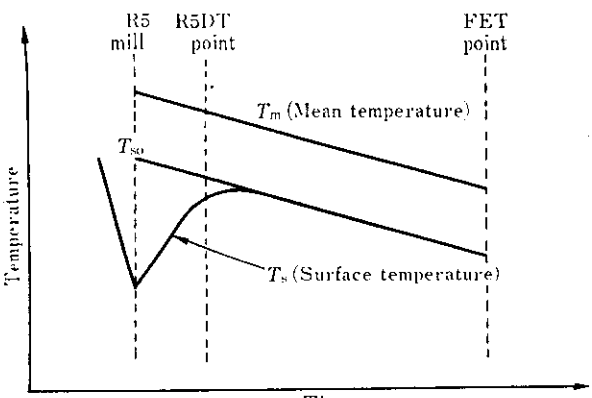


Fig. 5 Heat regenerative model at the rougher delivery side

σ: Stefan-Boltzmann constant (kcal/m^2·h·k^4)
T_a: Outdoor air temperature (°C)
t: Time from last rougher stand ON to rougher deliverly side thermometer ON (sec)
A, B: Constants to be determined by roughing time

Figure 5 shows the concept of heat regenerative model at the rougher deliverly side. In eq. **(8)**, quasi-stationary plate surface temperature T_{s0} is a temperature obtained on the assumption that the relation between the sheet bar thickness direction mean temperature and surface temperature of a plate in the stationary state at rougher delivery side is valid immediately after roughing. Eq. **(9)** obtained by regression analysis shows the relation between the calculated value of the temperature and the measured value of the surface temperature immediately after roughing.

2.3 Mill Pacing Control System

Mill pacing control system is operated by the discharge command to the extractor, on the basis of the heating pitch which is set by reheating furnace combustion control taking into consideration the shortest rolling pitch and the degree of progress of the slab on the line. This control is effected by automation.

In order to enhance furnace control accuracy and to improve rolling efficiency, it is important to set the shortest rolling pitch, which is controlled from the mill side, accurately at the time of charging the slab into the furnace. The finish rolling time of steel sheet, namely, the rolling speed of the finisher, greatly affects the rolling pitch. The rolling speed of the finisher is determined by the aimed finisher delivery temperature and rougher delivery temperature. Therefore, the shortest rolling pitch is preset by predicting rougher delivery temperature from the furnace discharge temperature and the quantity of roughing temperature drops while the slab is remaining in the furnace.

Further, the mill pacing control also has a jogging function, taking into consideration the collision prevention of slabs and time required for changing preset conditions.

2.4 Direct Digital Control

With the aim of refreshing the control system and raising the level of rolling pitch, the nucleus of the electric control system has adopted direct digital control. This control is applied to reheating furnace instrumentation, finisher entry delay-table, finisher rolling speed setting proper, run-out table, and coiler.

3 Operation Results

3.1 Reheating Furnace Combustion Control

3.1.1 Accuracy of roughing slab and sheet bar temperature model

(1) Slab and sheet bar temperature model
Figure 6 shows an example of calculated slab temperature by the differential model. Solid lines in the figure show the progress of the mean temperature, temperatures at the center and the surface, and the black dot shows the measured value of the surface temperature. **Figure 7** shows

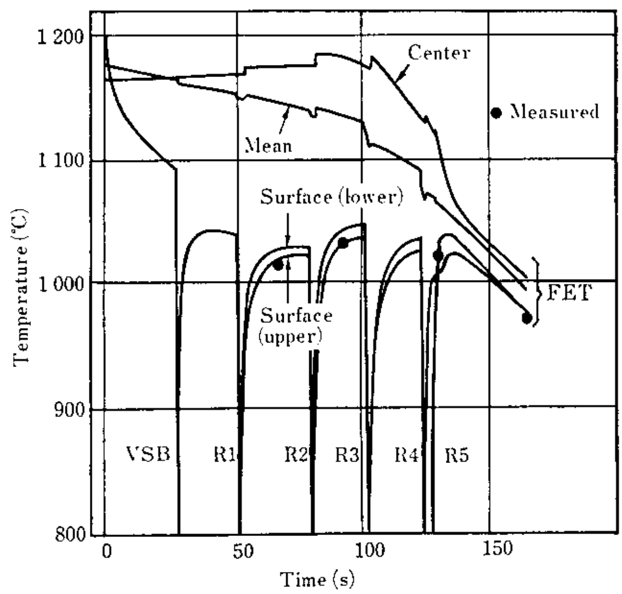


Fig. 6 An example of calculated temperature of slab and sheet bar by strict differential model

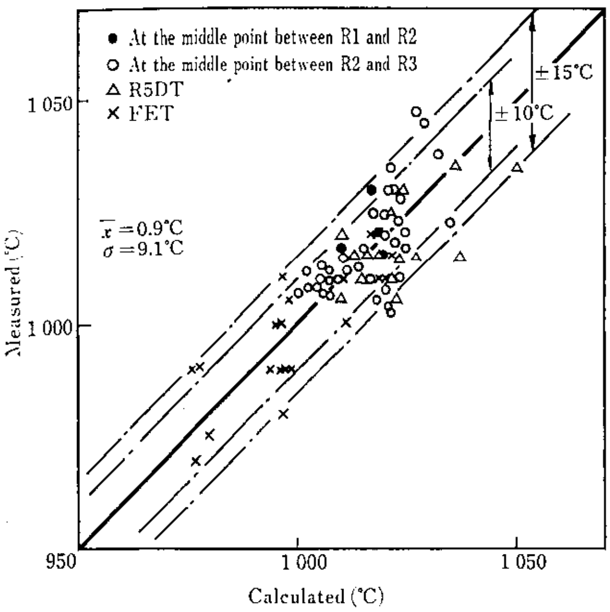


Fig. 7 Comparison of surface temperature between calculated value and measured value by differential model

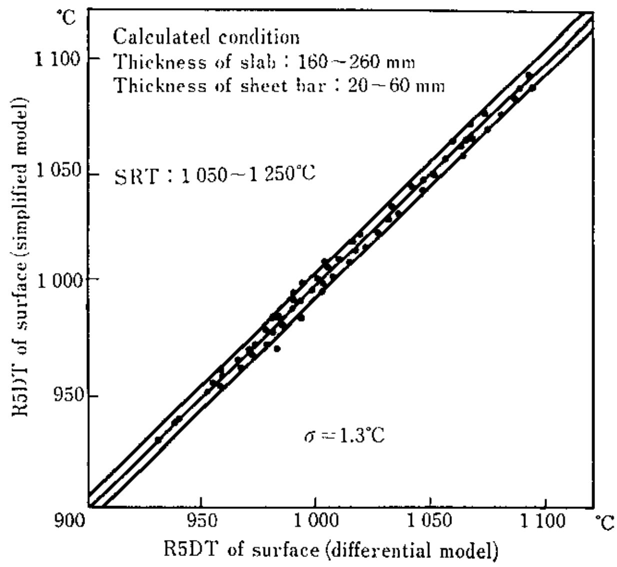


Fig. 9 Comparison of calculated surface temperature of sheet bar between simplified model and differential model

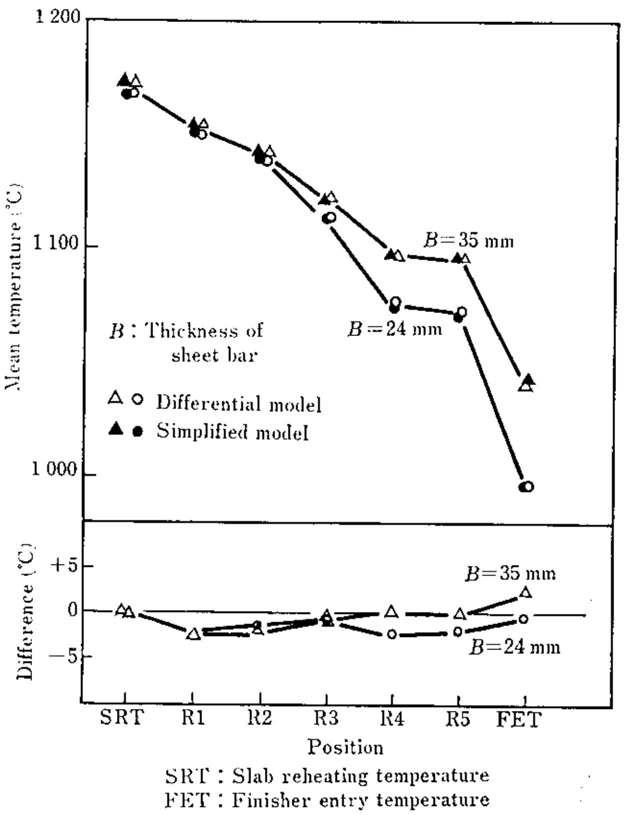


Fig. 8 Comparison of calculated mean temperature between differential model and simplified model

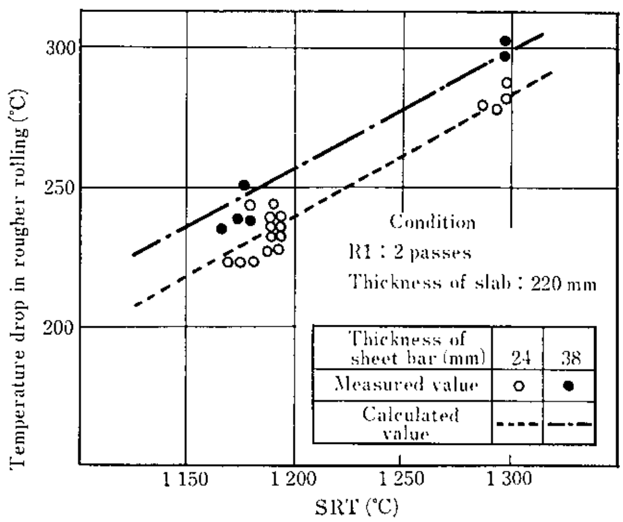


Fig. 10 Relation between SRT and temperature drop in rougher rolling

the correspondence between the calculated and measured values of the surface temperatures. When comparisons were made at various conditions; namely, at the intermediate temperature between R1 and R2; between R2 and R3; at rougher delivery temperature, and at finisher entry temperature, the overall accuracy was 9.1°C at the standard deviation.

Figure 8 shows the correspondence between the solution by the differential model and that by the simplified model used in the present system. The difference between them was ±3°C at each rougher delivery side.

(2) Heat regenerative model at rougher delivery side

Figure 9 shows the correspondence between the solutions by the difference model and the simplified model in respect of the last rougher stand temperature. Accuracy was 1.3°C at the standard deviation.

(3) Overall accuracy

Figure 10 shows correspondences between the calculated and measured values in respect of the relation between the quantity of temperature drop from the reheating furnace discharge to rougher delivery and the slab reheating temperature. This figure satisfactorily expresses the influence of the discharge temperature and rougher delivery-side sheet bar thickness, thereby confirming the practicability of this model.

3.1.2 Combustion control accuracy

First the measured temperature at the time of reheating furnace charging was taken into consideration, and then the discharge temperature was calculated by using the in-furnace slab temperature model. Finally, a correspondence was obtained between the results of the calculation of rougher delivery temperature by the rougher rolled sheet bar temperature model and its measured value, as shown in **Fig. 11**. The overall accuracy of the model was 12°C at the standard deviation, and it was confirmed that the model would sufficiently be used on-line.

Figure 12 shows an example of control results. In this figure, the aimed rougher delivery temperature is compared with the actual temperature. Although the aimed temperature, charging temperature and slab thickness varied complicatedly, the difference was only within about 20°C, indicating that the aimed values were satisfactorily followed.

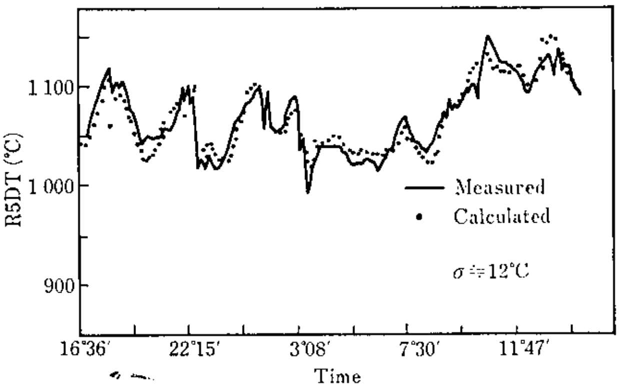


Fig. 11 Comparison of rougher delivery temperature (R5DT) between measured and calculated values

3.2 Mill Pacing Control

As mentioned in Sections 2 and 3, accurate setting of the shortest rolling pitch, which is controlled by the mill side, requires high accuracy in predicting the finisher rolling time and finisher threading speed. **Figure 13** shows a comparison between the predicted and measured values of finisher threading speed. The results in ± 10 m/min, indicating that rougher delivery temperature and finisher entry temperature, which are used for determining the finisher threading speed, have been accurately predicted. **Figure 14** shows the accuracy of the predicting calculation of slab tracking time at the rolling line, indicating that the time from VSB (vertical scale breaker) ON to F1 mill ON is 1.06 sec at the standard deviation, which means a contribution to decreasing the dispersion of discharge timing.

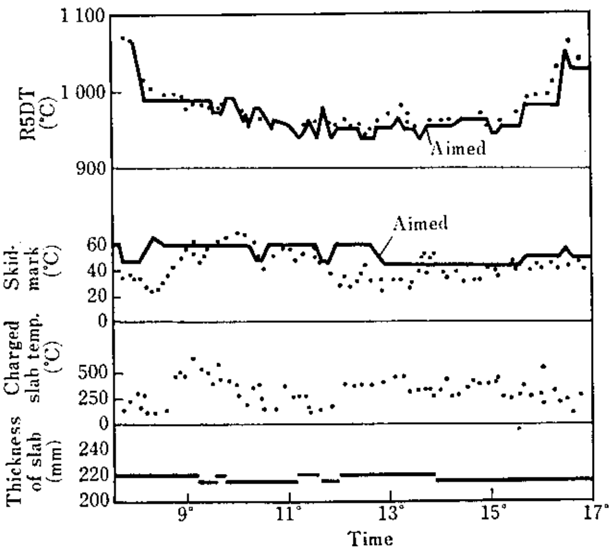


Fig. 12 An example of operational data of slab temperature by computer control

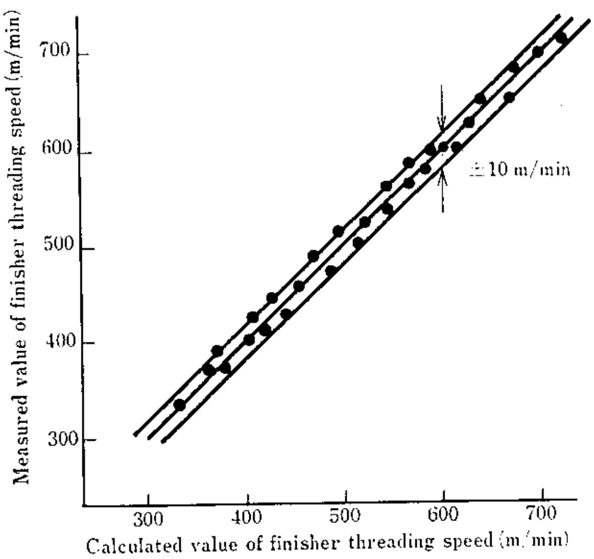


Fig. 13 Comparison of calculated and measured finisher threading speeds

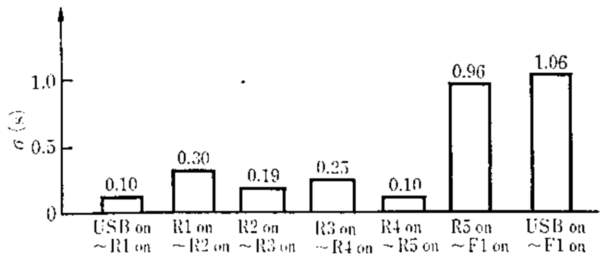


Fig. 14 Slab tracking time accuracy at mill line (Calculated value-measured value)

3.3 Direct Digital Control

The present modification greatly raised the levels of reliability, accuracy and responsiveness as shown in **Table 2.**

The present modification together with the on-line mill pacing control mentioned in the previous section gave such effective results as shown in **Fig. 15**. This figure compares the dispersion between the mill and table speed setting time and discharge timing by means of the F1 mill interval converted value. The execution of the present modification permitted shorting the time for changing the pre-set value of finisher rolling speed from average 12 sec to 5 sec, and the adoption of on-line rolling pitch control shortened the discharge timing delay from 10 sec to 3 sec, resulting in decreasing the F1 mill interval, at the time of finisher speed pre-set changes, from the previous 12 sec to 5 sec.

Table 2 Improved items

No.	Item	Original	New
1	Crop cut length ($\sqrt{v}$)	7.0 mm	3.2 mm
2	Setting up time of finisher rolling speed	12 s	5 s
3	Accelerated and decelerated rate at run-out table	75 m/min·s	110 m/min·s
4	Drift check	Yes	No
5	Looper response (height)	0.8 rad/s	2.5 rad/s

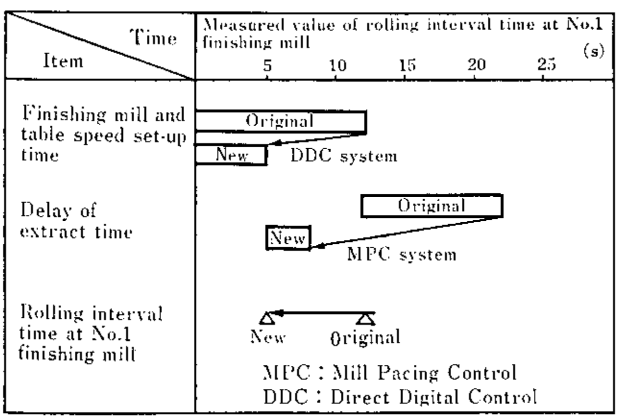


Fig. 15 Comparison of rolling interval time at No. 1 finishing mill between original and new by measured values

4 Conclusions

In the above, an outline and operation results of the optimum operation system developed at the Hot Strip Mill Plant of Mizushima Works have been reviewed. The development of the present system has brought about the following results:

(1) The rougher delivery temperature of sheet bars satisfactorily corresponded to the rapid changes in the aimed values within the range of about 20°C.

(2) Calculation accuracy of the temperature model of slabs and sheet bars is approximately 12°C at the standard deviation.

(3) Introduction of mill pacing control and direct digital control has made it possible to reduce the F1 mill interval at the time of finisher speed pre-set changes from 12 sec to 5 sec.

Anticipating the coming days when increased number of steel types and their improved quality will decidedly be demanded, the authors will endeavor to further improve the operation system.

References

1) I. Shimizu, T. Takeda and S. Umemoto: "Outline of Hot Strip Mill of Mizushima Works," *Kawasaki Steel Technical Report*, **5** (1973) 2, p. 4 (in Japanese)
2) J. Miyoshi, Y. Miyake and Y. Shinohara: "Intensification of Waste Heat Recovery at High-load Type Continuous Slab Reheating Furnace," *Kawasaki Steel Giho*, **14** (1982) 4, pp. 137–147
3) J. Miyoshi, Y. Miyake, K. Takagi, Y. Shinohara, M. Hotta and M. Obashi: "Improvement into High Heat Efficient Reheating Furnace of Pusher Type by Reinforcement of Recuperator," *Tetsu-to-Hagané*, **68** (1982) 8, S1 186
4) Y. Miyake, K. Fujiwara, K. Takagi, M. Obashi, N. Yamada and Y. Kawasaki: "Effect of Skid Shift in Hot Skid Pusher Furnace," *Tetsu-to-Hagané*, **67** (1981) 4, S364
5) T. Kondo, T. Konishi, K. Takagi, Y. Itoh, A. Toyokawa and T. Nakata: "Reinforcement of Drum Type Crop Shears in Hot Strip Mills," *Tetsu-to-Hagané*, **69** (1983) 9, S1 070
6) M. Obashi: "Heat Transfer Calculation of Continuous Slab Reheating Furnace Taking Heat Balance into Consideration," *Tetsu-to-Hagané*, **65** (1979) 4, S275