KAWASAKI STEEL TECHNICAL REPORT
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Development of Computer Control Techniques for Tandem Mill with Grooved Rolls*

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Synopsis:

Kawasaki Steel has recently developed computer control techniques for a 4-stand tandem mill with grooved rolls, which consists of set-up and dynamic control functions, at the billet mill in Mizushima Works. The essential part of the set-up control, with the main aim of controlling dimensions between bars, comprises sophisticated mathematical models to precisely predict such rolling parameters as material temperature, rolling force, and width spread. They are based on theoretical constructs and actual data from grooved rolling. For dynamic control to achieve uniform sectional dimensions along the length of the material, new sectional profile control techniques, utilizing roll gap control, has been developed, replacing the traditional tension control system. As hardware improvement, A.C. variable speed control systems were adopted in mill motors, among which all the main motors are digitally controlled. As the result, the dimensional accuracy of the product has been significantly improved in the mill.

1 Introduction

A modernization program for the production process for billet, bloom, and shape products, generally aimed at rationalizing the complex crisscrossing of in-processes between the two continuous bloom casters and the rolling mill, has been undertaken at Kawasaki Steel's Mizushima Works. A billet mill, which is a significant part of this modernization program, was brought into operation in February 1984.[1] The billet mill produces materials, mainly round and square billets, for the seamless pipe, bar, and rod rolling mill. The fundamental aims of the billet mill project were cost reduction and construction of on-line quality assurance system, with emphasis placed on continuous operation with the continuous casters and totally automatic operation.

In the construction of a process computer control system for the billet mill,[2] it was considered a necessity for fulfilment of these aims that piece-wise management of materials be realized throughout the process from material design through automatic operation of the process, to the management of operational results. This required perfect automatic operation of an entire process, with an additional condition of continuation of two separate production processes in which productivity levels were different. In addition, quality inspection equipment, for instance, defects detectors and a profile meter which measures sectional profile and dimensions, were actively developed and installed. Utilizing the signals from this equipment, computer control techniques for the reheating furnace and rolling mill were developed with the aim of total quality assurance.

The finishing mill of the billet mill, which is a 4-stand tandem mill with grooved rolls of the V-H type, has a

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roll-chance free function permitted by rapid stand change, allowing continuous operation with the continuous casters. For this reason, a universal control algorithm which can cover all sizes and steel grades was required. Furthermore, in the round billets which are material for seamless pipe, high dimensional precision is required, because these material sizes are calculated by the material design system individually for all cut billets.

To meet these requirements, computer control techniques for a tandem mill with grooved rolls were developed and put into practical use. Particularly significant, as it replaces the traditional tension control system, a new sectional profile control technology, utilizing roll gap control to achieve uniform sectional dimensions along the material, was developed. This is the world's first use of dynamic roll gap control in a grooved rolling mill; the technology is termed MFPC, Mizushima Fine Profile Control. Additionally AC variable speed control techniques were applied to the motor drive system of the tandem mill.

This paper presents an outline of the process control system for the billet mill and the computer control techniques for the finishing mill.

2 Configuration and Aims of the Process Control System

To realize continuous connection of the process and to achieve totally automatic operation and full piecewise control and management of materials in each process, rapid processing of a huge amount of information, as well as universal process control techniques, are indispensable. Therefore, a large scale hierarchically structured computer system was constructed, covering processes from the steel making plants to the billet mill, as shown in **Fig. 1**.

The features of the system are as follows:

(1) Clear division of functions by echelon.

(2) A unified network for process information involving the linking of all process devices, including sensors and automatic mechanical devices, in the process computer (P/C).

A total computer system on a large scale generally runs the danger of being an inflexible system for which software development is difficult, as a result of the volume of information and standards and the variety of configuration elements involved. Further, it is difficult to design individual elements of the system so as to avoid inconsistency with the whole system. Feature (1) described above was intended as a solution to these

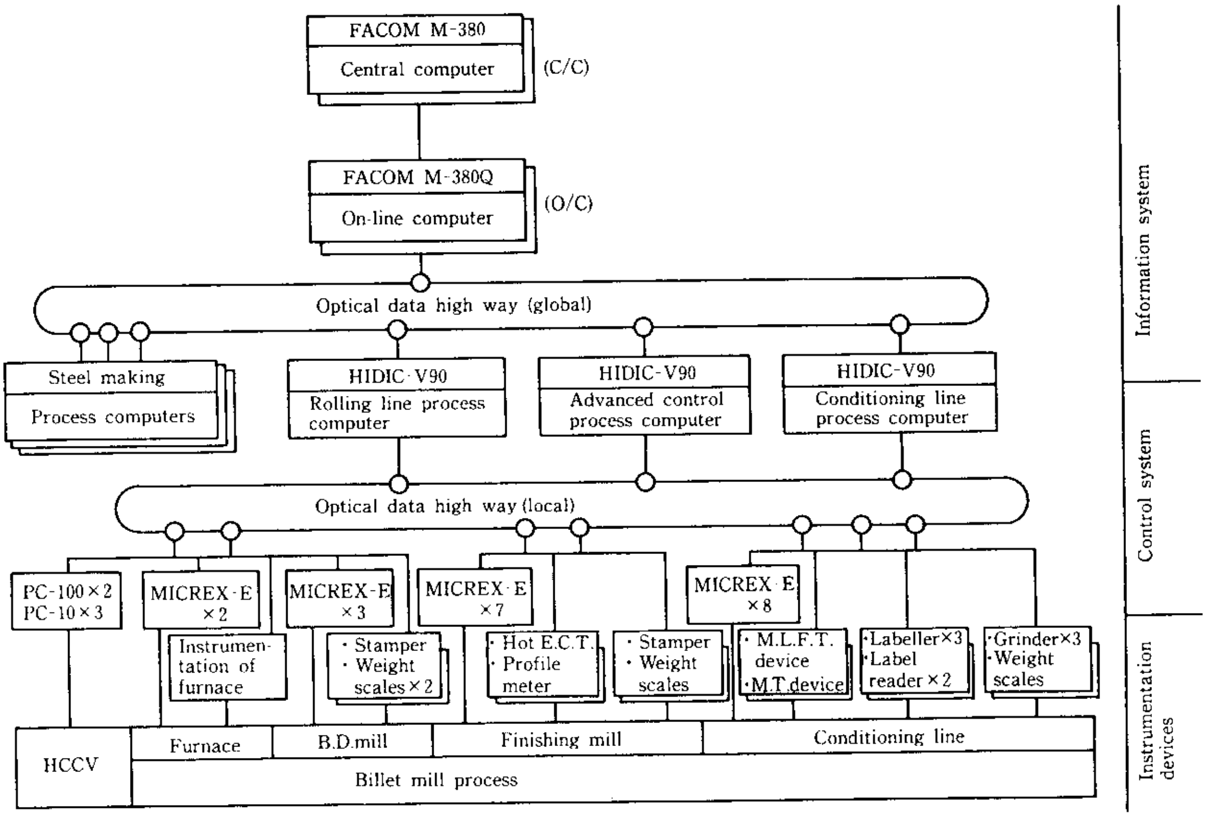

Fig. 1 Configuration of the billet mill information and control system

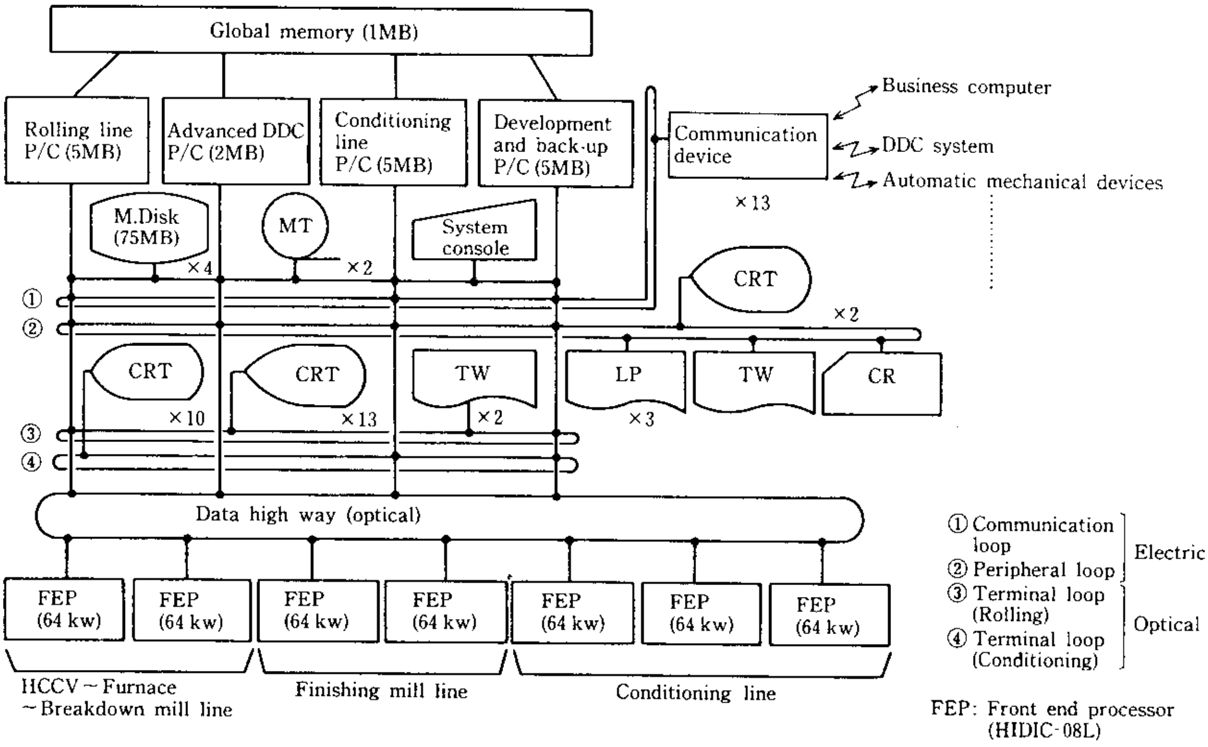

Fig. 2 Configuration of the billet mill process computer control system

problems. Concretely, the central computer (C/C)–batch processing–and the on-line computer (O/C)–real-time processing–have the function of data processing for production management; the P/C, process control, piece tracking, and actual data gathering; and the DDC (Direct Digital Control) system, direct drive control of actuators. As the interface between the echelons, as results of this division of function, has become very simple, and in addition, sufficient tests had been done for each echelon in advance, system-wide problems has been rare.

Moreover, with simple, unit sensors and automatic mechanical devices, it has been impossible to meet required levels of processing sophistication. For example, a weighing machine, which is in fact a sensor for measuring material weight, must not only weigh material and supply the results for operator guidance, but must also function as an essential part of the process control system: It must verify the identity of the material from information in the computer, measure data for feed-back and feed-forward control of the sawing machine and rolling mill, and search portions of the quality assurance data base system. Feature (2) was adopted in consideration of these requirements.

Figure 2 shows the configuration of the billet mill process computer control system, which is itself a significant part of the control system shown in Fig. 1. A multi-computer system, it consists of 4 HIDIC-V90 computers. From the view-point of process control, the special feature of the system is dynamic control of the finishing mill through the P/C. This feature has the following aims:

1. (1) Control on the basis of strict models and logical algorithms
2. (2) Ease of software development, as computer control for a grooved rolling mill was a new field for the authors

A problem arose as to whether the necessary cycle time for control could be assured; this was solved as follows:

1. (1) The optical data network loops for CRT information and control information were separated.
2. (2) A high-speed memory interface type PI/O (Process input output device) was adopted.

3 Control for Tandem Mill with Grooved Rolls

The finishing mill in the billet mill produces round billets (110 mmϕ~230 mmϕ) as materials for seamless pipe, square billets (115 mm$^\square$, 150 mm$^\square$) for wire and rod, and round bars (90 mmϕ~254 mmϕ), which are final products, from intermediate square materials (125 mm × 142 mm~300 mm × 280 mm) reduced through the roughing mill. The finishing mill is a V-H type 4 stand tandem mill with grooved rolls.

Specifications of the finishing mill are shown in

Table 1 Specifications of the finishing mill

Equipment	Specifications	
Finishing mill (VH mill)	Maker	: IHI
	Unit	: 4 × 2
	Type	: Horizontal mill × 2 × 2 Vertical mill × 2 × 2
	Roll size	: 950 mmϕ × 500 mm
	Screw down	: Motor drive
	Screw up	: Hydraulic drive
	Main drive gear ratio:	V1 stand 1/32.464 H2 stand 1/28.277 V3 stand 1/27.388 H4 stand 1/22.958
Main motor of finishing mill	Maker	: Fuji Electric
	Unit	: 4
	V1&H2	: AC1200 kW × 272/680 rpm
	V3&H4	: AC1400 kW × 318/795 rpm
	Control	: AC-VVVF, digital ASR control

Table 1. The features of the mill are as follows:

1. The mill possesses a roll-chance free function, in which only 5 minutes is required to change the entire series of stands for subsequent use with different sizes of billets.
2. Each roll has only one caliber.
3. The mill is a V-H type, non-twist mill.
4. The mill is very rigid, with a mill modulus of about 300 t/mm.
5. An AC variable speed control system including a digital computer is used with the main motors of the finishing mill.
6. A dynamic roll gap control system is adopted, the first use in the world in a grooved rolling mill.
7. A variety of sensor types is used, including profile meter, load-cells, and roll gap sensors.

In features (5)~(7) in particular, the production of round and square billets with high dimensional precision by use of high-level computer control techniques for rolling mills was targeted.

Since the start of operation, computer control techniques for tandem mill with grooved rolls have been developed for the improvement of dimensional precision. In particular, on-line set-up control and sectional profile control software functions have been developed for use in conjunction with the hardware described above.

3.1 On-line Set-up Control Technique

3.1.1 Development of mathematical models to predict rolling parameters

One purpose of set-up control is to decide manipulating variables (roll gap, roll revolution) which will control after-rolling dimensions to aimed values, regardless of such variables as material temperature, metallurgical composition, and roll diameter. The essential part of the set-up control for this purpose comprises sophisticated mathematical models to precisely predict such rolling parameters as material temperature, rolling force, height (material dimension in the screw down direction) and width (in the perpendicular direction to screw down). Therefore, models were developed of a sufficient level for application to on-line control.[3] The goal was development of unified models applicable without consideration of the grooved roll profile.

(1) Material Temperature Model[4, 5]

A unified analytic solution to a nonstationary 1-dimensional thermal conduction equation was determined, by means of which the reduction of material temperature due to atmospheric air cooling, water cooling, and thermal conduction to rolls can be calculated. Formerly, the nonstationary thermal conduction equation was solved separately for 3 cases according to surface area ratio m.

$$m = \frac{S \times (d/2)}{V} \cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

S: surface area
d: diameter or height
V: volume

In other words, the solution of the equation was formulated differently for cases of infinite flat plated ($m = 1$), infinite circular cylinders ($m = 2$), and spheres ($m = 3$). As a result, the traditional method of temperature prediction in bar and billet rolling generally involved the expression of equivalent sectional areas in terms of a circular cylinder. In contrast to this method, a unified solution was introduced in which the surface area ratio m is a variable. Experimental results on lead proved that this solution made it possible to predict material temperature accurately for any sectional profile, for instance, diamond or oval.

In addition, as the initial temperature, the result calculated from a differential equation for the thermal conduction for blooms in the reheating furnace is utilized. **Figure 3** shows a comparison of measured and calculated surface temperature for the up- and down-stream sides of the finishing mill. The precision of temperature calculation is now within ±20°C.

(2) Rolling Force Model

As a rolling force model, familiar formulae are utilized. Shida's formula[6] has been adopted in the calculation of deformation resistance, as has Shinokura's formula, for rolling force function. Furthermore, the correction term C_Q, which corrects for the influence of caliber profile, has been formulated

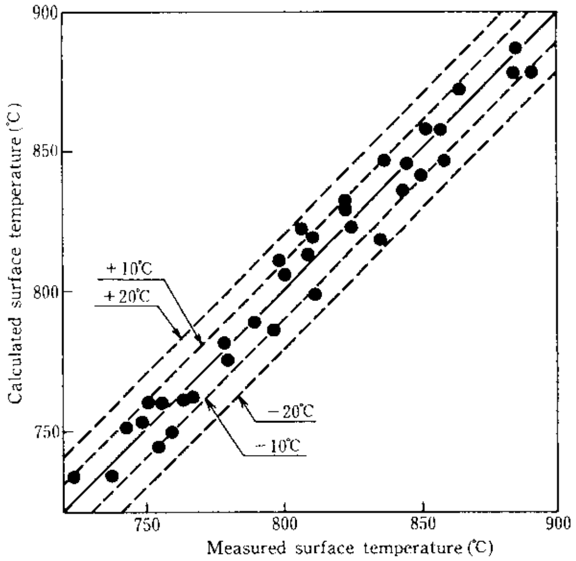

Fig. 3 Comparison between measured and calculated surface temperature

from an analysis of actual rolling data.

$$P = k_{fm} \times F_d \times Q \times C_Q \cdots\cdots\cdots\cdots\cdots (2)$$

P: rolling force
k_{fm}: mean deformation resistance
F_d: projected area of contact
Q: rolling force function

Figure 4 shows the degree of precision obtained in rolling force calculations. It is possible to calculate precisely to within ±10%, regardless of grooved roll profile.

(3) Gauge-meter Equation

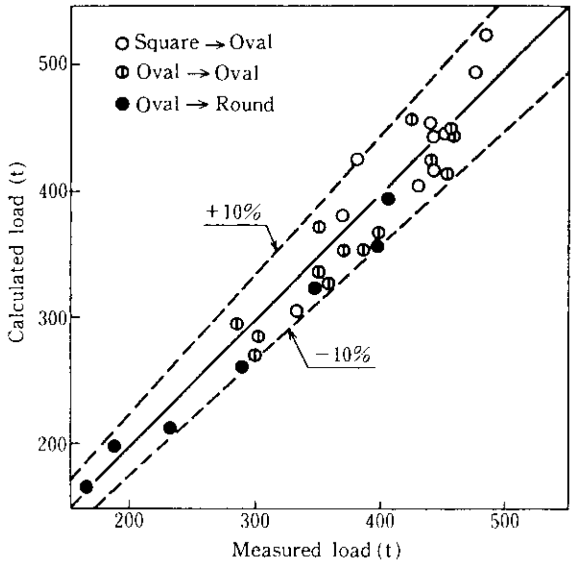

Fig. 4 Comparison between measured and calculated load

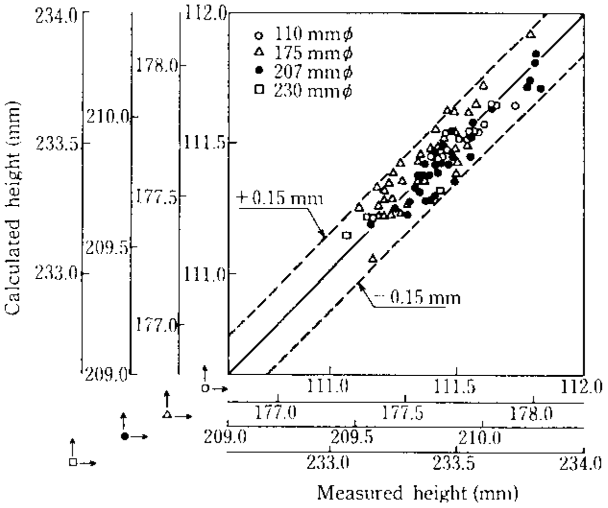

Fig. 5 Comparison between measured and calculated height

The gauge-meter equation consists of the roll deformation model (δ_R, δ_R^K) introduced based on the dynamic relation in the simplified grooved roll profile, and the deformation model for the mill housing (S_M) formulated on the basis of roll kissing experiments.

$$H = S_0 + [S_M(P) - S_M(P_0)] + \delta_R(P) - \delta_R^K(P_0) + 2H_K \cdots\cdots\cdots (3)$$

H: height after rolling
S_0: roll gap without load
S_M: deformation of mill housing
δ_R: roll deformation during rolling
δ_R^K: roll deformation at pre-load calibration
P: rolling force
P_0: rolling force at pre-load calibration
H_K: groove depth of grooved roll

Figure 5 shows the precision obtained in the height calculation, which, it can be seen, is within ±0.15 mm, regardless of material dimensions.

(4) Width Spread Model

The essential control point in grooved rolling is control of the width dimension, which is the free-side surface of the material during rolling, to the aimed value. As the width spread model, Shinokura's model,[7] shown in Eq. (4), was adopted.

$$\frac{B_1 - B_0}{B_0} = \alpha \times \frac{\overline{l_d}}{B_0 + 0.5H_0} \times \frac{F_H}{F_0} \cdots\cdots (4)$$

B_0: width before rolling
B_1: width after rolling
H_0: height before rolling
F_H: sectional area of material removed by the grooved roll profile
F_0: sectional area of material before rolling

$\overline{l_d}$: mean projected length of contact

α: coefficient dependent on caliber type

Equation (4) expresses width spread by geometrical parameters alone. On the other hand, as shown in **Fig. 6**, when material temperature is less than about 850°C, width variation characteristics depend on material temperature. Since it can be considered that this temperature dependence is due to the influence of the phase transformation from austenite to ferrite, the coefficient was formulated by analysis of actual rolling data.

$$\alpha = \alpha(\theta, C, \varepsilon, B_0/B_K) \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

θ: material temperature

C: carbon content

ε: strain

B_K: groove width of grooved roll

As shown in **Fig. 7**, the precision of the width spread model, after formulation as in Eq. (5), is within ±0.6 mm. As described above, the precision of each model has reached a sufficiently high level for application to on-line control.

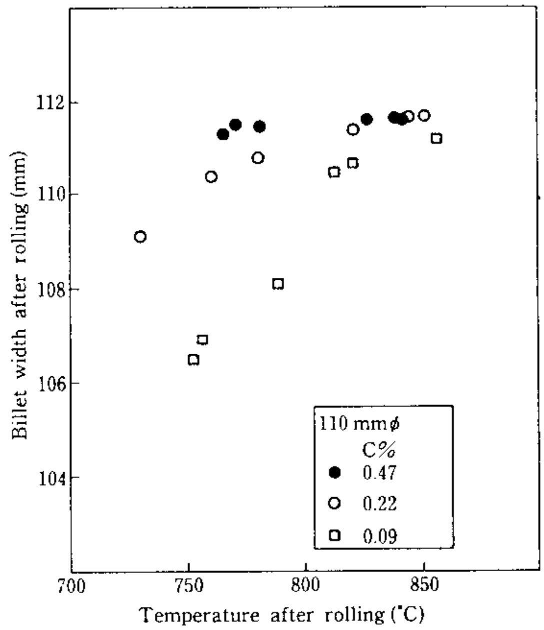

Fig. 6 Dependence of billet width on temperature

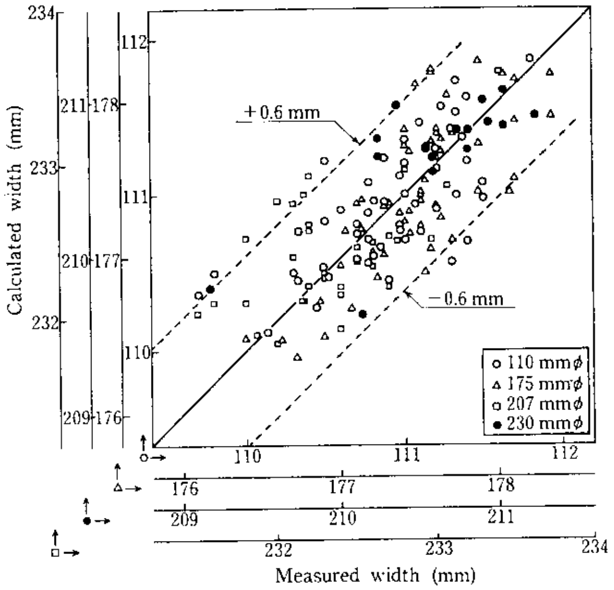

Fig. 7 Comparison between measured and calculated width

3.1.2 On-line set-up control and practical use

As already stated with regard to on-line set-up control, by utilizing the mathematical models described previously, the variation of the sectional profile and the material temperature at each stand can be predicted; the manipulating variables (roll gap and roll revolution) necessary to obtain the final aimed dimension (aimed height and aimed width) are decided for each material individually before rolling. The calculation flow for on-line set-up control is shown in **Fig. 8**; features of the flow are described in the following.

In grooved rolling, a roll profile decided by a roll pass design system acts as a constraint on on-line control. On-line set-up control, this means, is closely related to roll pass design. Concretely speaking:

(1) The drafting schedule (i.e., aimed dimensions at each stand) decided by the roll pass design, is taken as the initial condition for set-up control, and on the basis of this initial condition and the mathematical models, the actual aimed dimensions after rolling at each stand are calculated by means of a convergent calculation, as described below.

(2) The process computer receives the grooved roll profile information from the computer which performs roll pass design for each roll individually. On the basis of this information, variations in the sectional profile of materials are calculated.

It has been taken as a principle that the manipulating variable for the final height dimension is the roll gap of the H-stand, and that for the final width dimension is the roll gap of the V-stand. Accordingly, for each combination of V-H stands (V1-H2 and V3-H4), the dimensions after each V-H combination are examined, and the height dimension after the V-stand (i.e., the width dimension before the H-stand) is corrected, so as to obtain a width within the aimed value. Repeating the correcting calculation in this manner, i.e., performing a convergent calculation, yields the roll gap and roll revolution at each stand necessary to obtain the aimed height and width simultaneously.

Examples of results calculated by set-up control are shown in **Table 2**. The material temperature in case 2 is

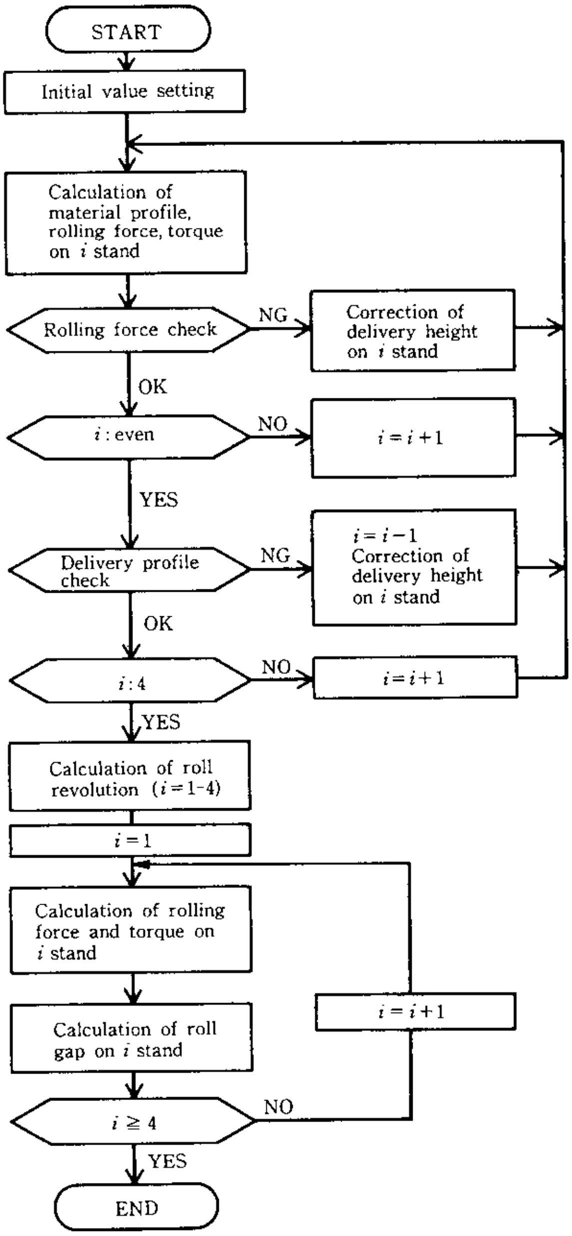

Fig. 8 Calculation flow for on-line set-up control of finishing mill

lower than in case 1; that is, the width spread in case 2 is less than in case 1, as shown in Fig. 6. For V1 and V3, which are the manipulating stands for width, the set-up control calculation result for roll gap is larger in case 2 than in case 1. It can be seen that this calculation result takes into consideration characteristics of width spread.

Using set-up control, rolling dimension precision has been improved to the following degree:

Height dimension σ: 0.17 mm ⟶ 0.15 mm
Width dimension σ: 0.44 mm ⟶ 0.30 mm
(For round billets with 110 mm diameter)

Table 2 Examples of calculated data by set-up control

Case	Stand	Height (mm)	Width (mm)	Temp (°C)	Load (t)	Roll gap (mm)	Roll speed (rpm)
1	V1	115.1	150.1	830	386	9.3	14.90
	H2	122.5	132.5	837	363	7.7	17.81
	V3	100.9	138.4	843	268	8.3	21.52
	H4	111.3	111.3	848	251	5.8	25.03
2	V1	115.7	150.7	818	369	9.9	14.95
	H2	122.6	132.5	826	375	7.8	17.85
	V3	101.9	138.3	832	244	9.4	21.53
	H4	111.3	111.3	837	267	5.7	25.03

Size = 110 mmϕ, Carbon = 0.10%

3.2 AC Variable Speed Motor Control System

The AC motor is generally superior to the DC type in maintainability and resistance to external factors. Furthermore, AC motor offers the advantages of good efficiency and significant energy savings. The major problem has been whether better control performance could be obtained than with DC motors. In the world's first use in 4-stand tandem mill, an AC digital motor-drive system was applied to the main motors of the finishing mill. Excellent control performance and speed precision, better than with DC motors, was obtained, and significant improvement in dimensional precision and productivity were achieved.

In addition, AC variable speed control (analogue vector control) was applied to the screw down motors and table auxiliary drive motors, and a complete AC motor-drive system was thus realized.

3.2.1 AC digital motor-drive system

The main motors of the finishing mill are thyristor motors (1 200 kW × 2, 1 400 kW × 2), which are completely digital-controlled. Their features and performance are as follows:

(1) Maintenance free, high efficiency (improvement of 2.5% over DC motors) operation has been achieved by adoption of AC motors.
(2) High control performance has been achieved by digital control; concretely, the precision of speed control is 0.24% and the control response is $\omega_c = 25$ rad/s. In addition, because more complete trouble shooting is now possible, reliability and maintainability have been greatly improved.
(3) The thyristor converter system consists of a 12-phase rectifier which limits torque ripple and high frequency noise.
(4) A multi-processor was adopted in the digital control section, and an optical data high-way as the interface to the plant-controller. By these means, it was pos-

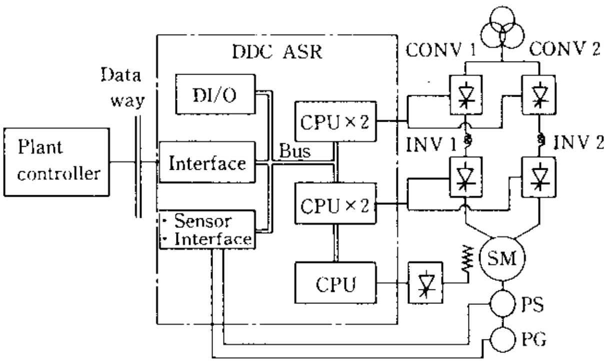

Fig. 9 AC digital motor-drive system

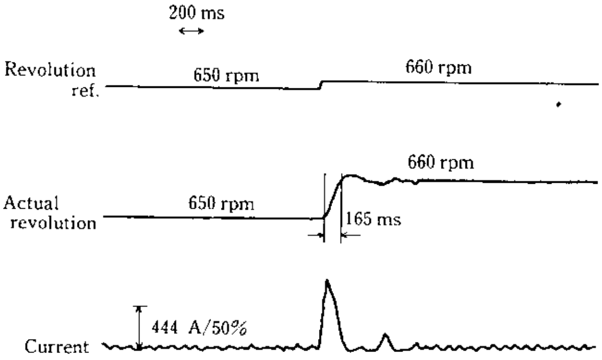

Fig. 10 Step response of AC digital motor-drive system

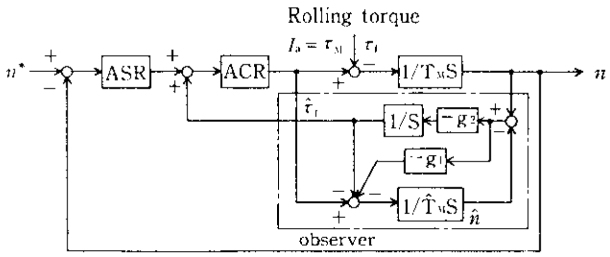

Fig. 11 Block diagram for impact drop compensation

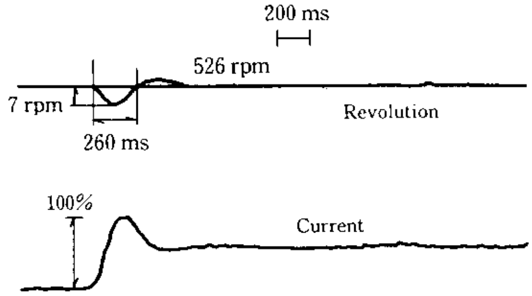

Fig. 12 Impact drop without observer control

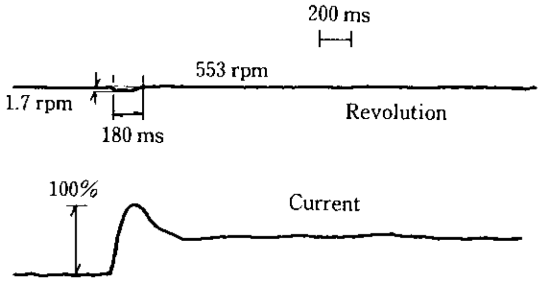

Fig. 13 Impact drop with observer control

sible to cope with requirements for high speed and high performance. Thus, a drive system which would be harmonious with the system as a whole was completed.

Figure 9 shows the fully digital controlled thyristor motor-drive system, and **Fig. 10** shows the step response of speed, as controlled by AC digital motor-drive system.

3.2.2 Impact speed-drop compensation by observer control

In a tandem rolling mill such as the finishing mill, speed impact drop when material bites into the rolling mill has a great influence on the dimensional precision of products, in particular, on top ends. The observer control technique shown in **Fig. 11** was applied to compensate for such impact drop. Nonstationary load torque at the time of material biting can be predicted by an observer from motor torque and speed; the predicted load torque is then inputted to an ACR (automatic current regulator) as a torque instruction, meaning motor speed is controlled and compensation made for the impact drop. **Figure 12** shows actual data without observer control and **Fig. 13**, with observer control. Though both sets of data show speed impact drop under the same rolling conditions, it can be seen that the quantity of impact drop is reduced from 0.29 %·sec to 0.07 %·sec with observer control. As a result of the motor control techniques described above, the effect of speed impact drop on materials has been minimized, and, in consequence, dimensional precision has been greatly improved.

3.3 Dynamic Control of Sectional Profile

In tandem mill with grooved rolls, the tension control system found widespread acceptance in practical use as a means of dimension control along the length of material. The tension control system is able to absorb the speed imbalances of the main motors and maintain uniform tension. This system was instrumental in achieving stable rolling over the length of the product. However, when there are temperature differences along the material length, the tension control system cannot meet the requirement of simultaneous control of height and width. This is because there are many factors other than tension which cause dimensional variations in actual rolling, it is difficult to measure actual tension, and the tension control system has only one manipulating value. Based on these considerations, a mechanism was adopted in which the roll gap is dynamically adjustable during rolling. Further, a sectional profile control technique (MFPC), based on roll gap control, was developed and applied for the first time in the world.

Figure 14 shows an example of dimensional variations after the rolling of a round billet with a rolling force variation of about 120 t at a skid mark. The decrease in width when rolling a skid mark zone is caused by temperature difference and attributed to the width-spread properties of material shown in Fig. 6. **Figure 15** shows case in which the roll-force AGC (termed BISRA-AGC) used in flat rolling is applied to all stands of the finishing mill. It can be seen that the width variation is greater than when there is no control, as shown in Fig. 14. The reason for this is that the width at the skid mark zone before H4 rolling is reduced by the V3 roll gap control. As described above, it is impossible to obtain a uniform sectional profile by the simple application of dynamic roll gap control (i.e., AGC), as used practically in flat rolling, to a V-H tandem mill with grooved rolls.

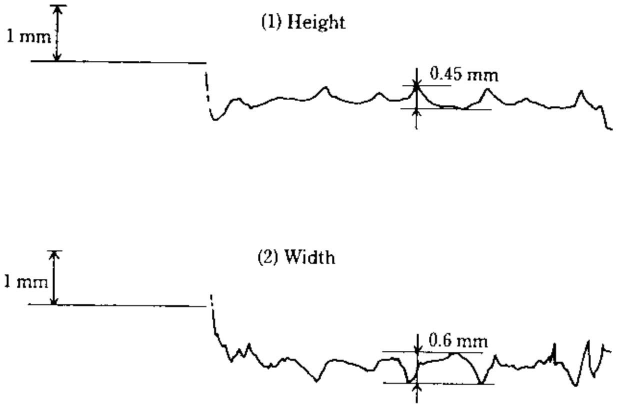

Fig. 14 Dimensional variation after rolling without control

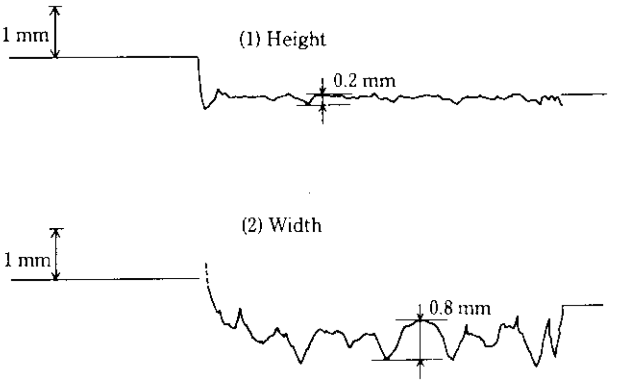

Fig. 15 Dimensional variation after rolling with BISRA-AGC

For this reason, a new control method was developed based on the width spread model shown in Eqs. (4) and (5) above. The concept of the control method is described below. (In the following, Δx_i denotes the difference from a lock-on point and i the stand number.)

(1) The height dimension is controlled by BISRA-AGC at the H4 stand.

(2) The process computer periodically calculates the temperature variation $\Delta\theta_3$ from the rolling force variation ΔP_3 at the point where material is passing the V3 stand by using the linearized equation (6).

$$\Delta P = \frac{\partial P}{\partial \theta} \times \Delta\theta + \frac{\partial P}{\partial h} \times \Delta h \cdots\cdots\cdots\cdots (6)$$

Here, Δh is height variation after rolling and can be calculated by the gauge-meter equation (3). The influence coefficient $\partial P/\partial\theta$, $\partial P/\partial h$ can be calculated by the rolling force model (2).

(3) The temperature variation at the H4 stand, $\Delta\theta_4$, is predicted from $\Delta\theta_3$. For simplicity, $\Delta\theta_4$ is considered equal to $\Delta\theta_3$.

(4) The variation in the width spread ratio at the H4 stand, $\Delta\beta_4$, can be calculated from $\Delta\theta_4$ by using the linearized equation (7).

$$\Delta\beta = \frac{\partial\beta}{\partial\theta} \times \Delta\theta \cdots\cdots\cdots\cdots\cdots\cdots\cdots (7)$$

The influence coefficient $\partial\beta/\partial\theta$ can be calculated by the width spread models (4) and (5).

(5) Using $\Delta\beta_4$, the width variation before H4 rolling, ΔB_4, which will make the width after H4 rolling uniform, is calculated. Considering the variations in width spread ratio, $\Delta\beta$, and width before rolling ΔB, from the lock-on point:

$$(\beta_L + \Delta\beta) \times (B_L + \Delta B) = b_L \cdots\cdots\cdots (8)$$

Equation (9) is derived from Eq. (8):

$$\Delta B = -\Delta\beta \times \frac{B_L}{\beta_L} \cdots\cdots\cdots\cdots\cdots\cdots (9)$$

The process computer calculates ΔB_4 by Eq. (9) from $\Delta\beta_4$. Here, b is width after rolling and the suffix L, the value at the lock-on point.

(6) The width variation before H4 rolling, ΔB_4, is equal to the height variation after V3 rolling, so that at the V3 stand, the process computer periodically corrects the aimed height after V3 rolling by ΔB_4 and controls the roll gap so as to obtain the aimed height.

The process computer performs the processing described above periodically for every control cycle (70 ms). In short description, MFPC is a control method

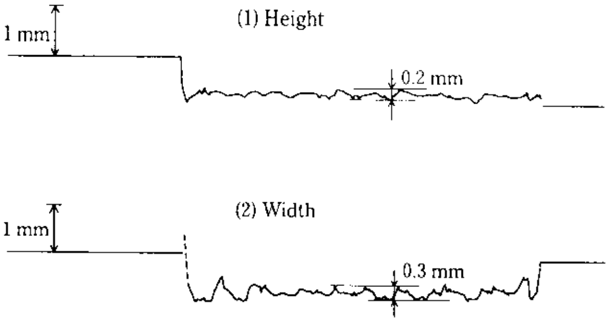

Fig. 16 Dimensional variation after rolling with MFPC

which controls roll gap while correcting the aimed value periodically at the V3 stand. **Figure 16** shows the result of its application. It can be seen that the dimensional variations of both height and width have been reduced from results in the other examples.

With this method, improved control precision can be expected with improved precision of calculation of the influence coefficients in Figs. (6) and (7), in particular of the width spread model.

4 Conclusions

In the field of tandem mills with grooved rolls, the tension control system was originally developed as the central control technique for the rolling mill. The basic concept of tension control, however, was not to control the material dimensions and profile actively; in other words, it was negative concept intended to avoid major disruptions in profile control. The present study, on the other hand, has proved, at the finishing mill of the billet mill, the effectiveness of MFPC by real-time control along the bar and of rolling mill set-up control. The methods described above, it is expected, will be expanded into a concept for positively realizing good profile, shape, and quality in flat rolling by control techniques, and will have great influence on shape and bar rolling technology. In the future, the authors will further expand the concepts described here, aiming at quality improvement in shape, bar, and rod products.

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