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Automatic Flatness Control System in Tandem Cold Rolling Mill for Ultra-thin Gauge Strip[*]

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1 Introduction

With the recent technological progress in computer and automation, the automatic operations at cold rolling mills have been widely prevalent. The No. 6 tandem cold rolling mill (TCM), constructed at the No. 1 Cold Rolling Plant of Chiba Works in 1963,[1] was revamped into a full continuous mill in 1984.[2] This conversion came to achieve both aims of automatization and labor saving in the operation of cold rolling mills. The No. 6 TCM, which is a main cold rolling mill for ultra-thin gauge strip (average thickness, 0.24 mm), rolls about 85 000 t/month of cold-rolled steel sheets for tinplate, tin-free steel and galvanized iron.

Because of the growing requirements for cold-rolled steel sheets with thinner gauge and better flatness quality, the necessity for automatic flatness control (AFC) has increased, far beyond the levels of conventional flatness control by mill operators' skill.

In order to answer this requirement and to prevent probable troubles caused by bad flatness, the AFC system based on feedback control has been developed at the last stand in the No. 6 TCM. The following is an outline of the new automatic flatness control system.

2 Outline of Equipment

2.1 Outline of No. 6 TCM

The No. 6 TCM was revamped into a full continuous mill in July 1984 in order to improve quality, yield ratio, unit consumption, and productivity of rolling products. **Table 1** shows the specification of the No. 6 TCM. The features of this mill are as follows:

(1) The average thickness is very thin (0.24 mm).

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Table 1 Specifications of 6-stand tandem mill

Type	Fully continuous 6 stand tandem (4-Hi)
Rolled material	Mild steel (for tin plate, TFS, GI)
Max. mill speed (m/min)	2 260
Delivery thickness (mm)	0.1 ~ 1.0
Strip width (mm)	508 ~ 1 295
Work roll diameter (mm)	495 ~ 610
Backup roll diameter (mm)	1 270 ~ 1 427
Max. roll bending force (tf/chock)	45 (increase) 45 (decrease)
Application	Direct

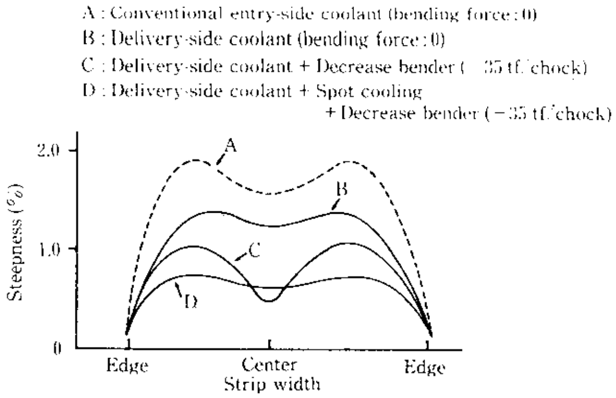


Fig. 1 Simulation of steepness (Coolant temperature 25°C, 0.17 mm guage × 750 mm width)

Table 2 Comparison of actuator between conventional system and developed system

	Conventional system	Developed system
Work roll bender force		
Upper limit (tf/chock)	50	45*1
Lower limit (tf/chock)	0	−45
Coolant		
Location	Entry side	Delivery side
Number of channels	—	26
Channel width (mm)	—	52
Flow level	—	8

*1 Symmetrical and asymmetrical

(2) The actual rolling speed is above 2 200 m/min.

(3) The production tonnage is about 85 000 t/month.

Following an increase of availability after the revamping to a full continuous mill, there came a problem with the control of the last stand's work roll thermal crown. In order to improve flatness control not by empirical and unstable operations by a monitor television but by a high-performance automatic control, the flatness sensor and the actuators were installed and the automatic flatness control system was developed.

2.2 AFC System

2.2.1 Choice of actuators

For the development of AFC system at the No. 6 TCM, two types of simulation model were selected to check out the capacity of actuators. One was the Shohet model about roll bending, the other was the thermal crown model for work rolls by the calculus of finite difference.[3)]

Figure 1 shows the results of simulation to adjust the center buckle by using the work roll bender and the zone coolant. This result elucidates the following three points:

(1) Changing the work roll coolant position from entry-side to delivery-side decreases the steepness of center buckle by 0.5%.

(2) Using the decreasing work roll bender of −35 tf/chock decreases center buckle, but increases quarter buckle.

(3) Selective zone-controlled roll coolant system, which is to optimize the distribution of the coolant flow along the strip width, controlls quarter buckle.

Table 2 shows a comparison of actuators between the conventional and the developed systems. The features of the developed system are as follows:

(1) Adding the decreasing work roll bender enables a continuous control from the increasing work roll bender to the decreasing work roll bender.

(2) The bending force control has both symmetrical and asymmetrical[4)] controls.

(3) The selective roll coolant system is installed at the delivery-side of the stand, and this coolant system can select eight flow levels along the strip width.

2.2.2 Flatness sensor

A flatness sensor is the most important part of the AFC system. The contact roll type sensor (Stressometer) is applied in this system in consideration of the stability and response of output. In the past, there were no cases of using the contact roller type flatness sensor at a high speed and ultra-thin gauge mill such as the No. 6 TCM, because of the anxiety of scratches between the sensor and strip. In this system, a more sophisticated helper driving system of sensor roller which permits a synchronization of the sensor speed and the strip speed prevents the scratches.

Table 3 shows the specifications of the flatness sensor installed. **Figure 2** shows an outline of the sensor. Basically, the designed channel width of the sensor is 52 mm the same as the width of the zone coolant channel. At strip edges where more accurate output is

Table 3 Specifications of shape-sensor

Roll diameter	(mm)	313
Accuracy (2σ)	(I-unit)	2.6
Period of output	(s)	0.35
Number of channels		
52-mm wide channel		10
26-mm wide channel		30
Total		40

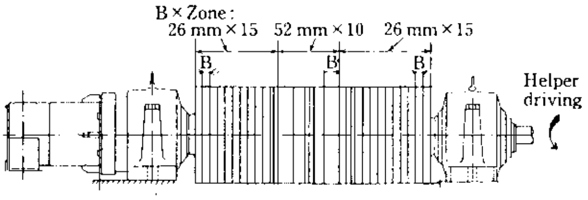


Fig. 2 Outline of shape sensor (STRESSOMETER)

required, the channel width of the sensor is a half (26 mm) of the basic channel width.

The measuring principle of the Stressometer is as follows: Load meters in each channel measure the distribution of the tension across the strip, so as to change this distribution into that of elongation by Eqs. (1) and (2).

$$\Delta\sigma_i = \frac{F_i - \bar{F}}{\bar{F}} \times T \quad \cdots\cdots(1)$$

$$l_i = \frac{\Delta\sigma_i}{E} \quad \cdots\cdots(2)$$

F_i: Output at i channel
$\bar{F}$: Average of F_i
T: Actual tension (kgf/mm^2)
$\Delta\sigma_i$: Distribution of tension (kgf/mm^2)
E: Young's modulus (kgf/mm^2)
l_i: Difference of elongation at i channel

Figure 3 shows the steepness comparison results between off-line and on-line measurements. The on-line measurement was obtained by the Stressometer, and the off-line measurement was taken while the sheets were on the flat table.

Even though these are different types of flatness, on-line measurement results coincide with off-line measurements. **Figure 4** shows the schematic diagram of the AFC system combined with the actuators and the sensor.

2.2.3 Control method of AFC system

Before referring to the control method of this AFC system, the characterization of the flatness must be explained. At first, the output of the flatness sensor,

Fig. 3 Steepness comparison between off-line and on-line measurement

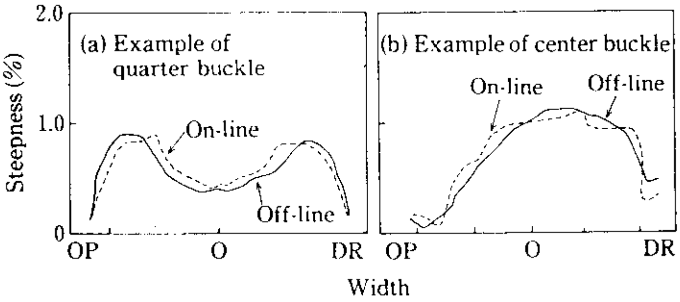
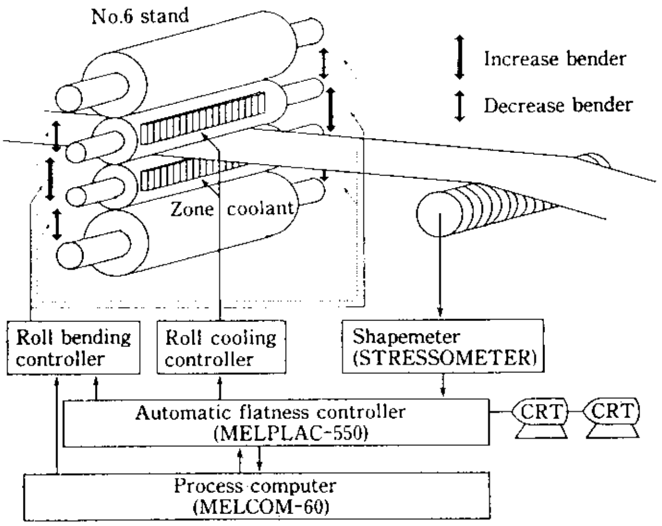


Fig. 4 Schematic diagram of automatic flatness control system



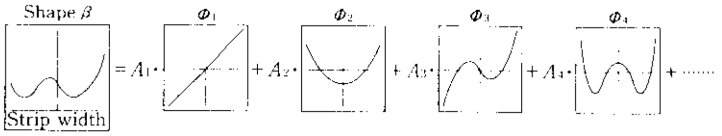


Fig. 5 Recognition of shape pattern

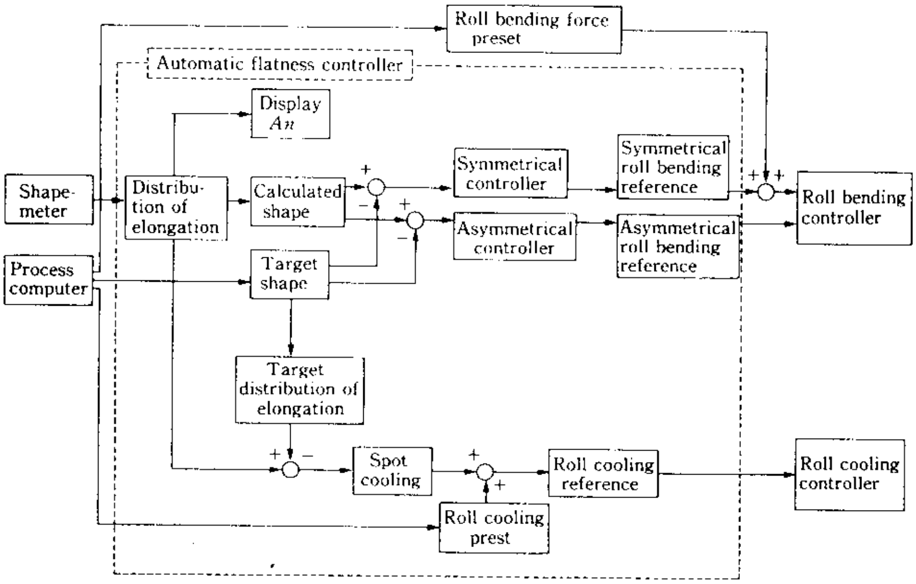


Fig. 6 Block diagram of automatic flatness control

which is the distribution of elongations, is expanded into the orthogonal function as the function of X axis of coordinate across the strip.[5,6] Where, β is explained as Eq. (3) with the orthogonal function from 0 degree to n degrees, i.e. from $\phi_0(X)$ to $\phi_n(X)$. The flatness can be expressed by each function's coefficients from A_0 to A_n.

$$\beta = A_0\phi_0 + A_0\phi_0 + A_1\phi_1 + \cdots + A_n\phi_n \cdots\cdots(3)$$

where $\sum_i \phi_l\phi_m = 1(l = m)$

$= 0(l \neq m)$

i: a position across the strip

Through this characterization of the flatness, it is easy to recognize the pattern of the flatness as shown in **Fig. 5**. The block diagram of AFC system is shown in **Fig. 6**. An aiming shape and a preset value of each actuator are calculated by process computer. The symmetrical flatness component with respect to the mill center across the strip is controlled by the symmetrical bender force. Also the asymmetrical flatness component is controlled by the asymmetrical bender force.

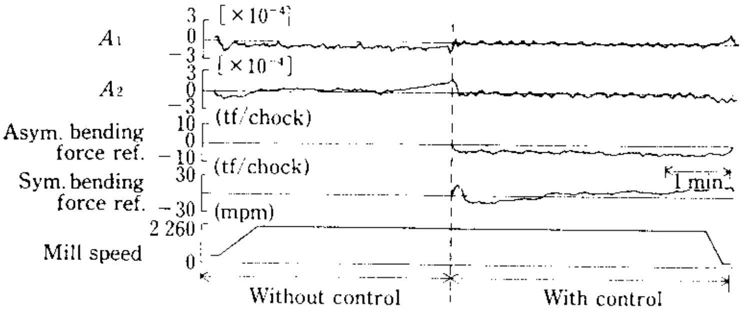
The spot cooling control, which can select the coolant level of the specific channel, is applied to a zone of large fluctuation from the aimed shape.

3 Effect of AFC System

3.1 Effect of Bending Control System

An example of the automatic work roll bending control is shown in **Fig. 7**. When the bender control is

Fig. 7 Example of roll bending control



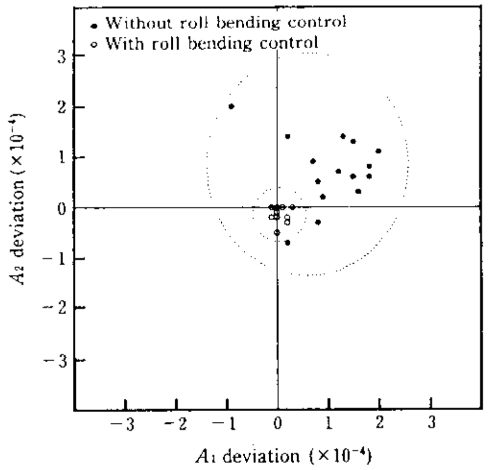


Fig. 8 Effect of roll bending control

"off", the asymmetrical flatness component shown by A_1 constantly has a value away from the horizontal axis and the symmetrical flatness component shown by A_2, for example, edge wave or center buckle, varies as time goes on. When the bender control is "on", A_1 and A_2 are also controlled to nearly zero. It was recognized that the work roll bending had a profound effect on controlling the edge wave, the center buckle and the one side wave.

Figure 8 shows the effect of work roll bending control on many data. When the bender control is "off", the measured flatnesses are distributed largely on A_1 A_2 coordinates. When the bending control is "on", they focus on nearly the origin. These facts also showed that the work roll bending had a profound effect on controlling the edge wave, the center buckle, and the one side wave.

3.2 Effects of Zone Cooling

The effects of delivery-side coolants and the spot cooling are shown in **Fig. 9**. This change of flatness is very similar to the result of the simulation shown in Fig. 1. And the delivery side coolants had significant effects on controlling center buckles compared with the entry-side coolants. In addition, Fig. 9 shows that the maximum steepness is decreased to less than 0.8% (i.e. marked improvement in flatness) by the spot cooling control applied to the local flatness fluctuation.

3.3 Total Effect

Figure 10 shows the total effect of work roll bending control and cooling control. The three points are recognized as follows:

(1) Without AFC, A_2's deviation is larger than A_4's deviation.
(2) When bending control is "on", A_2 value becomes smaller, but A_4 becomes larger.
(3) With the bending and spot cooling control, the deviation of both A_2 and A_4 become small, and the absolute values of A_2 and A_4 also decrease.

This means that not only the simple shape, such as edge wave or center buckle, but also the complex shape is controlled to a very flat shape by this system.

Figure 11 shows the effects of AFC system on the edge strain ratio at temper mill. The edge strain occurs because of the bad flatness of strip. When the edge

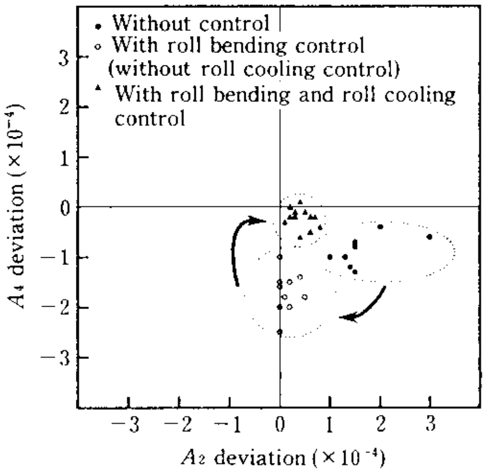


Fig. 10 Effect of roll bending and roll cooling control

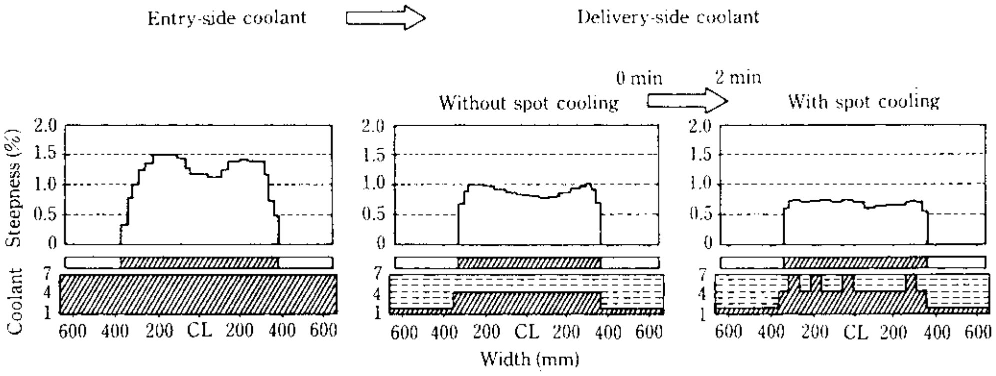


Fig. 9 Effect of delivery-side coolant and spot cooling

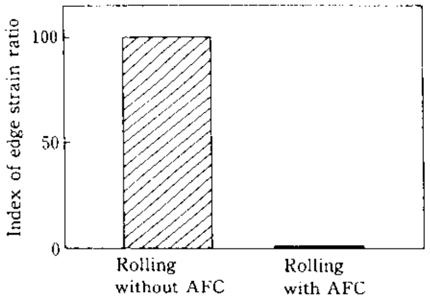


Fig. 11 Effect of AFC system on edge strain ratio at temper mill (Comparison of edge strain ratio between with and without AFC when the latter value is taken as 100)

strain ratio was taken as 100% without AFC, the ratio decreases to 0% with the AFC.

This AFC system has the simple actuators compared with the other flatness controller, but has proved very effective with its flatness sensor supplying stable outputs. Furthermore, the same type of AFC system was installed on the No. 3 TCM at the No. 2 Cold Rolling Plant of Chiba Works,[7] and it has been operating satisfactorily.

4 Conclusions

In order to improve the quality of flatness, the automatic flatness control system was developed and installed at the No. 6 TCM, the main mill for ultra-thin gauge cold rolled strip in Chiba Works.

The features of this system are as follows:

(1) The sophisticated helper driving device of this system permits the application of the contact roller type sensor with stable and quick response to a high speed and an ultra-thin gauge cold rolling mill.

(2) The actuators, which consist of an increasing and decreasing work roll bender and the selective work roll zone cooling system, were developed and have been installed.

The effects of this AFC system are as follows:

(1) The control not only for simple shape by work roll bender, but also for complex shape, such as quater buckle, has been realized by the zone cooling system.

(2) As a result, the maximum steepness is decreased to less than 0.8%, and defects caused by bad flatness have been drastically decreased.

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