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Synopsis :

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1 Introduction

Requirements with respect to dimentional accuracy, such as the thickness and width of hot strip mill products, have become increasingly strict because of customer's desire for yield improvements and rationalization measures such as automation and high-speed and continuous processing techniques for the fabrication of steel sheets.

The dimensions of hot strip mill products are largely determined by the rolling conditions of finishing mills. Ordinarily, finishing mills are six- or seven-stands tandem mills with a looper provided between each of two successive stands for controlling the inter-stand strip tension. The loopers absorb the mass-flow imbalance of each stand arising from errors in the setting of the roll velocity and screwdown position of the mills, and variations in rolling conditions, such as changes in the screwdown setting, and temperature changes in the longitudinal direction of the strip. Loopers also give tension to strip between stands. The loopers, looper drives, mill roll drives, their control devices and the strip between stands are collectively known as the finishing mill looper system. The principal functions of looper systems are:

(1) To maintain constant strip tension between the stands, which substantially influences dimensional accuracy (hereinafter referred to as "tension control")
(2) To maintain constant stored strip quantities between the stands in order to ensure operational stability (hereinafter referred to as "looper height control").

In response to demands for improved performance of these functions, in the looper system hardware area, hydraulic loopers,[1,2] low inertia loopers,[3] and tension measuring mechanisms[1] have been developed, and new software has come into use, including multivariable control of height and tension[4] in conjunction with tension measuring mechanisms in addition to the hitherto existing looper height control.

Further, so-called looperless rolling techniques[5,6] which control strip tension between the stands by means of the mill motor, without using loopers, have been developed and employed in actual production.

At the Mizushima hot strip mill, these finishing mill tension control systems were comprehensively studied, and on the basis of the results, the looper system for the latter stands was revamped, while a looperless control method was adopted for the former stands. Since good operating results were obtained, we present a summary report on these innovations.[7,8,9,10]

2 Conventional Looper Systems

A representative type of conventional looper system is shown in the block diagram of **Fig. 1**. In this figure, the looper height is the controlled variable, and the looper height control system employs closed loop control, whereas the tension control system employs open loop control.

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** Mizushima Works

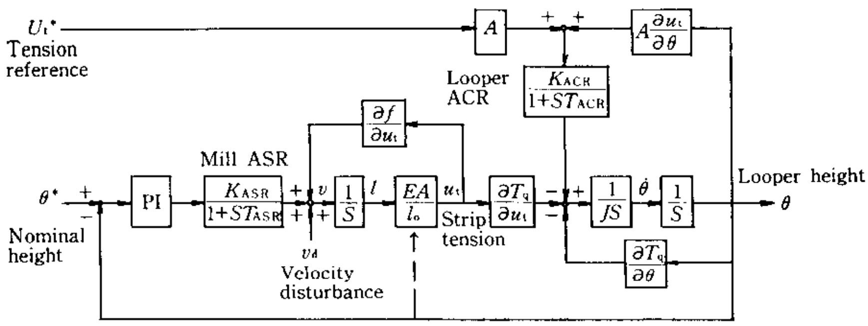


Fig. 1 Block diagram of looper system (conventional type)

In this conventional system, tension is controlled by regulating the looper height, and this, combined with the large moment of inertia of the looper, causes detrimental effects to quality and operation, such as shortage of width immediately after threading and unstable operation due to hunting of the loopers. Therefore, in order to examine the actual operating conditions and design the optimum looper system, measurement of actual strip tension and analysis by means of simulation models were carried out.

2.1 Variations in Tension during Rolling and Effects upon Product Dimensions

The looper shown in **Fig. 2** was used to measure tension during rolling. The vertical force of the looper rolls was measured by the torsion bar method, and the strip tension was calculated from the measured values with corrections of the inertial forces of the rolled strip and loopers by using the output of an accelerometer. From the geometric relations of the looper system as shown in **Fig. 3**, the tension can be calculated as follows:

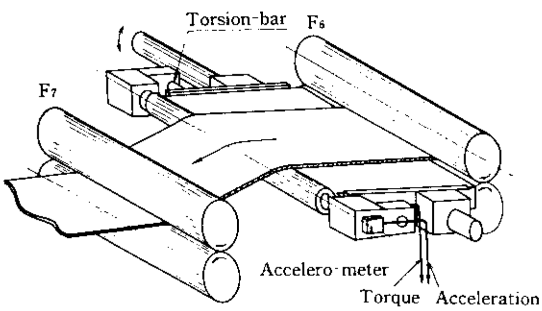


Fig. 2 Schematic diagram of looper system (measuring method of strip tension)

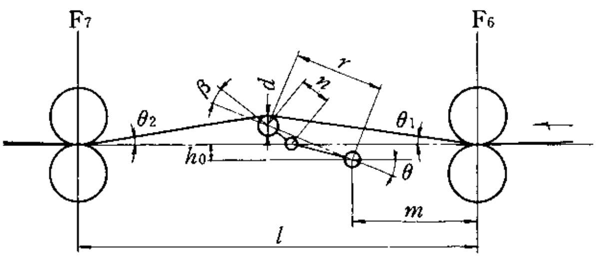


Fig. 3 Model for calculation of strip tension

$$\theta_1 = \tan^{-1}\left(\frac{r \cdot \sin\theta - h_0 + d/2}{m + r \cdot \cos\theta}\right) \quad \cdots\cdots(1)$$

$$\theta_2 = \tan^{-1}\left(\frac{r \cdot \sin\theta - h_0 + d/2}{l - m - r \cdot \cos\theta}\right) \quad \cdots\cdots(2)$$

$$M_u = \frac{I_u \cdot \alpha}{n \cdot \cos\beta} \quad \cdots\cdots(3)$$

$$M_s = m_s \cdot (g_0 + \alpha \cdot \cos\theta) \cdot n \cdot \cos(\theta + \beta) \quad \cdots\cdots(4)$$

$$T_0 = \frac{M_0 - M_u - M_s}{n \cdot (\sin\theta_1 + \sin\theta_2) \cdot \cos(\theta + \beta)} \quad \cdots(5)$$

where,
- I_u: moment of inertia of looper head
- m_s: half weight of strip between stands
- g_0: acceleration of gravity
- α: values measured by looper accelerometer
- M_0: torque measured by looper load-cell
- T_0: total strip tension
- M_u: acceleration correction term
- M_s: strip weight correction term

An example of the results of tension measurements obtained as described above is shown in **Fig. 4**. This figure displays the greatest tension fluctuation among all the actual examples of these measurements. An excessive tension, reaching as much as about 6 kgf/mm^2, was generated immediately after threading. Tension fluctuation during hunting was large, and loop formation was also observed in the rolled strip. This hunting of the looper resulted from inadequate coordination of looper action with tension fluctuation. It appears that adequate control of constant tension is difficult by conventional looper height control.

Figure 5 displays the maximum excessive tension values occurring immediately after threading, as shown in Fig. 4. It is apparent from the figure that maximum tension increases in inverse proportion to the cross-sectional area of the strip. This phenomenon could be anticipated from the fact that the looper system operation is based on a balance between the total tension, the looper driving forces, and the inertial force of the looper. Therefore, the moment of inertia of the looper drive system must be reduced, and the looper rising method must be reconsidered.

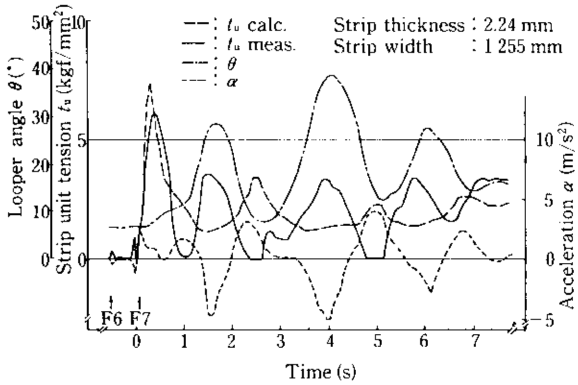


Fig. 4 An example of measured strip tension

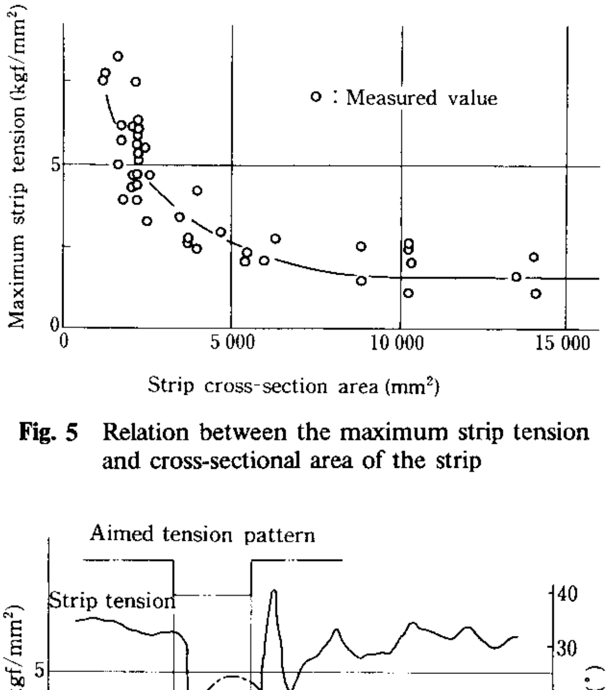


Fig. 5 Relation between the maximum strip tension and cross-sectional area of the strip

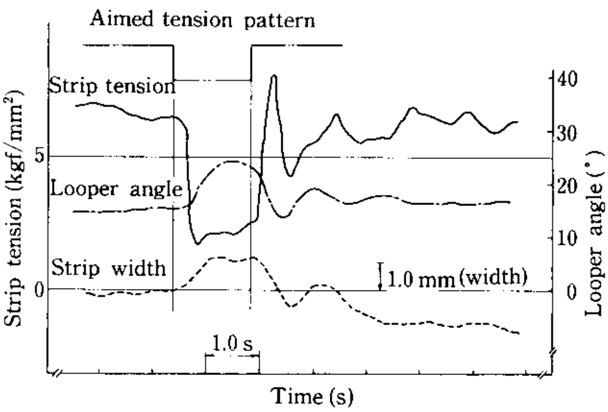


Fig. 6 Relation between the strip tension and the strip width

Figure 6 shows the results obtained when the tension reference value was changed during rolling in order to observe the effects of tension changes on strip dimensions, and in particular shows the simultaneous changes in strip width. This figure shows that the strip width changes with changing tension, but that these variations do not entirely coincide. This fact presumably indicates that the variations in strip width are not necessarily caused by the roll gap, but are, rather, largely due to creep deformation between stands. On the other hand, variations in strip thickness are primarily due to variations in the roll gap caused by variations in roll force at the upstream and downstream stands. Changes in strip thickness are as much as about ten times the magnitude of the strip thickness changes as estimated from the changes in strip width.[7]

Judging from these results, the conventional looper height control method is inadequate in meeting the demands in recent years for a higher level of dimensional accuracy.

2.2 Study of Looper Systems by Simulation Model

As indicated in Sec. 2.1, particularly excessive tension is generated immediately after threading, and the influence of tension variations on the dimensional accuracy of the strip cannot be disregarded. In order to solve such problems, tension variations in various types of looper systems were studied by means of a simulation model[11] of the finishing mill, using a general simulation language for continuous systems.

As shown in **Table 1**, three types of looper systems, i.e., a conventional electric looper (large moment of inertia), a new electric looper (low-inertia electric looper with tension detector), and a hydraulic looper (with tension detector) were studied.

The simulation results obtained when a screwdown disturbance was given to these looper systems are shown in **Fig. 7**. The tension control of the conventional looper system is of an open loop type, which is inadequate for coping with the disturbance, resulting in large tension fluctuation values as well as a long settling time for the tension and looper height.

On the other hand, in the case of the new electric

Table 1 Performance comparison of each looper by simulation

	Looper type	Performance		
		GD^2 * (kgf·m²)	Type	Tension feedback
a	Conventional electric looper	4 853	Geared	×
b	New electric looper	1 823	Gearless	○
c	Hydraulic looper	2 497	Hydraulic servo-mechanism	○

*GD^2: moment of inertia

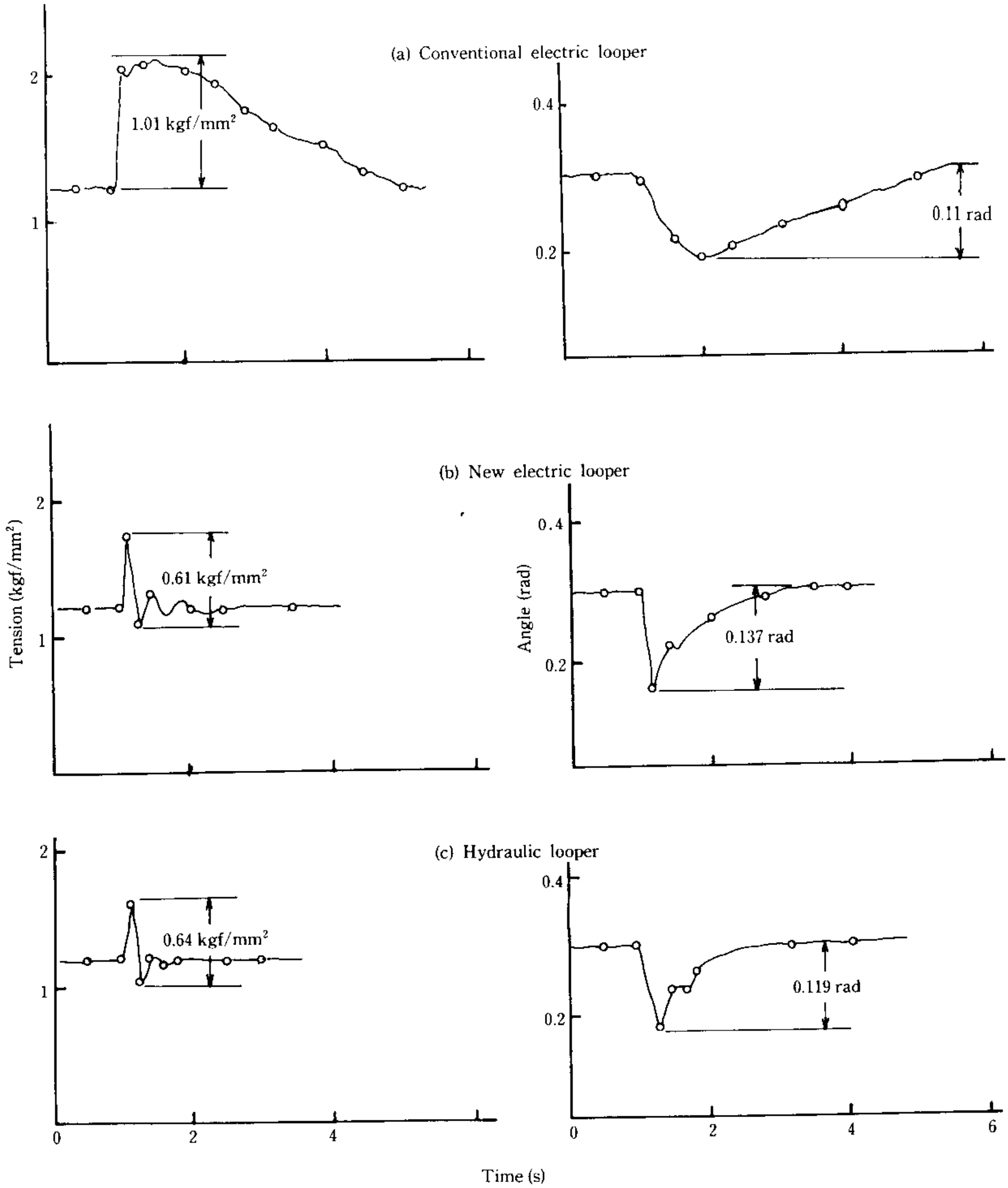


Fig. 7 Looper tension and angle response at screw down disturbance ($\Delta s = 100\,\mu$, Rolling size: 3.2 × 1 250 mm)

looper and hydraulic looper systems, tension fluctuation can be kept low by the feedback of measured tension values, and, in addition, the settling time for both the tension and the looper height can be substantially shortened. Therefore, it appears that these systems can adequately cope with, for example, even the tension fluctuations due to the screwdown disturbances of recently developed hydraulic screwdown AGC (automatic gage control) devices.

From these results, it can be concluded that improvement of the performance of looper systems requires, first of all, the provision of suitable tension measuring device in order to make tension control possible and, secondly, improvement in the response characteristics

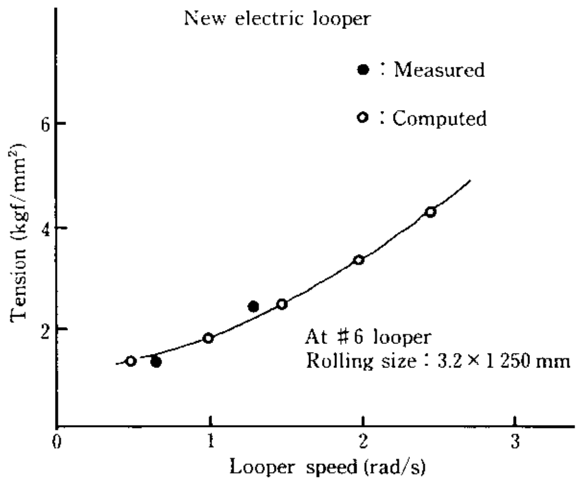


Fig. 8 Relation between tension and looper speed

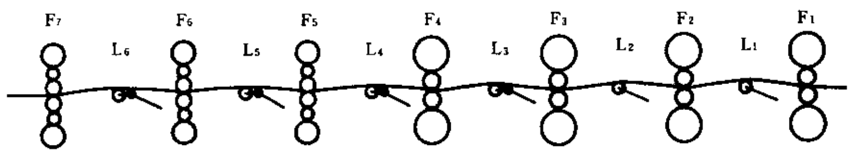
of loopers, such as reducing the inertia of looper equipment.

The results of calculation and actual measurement of tension fluctuations during looper rising immediately after threading are shown in **Fig. 8**. This figure shows the relation between looper rising velocity and maximum tension during rising, and indicates that the strip tension in the top end part varies with the looper rising velocity.

3 Modification of Finishing Mill Tension Control System

3.1 System Configuration

On the basis of the results of the investigations mentioned in the previous chapter, the tension control system of the finishing mill in the Mizushima hot strip mill was replaced in March 1982. **Figure 9** shows specific items of this modification of the tension control system. Before modification, the No. 1 to No. 5 loopers were air-cylinder-driven, and the No. 6 looper was electrically driven (with a reduction gear). Closed loop height control and open loop tension control were effected by analogue control device. On the other hand, after the modification, the No. 3 to No. 6 looper bodies were replaced by new devices with tension measuring mechanisms (load cells) in order to make closed loop tension control possible, the No. 4 to No. 6 looper drives were replaced by the looper shaft direct electric drive in order to improve the control response by lowering the inertia, and the No. 6 drive system was shifted to the No. 3 looper. Also, direct digital control by computer was introduced into the control system, with the aim of improving precision in control of the height and tension. Furthermore, in the looper system, height and tension control systems were closely linked and formed a mutual interference system as shown in Fig. 1. This mutual interference was eliminated on the basis of the multivariable control theory, which will be described later, and the control system shown in the block diagram of



Before replacement	Electric motor 75 kW × 515 rpm GD² = 4 853kg·m²	Air cylinder (Power + Ballance) GD² = 1 466 kg·m²	
	Analogue control {Height control-Feed back loop Tention control-Open loop		
After replacement	Electric motor (Gearless) 74 kW × 44 rpm GD² = 1 823 kg·m² with tention measurement (load cell)	Old No.6 75 kW × 515 rpm	Air cylinder Application of looperless control
	Direct digital control Height control Tention control Soft touch control		

Fig. 9 Comparison between before and after looper system replacement

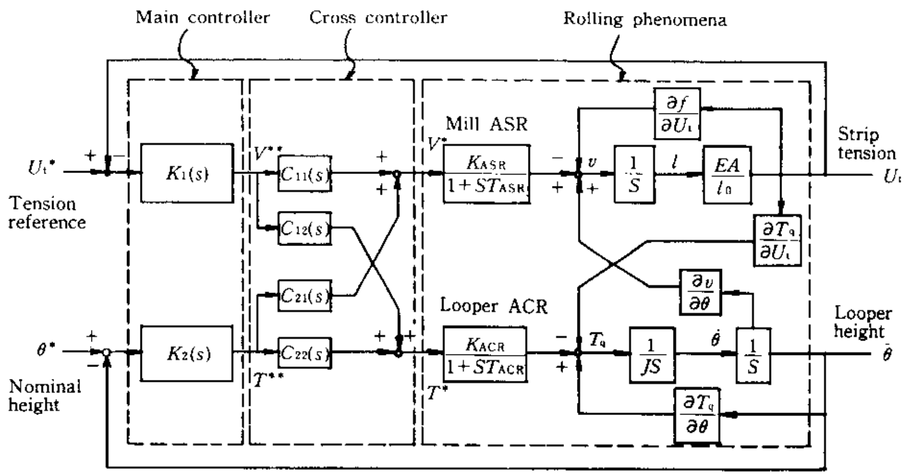


Fig. 10 Block diagram of looper sytem (multivariable controller)

Fig. 10 was configured.

As shown in Fig. 2, by means of the torsion bar which connects the looper frame and the looper roller, the tension measuring mechanism detects, as torque, the normal force which is exerted upon the looper roller due to the strip tension. Also, an accelerometer was installed at one side of the looper roller bearing in order to compensate for the inertial force which accompanies the fluctuations in looper height. In addition, looper rising velocity control was introduced in order to prevent excess tension in the top end part of the strip.

Furthermore, in an effort to save energy, the sheet-bar thickness was increased and low temperature discharging operation of the reheating furnace was implemented. Therefore, since tension control by means of loopers at the former stands of the finishing mill would require considerable strengthening and increases in capacity of the loopers and their drives, looperless control was introduced in the No. 1 and No. 2 loopers to improve tension control characteristics and equipment investment efficiency without replacing the loopers and their drives.

3.2 Elimination of Interference in Looper System in Accordance with Multivariable Control Theory

The controlled variables of the looper system are the looper height θ and the tension U_t, and the manipulated variables are the looper motor torque reference T^* and the former stand main drive speed reference V^*.

In Fig. 1, since interactions between the looper height θ and the tension U_t occur due to rolling phenomena, the removal of this mutual interference term and elimination of interference from the system are necessary. The multivariable control theory, which is summarized below, provides a means of effecting this elimination of interference.

If the portion of Fig. 10 corresponding to rolling phenomena is represented by a transfer function matrix, then the following equation holds:

$$\begin{bmatrix} U_t \\ \theta \end{bmatrix} = \begin{bmatrix} g_{11}(s) & g_{12}(s) \\ g_{21}(s) & g_{22}(s) \end{bmatrix} \begin{bmatrix} V^* \\ T^* \end{bmatrix} = G(s) \begin{bmatrix} V^* \\ T^* \end{bmatrix} \quad \cdots\cdots(6)$$

where, $g_{11}(s)$, $g_{12}(s)$, $g_{21}(s)$ and $g_{22}(s)$ denote the transfer functions from V^* to U_t, T^* to U_t, V^* to θ and T^* to θ, respectively. Suppose that $g_{12}(s) = g_{21}(s) = 0$ in Equation (6); then, only V^* and T^* affect U_t and θ, respectively, which constitutes an interference-free system. However, in the actual process, since $g_{21}(s)$ and $g_{12}(s)$ are not zero, a mutual interference system is formed. Therefore, by setting up new manipulated variables V^{**} and T^{**} as well as the cross controller $C(s)$ as shown in Fig. 10, and selecting $C(s)$ so that the transfer function matrix $G(s) \cdot C(s)$ is diagonalized, mutual interference between U_t or θ and V^{**} or T^{**} can be eliminated.

That is, it suffices to determine $C(s)$ as shown in Equation (7) below and to form the control system accordingly.

$$C(s) = \begin{bmatrix} c_{11}(s) & -c_{22}(s) \cdot g_{12}(s)/g_{11}(s) \\ -c_{11}(s) \cdot g_{21}(s)/g_{22}(s) & c_{22}(s) \end{bmatrix} \quad \cdots(7)$$

However, not only in the case of this looper system, but in general, the $C(s)$ expressed in Equation (7) is quite complicated. Therefore, by transforming $G(s) \cdot C(s)$ into a unit matrix at $\omega = 0$, $C(s)$ was transformed into a constant matrix, in accordance with Rosenbrock's proposal.[12] Thus, $G(s) \cdot C(s)$ is completely diagonalized at $\omega = 0$; however, one cannot guarantee that non-diagonal terms will vanish in other frequency domains.

Nonetheless, it was verified that, for practical purposes, the transfer function matrix remains sufficiently close to diagonal form in the frequency domain required for ordinary looper systems. The scheme shown in Fig. 10 is a block diagram of a looper multivariable control system including this cross controller $C(s)$. $K_1(s)$ and $K_2(s)$ are called the main controllers and are ordinarily PI controllers which constitute a feedback control system as a control loop independent of both the looper height θ and tension U_t.

3.3 Introduction of Looperless Control

Figure 11 shows the scheme of looperless control, in which the tension between the stands is calculated on the basis of process data such as the current and voltage of the former main motor and the roll force, and the velocity of the former main motor is regulated by feedback control.

With the notations

G_m: motor torque (kgf · m)
G_L: rolling torque (kgf · m)
G_e: idling torque (kgf · m) (mechanical loss at mill drive system)
G_a: speed regulating torque (kgf · m)
T_b: backward tension (kgf)
b: backward tension arm (m)
T_f: forward tension (kgf)
c: forward tension arm (m),

the following equation holds.

$$G_m = G_L + G_e + G_a + b \cdot T_b - c \cdot T_f \quad \cdots (8)$$

If a and F denote the torque arm and rolling force, respectively, then

$$G_L = a \cdot F \quad \cdots\cdots (9)$$

However, the contribution of the tension torque term $c \cdot T_f$ to G_m is generally very small, and in the case of looperless control, the control precision depends largely upon the accuracy of this tension calculation.

Consequently, the accuracy of calculation of rolling torque is improved by making a correction in accordance with the change in rolling conditions after the load-on of the next stand, using the following formulas:

$$a = a_0(1 + \Delta a) \quad \cdots\cdots (10)$$
$$\Delta a = f(H_0, h_0, R'_0, \Delta H, \Delta h, \Delta R') \quad \cdots\cdots (11)$$

Where, a_0 denotes the torque arm locked-on during rolling without tension, H_0, h_0, and R'_0 denote the entry strip thickness, delivery strip thickness, and flattened roll radius, respectively, and ΔH, Δh and $\Delta R'$ denote the changes in entry strip thickness, delivery strip thickness, and flattened roll radius, respectively, after lock-on.

In addition, the tension arms b and c in Equation (8), quantities which had previously been regarded as constant, are now corrected in accordance with changes in rolling conditions.

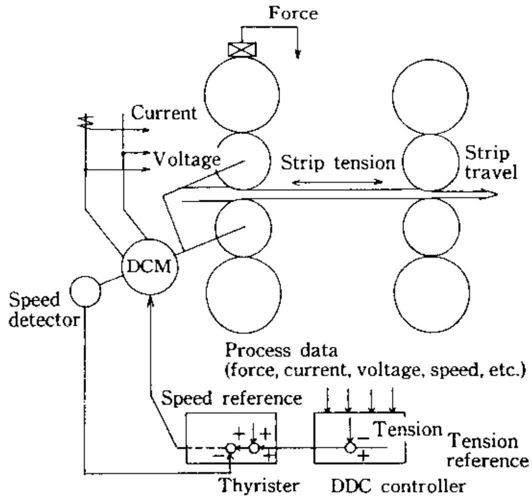


Fig. 11 Configuration of looperless control

Also, among the above-mentioned variables, the entry and delivery strip thickness H and h are calculated by determining the strip thickness by a gage meter formula and tracking by means of a DDC controller.

4 Effects of Modifications

By implementing the above-mentioned modifications of the finishing mill tension control system, the following effects were obtained.

(1) Good height and tension controllability were obtained by introducing actual tension control and multivariable control for the No. 3 to No. 6 loopers and employing DDC. **Fig. 12** shows an example of a control chart recorded during actual rolling operation.

(2) Good tension controllability was obtained without loopers by the introduction of looperless control for

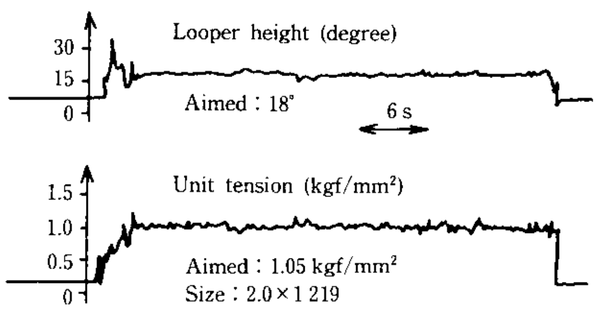


Fig. 12 Actual chart of looper height and tension (after replacement)

the No. 1 and No. 2 loopers. **Figure 13** shows an example of a control chart recorded during actual looperless rolling.

(3) Strip width accuracy improved since the tension disturbances which affect strip width diminished. **Figure 14** shows an example of the charts of the finisher delivery width meter before and after the modifications.

(4) Due to the development of actual tension control, i.e., the introduction of finishing mill AWC (automatic width control) for adjusting the tension in accordance with the deviation of the finisher delivery width meter output from the width reference, strip width accuracy was further improved, and a reduction of 2.5 mm in excess width was achieved. **Figure 15** shows the distribution of average excess width of finisher delivery, before and after the modification of the looper system.

(5) As regards the improvement of strip thickness accuracy, in the Mizushima hot strip mill, the F_5 to F_7 stands were replaced by the 6 high HC mill in September 1983, and at the same time hydraulic screwdown AGC was introduced; thus, improvement in strip thickness accuracy in both the strip width and strip length directions was achieved.[13] The prior modification of the tension control system substantially contributed to the improvement in strip thickness accuracy, especially the employment of hydraulic screwdown AGC, and operational performance.

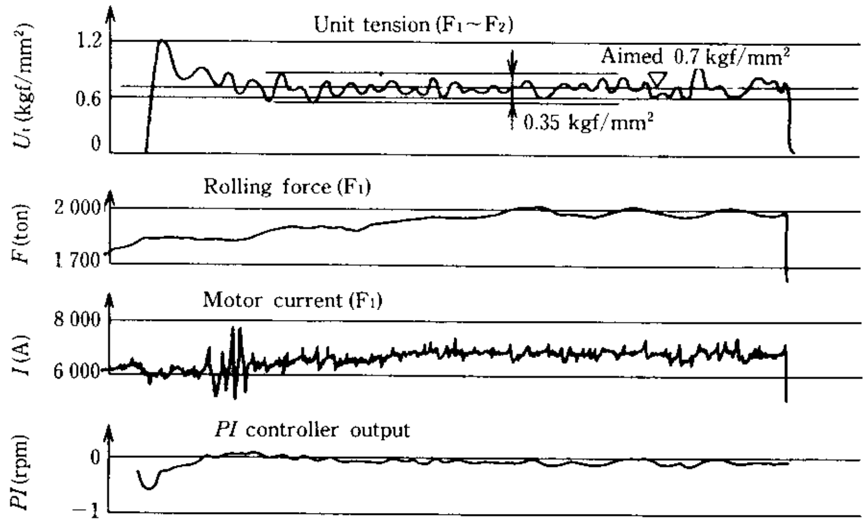


Fig. 13 Actual looperless rolling chart

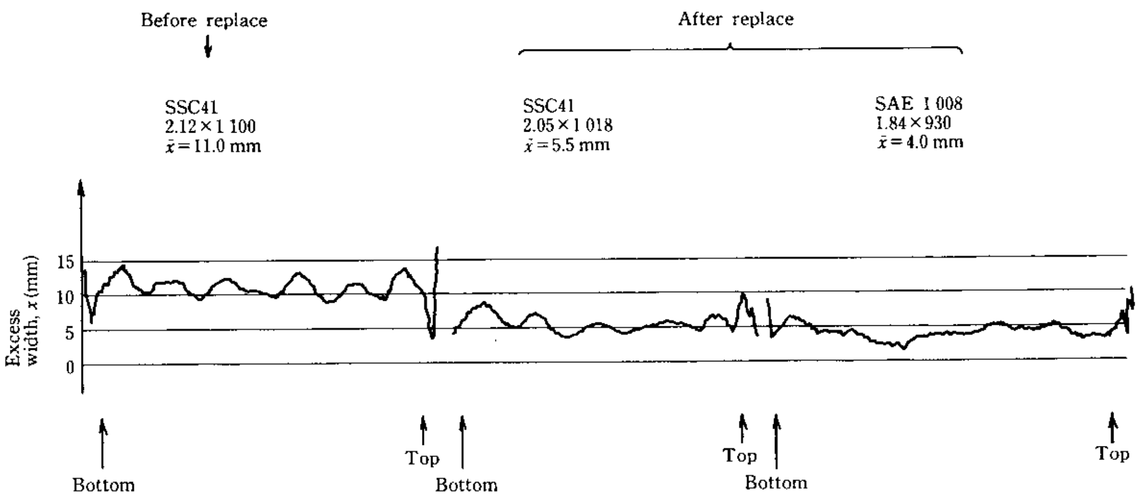


Fig. 14 Typical actual width chart of finisher delivery

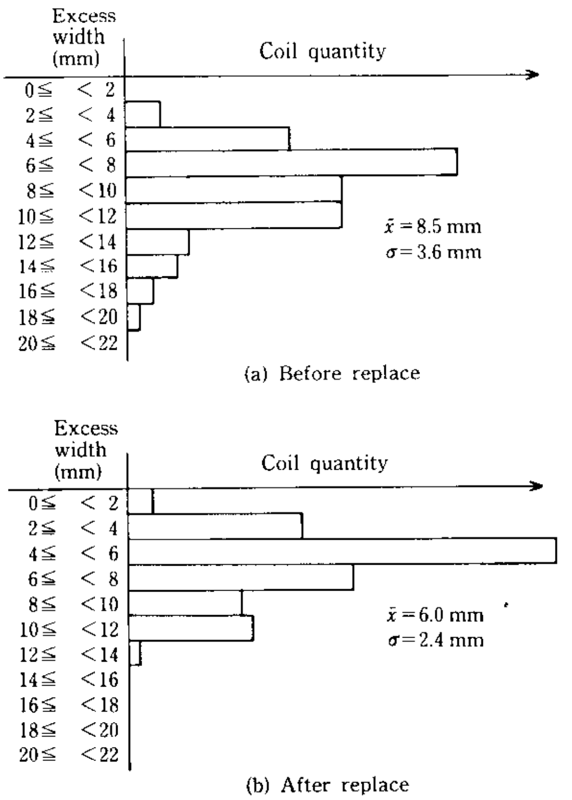


Fig. 15 Reduction of strip width after revamping (strip size: thickness; 3.0~4.0 mm, width; 1101 ~1350 mm)

5 Conclusions

As mentioned above, high sensitivity response and high precision were achieved by modifying the finishing mill tension control system, i.e., employing low-inertia loopers equipped with strip tension detecting mechanisms for the finishing mill's latter stands, adopting closed loop tension control, introducing looperless control for the former stands, and converting these control devices into the DDC type. At the same time, improvement in strip width accuracy was achieved by setting up a finishing AWC system. Furthermore, the stability of the rolling operation was increased, and in fact this increased stability was secured even after the subsequent modifications of the finishing rolling mill, such as the introduction of hydraulic screwdown AGC, thus contributing to the improvement of strip thickness accuracy.

As regards the improvement in strip width accuracy, in addition to the modification of the finishing mill tension control system, a strip width control system was also introduced into the roughing mill. Moreover, an overall strip width control system for both the roughing and finishing mills is now being developed and this is expected to further improve the strip width accuracy. This system will be employed in the hot strip mills of both the Chiba and Mizushima Works, and will hopefully make it possible to meet the customers' demands for improvement of dimensional accuracy, which will undoubtedly become even more stringent in the future.

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