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Advanced Process Control Technologies for Realization of Endless Hot Strip Rolling

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Kawasaki Steel was the first in the world to start the so-called "endless hot strip rolling" at the No. 3 Hot Strip Mill in Chiba Works by realizing hot sheet bar joining and continuous finishing rolling in 1996. In order to realize hot endless rolling, highly accurate process control and full automation with high reliability are necessary and Kawasaki Steel developed central control technologies for this process including mill pacing control, flying joining control, finishing mill joint stabilization, flying gauge change control and fully automatic high-speed shear and coiler control. With these new technologies, the stable endless hot strip rolling process has been made possible and the quality of products has been improved. As a result, it has become possible to produce thin-wide strips and ultra-thin strips exceeding past rolling limits and in addition, to develop and produce new products making use of lubricated rolling and/or force-cooled rolling.

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1 Introduction

The Chiba Works of Kawasaki Steel started operation of its No. 3 Hot Strip Mill in May 1995 and in 1996, was the first in the world to achieve "endless hot strip rolling". This mill was constructed to respond to users' severe requirements for quality and to their demand for a wider range of product size, thinner products in particular, and thus maintain the company's competitive power into the 21st century.[1-3] Endless hot strip rolling is a process that can only be realized by fully automated technologies with high accuracy and high reliability throughout the process from extraction of the slabs, the reheating furnace to coiling at the coil transfer, not to mention joining of the sheet bars. In this report, we explain the key process control technologies supporting the endless rolling process.

2 Formation of Equipment and Key Control Technologies

The arrangement of the rolling equipment in the No. 3 Hot Strip Mill and the key control technologies for endless hot strip rolling are shown in **Fig. 1**.

Sheet bars are joined on the fly in endless hot strip rolling, therefore, it is indispensable to supply sheet bars to the bar joining machine located before the finishing mill without any interruption so as to join, stabilize and roll these bars and to continuously coil the rolled strips. In order to satisfactorily perform these processes, we newly developed the following process control technologies and automation technologies.

(1) Overall rolling pitch control within an endless rolling group which surpasses the conventional concept of rolling pitch control for individual sheets. This overall control consists of a number of controls and technologies such as high-accuracy extraction pitch control based on the estimation of the sheet bar intervals on the mill line and optimization of the coiling-out timing from the sheet bar coiler.

(2) Flying joining control consisting of a high-accuracy "catch-up" control which allows the joining cars and succeeding bars to follow the tailing end of the preceding bars at high accuracy and to properly maintain tension on the sheet bars at joining.

(3) High-accuracy gauge control and flying gauge change control achieved by variable rigidity control, dynamic controls composed of absolute gauge AGC and X-ray monitor AGC and high-accuracy set-up control in finishing rolling of joined sheet bars.

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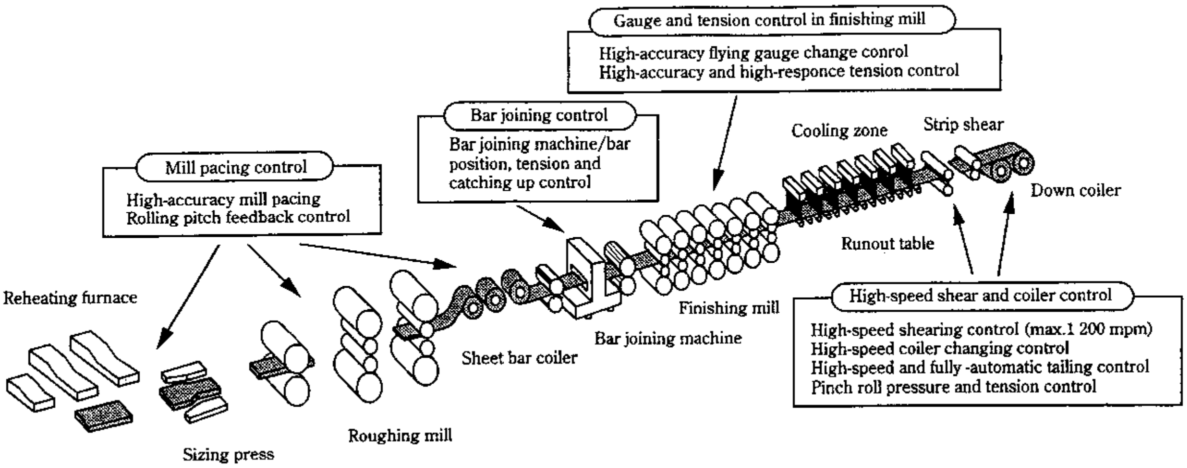


Fig. 1 Endless hot strip rolling equipments and key technologies of process control

(4) High-accuracy and high-response tension control using an AC motor driven high-speed response mill and a low inertia looper and finishing mill joining part stabilization control by means of mass-flow control.

(5) Fully automatic high-speed shear and coiler control consisting of high-speed shearing of strips passing through the finishing mill, selective change of the winding-up coiler and coiling and tailing end fixed position stop control at the end of high-speed coiling.

The main specifications of the endless hot strip rolling process and the basic specifications of the equipment are shown in **Table 1**.[4)]

Table 1 Main specifications of endless hot strip rolling and equipments

	Items		Specification
Available size of producuts	Thickness	(mm)	0.8～6.0
	Width	(mm)	780～1 900
Endless rolling	Bar thickness	(mm)	20～40
	Min. pitch	(s)	45
	Number of coils at an endless train		Max. 15
Flying gauge change	Thickness	(mm)	±1.5
	Width	(mm)	+50 −100
Sheet bar coiler	Coilling speed	(m/min)	Max. 340
	Recoilling speed	(m/min)	Max. 150
Bar joining machine	Type		Self driving with sheet bar carriage
	Driving speed	(m/min)	Max. 60
	Heating		Induction heater
Strip shear	Shearing speed	(m/min)	1 200
	Shearing thickness	(mm)	0.8～6.0

3 Process Control Technologies for Endless Hot Strip Rolling

3.1 Rolling Pitch Control

The most important requirements for rolling pitch control, i.e., mill pacing, for rolling materials processed by conventional batch rolling is to achieve the highest rolling efficiency corresponding to the capacity of the equipment without causing various troubles on the mill line such as rolling materials colliding with each other or entering the line before changes in the setting of each equipment are completed. Concretely speaking, the requirement was to find the locations on the line where the rolling materials interfere with each other or with equipment by highly accurately estimating the loci of the leading and tailing ends of rolling materials on the basis of the transfer pattern of each rolling material as well as an estimation of the time required for changing various settings such as the degree of the side guide opening, thus determining the proper extraction pitch so that no interference occurs at these locations.

On the other hand, the most important role of mill pacing in endless rolling is to determine an adequate extraction pitch and timing for roughing mill rolling so that succeeding bars are continually supplied to the bar joining machine following the preceding bars which are being rolled in the finishing mill and furthermore, no temperature drop should occur in rolling materials due to unnecessary stand-by time. The basic technology is to make a highly accurate estimation as in the case of batch rolling, however, what must be considered, is how to prevent rolling materials from interfering with each other and with the equipment in the roughing rolling process and to steadily supply materials to the bar joining machine by accurately estimating the difference in the rolling time caused by materials' sizes and rolling schedules at the roughing rolling of all materials in the group, by properly judging the proprieties for joining at the joining process and by deciding the transfer conditions for achieving joining while all slabs in the same endless rolling group are in the reheating furnace. Therefore, we took the coiling-out timing of the preced-

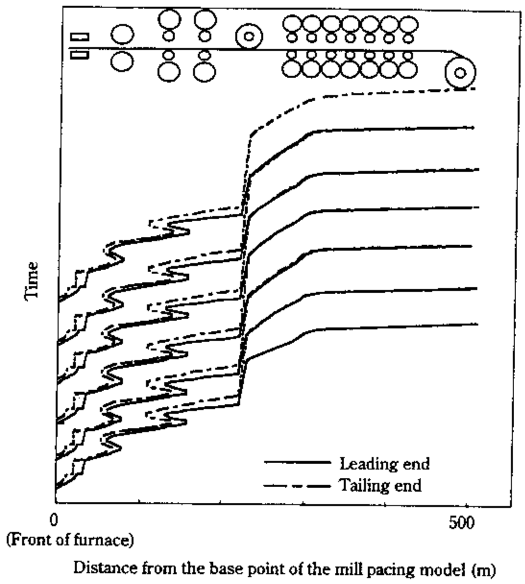


Fig. 2 Example of the result calculated by the mill pacing control system

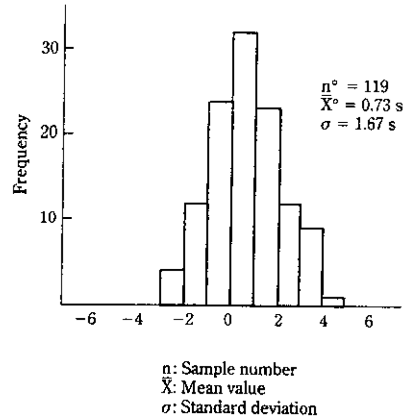


Fig. 3 Results of sheet bar waiting time in sheet bar coiler

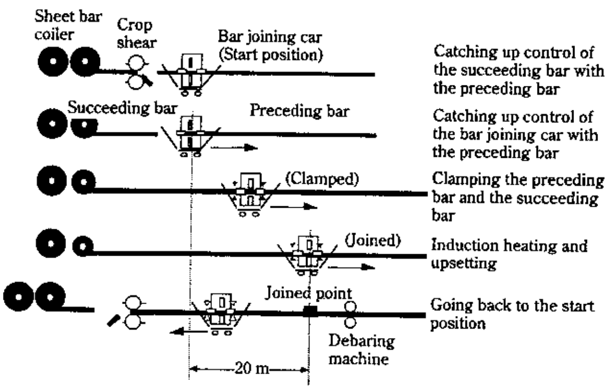


Fig. 4 Sequence chart of bar joining machine

ing bars as the extraction pitch for the succeeding bars and adopted a method that unifies the roughing rolling time of all sheet bars in the group by setting the rolling time to that of the bar requiring the longest time among those in the group.[5] Thin unification was achieved by positively keeping succeeding bars waiting to enter into each piece of equipment of the roughing mill until the time determined by the mill pacing comes. As a result, sheet bars whose roughing rolling time is short are extracted early from the reheating furnace and interference problems in the roughing rolling process are dissolved by this easy method without the trouble of doing complex calculations such as convergence calculation. With this procedure, the joining of many groups of endless sheet bars is made possible.

On the other hand, this rolling pitch control system also has a feed-back control function which absorbs disturbances in rolling by reflecting the difference between the estimated and actual time on the stand-by time for succeeding bars at roughing rolling as well as an extraction timing for extracting materials. Even when operation is retarded on the mill line due to having both batch rolling materials and endless rolling materials together, this feed-back control is effective for rectifying the situation by promptly detecting the condition.

Figure 2 shows an example calculation of a transfer schedule. It can be seen that the tailing end of the proceeding bar and the leading end of the succeeding bar meet at the location of the bar joining machine and are joined without any problem. **Figure 3** shows the waiting time in the sheet bar coiler under the present conditions. The standard deviation (σ) is 1.67 s showing that steady endless rolling has been realized.

3.2 Flying Joining Control

In flying joining control, as shown in **Fig. 4**, a series of processes are completed within the 20 m stroke of the bar joining car by going through induction heating and upsetting under adequate conditions after catching up of the succeeding bar with the preceding bar, catching up of the joining car with the preceding bar, clamping of the preceding bar and clamping of the succeeding bar.[6] In order to actualize these processes, we developed new process control technologies including "catch-up" control for the bar joining car, catch-up control for the leading end of the succeeding bar and sheet bar tension control for joining bars at the inlet side of the finishing mill.

For the catch-up control for the bar joining car, the system controls the joining car to catch up with the tailing end of preceding bar which has been paid out from the sheet bar coiler. In this control, the bar joining car starts running at the best timing because the position of the tailing end of the preceding bar is being continuously recognized by a leading and tailing end position detector installed on the joining car. Then, the speed of the joining car is controlled in such a way that the tailing end of the preceding bar comes to the center of the

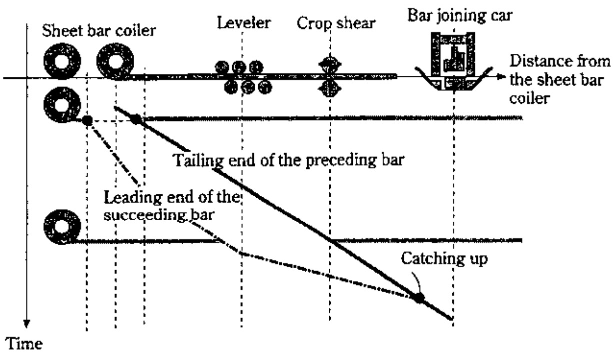


Fig. 5 Catching up control of the succeeding bar

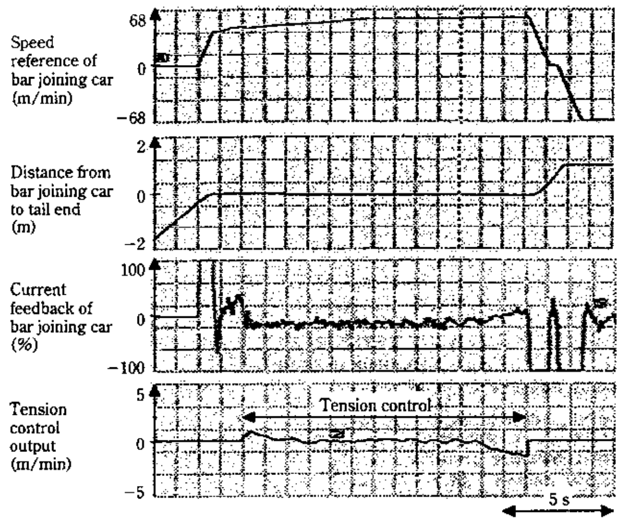


Fig. 6 Chart of bar joining car control

inductor. Ordinarily, positioning of the joining car is completed within 5 s from the time when the tailing end of the preceding bar comes into the bar joining machine.

In the catch-up control for the succeeding bar, the system controls the succeeding bar, while paying out the preceding bar from the sheet bar coiler, to catch up with the tailing end of the preceding bar which has been paid out from the sheet bar coiler. A conceptual diagram of the catch-up control of the succeeding bar is shown in **Fig. 5**. This control system consists of a function to determine the paying out start timing for succeeding bars and a function to determine the speed of succeeding bars after being paid out. The paying out start timing for succeeding bars is determined by taking the fluctuation of the preceding bar's speed based on the remaining length of the coiling of the preceding bar and the rolling schedule into consideration. After paying out, the system controls the distance between the preceding and succeeding bars to such a distance that the tailing end of the preceding bar and the leading end of the succeeding bar can be cut by the crop shear successively. Then, the system controls the distance to become the shortest immediately before the joining car and then both bars butt against each other. Butting occurs immediately after completing the above mentioned positioning of the joining car.

In the sheet bar tension control for joined bars at the inlet side of the finishing mill, the speed of the joining car is controlled so that excessive tension is not applied and no sagging occurs in the sheet bar after the tailing end of the preceding bar is clamped by the joining car.

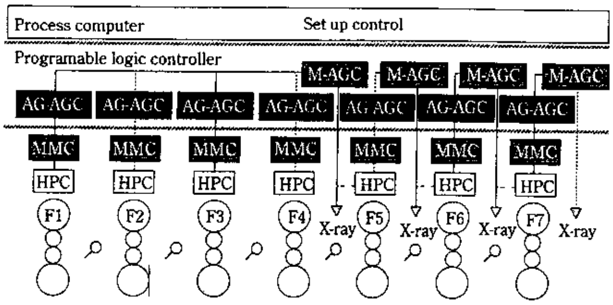
An example of the control from the time when the tailing end of the preceding bar comes close to the joining car is shown in **Fig. 6**. The holizontal axis is time and the vertical axises are speed of the bar joining car, distance from the bar joining car to the tailing end of the preceding bar, current of the bar joining car and output of the sheet bar tension control. The figure shows that the catch-up control starts at the best timing for the joining car and after about 2 s, clamping of the preceding bar is completed and steady tension control starts in this example.

Photo 1 Sheet bar joining machine

With the above described catch-up control system and tension control system having been developed, it has become possible to steadily perform flying joining. **Photo 1** shows an external view of the bar joining machine. In addition to a driving mechanism, the joining car is provided inside with an induction heater for heating the joining ends of the bars, clamps for holding sheet bars and an upsetting device for upsetting clamped sheet bars.

3.3 Flying Gauge Change Control

In order to produce long strips with partially different sizes and in order to realize expansion in limiting the size of the hot rolled sheet bars, it becomes necessary for the finishing mill to be able to change the gauge of strips while in operation. In order to accurately and steadily perform flying gauge changes, the important matters are a high-accuracy set-up control to accurately



HPC : Hydraulic position control
MMC : Mill modulus control
AG-AGC: Absolute gauge AGC
M-AGC : Monitor AGC
∇ : Thickness gauge

Fig. 7 Outline of automatic gauge control system

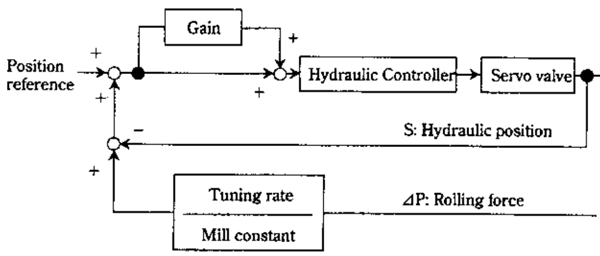


Fig. 8 outline of mill modulus control (MMC)

estimate the various target values such as roll gap, and high-accuracy trucking for matching roll gap changing timing at each stand to flying gauge change positions. In addition to these matters, the steady and highly accurate flying gauge change control has been actualized by combining mill modulus control (MMC) with high-response and high-speed control cycles by means of hydraulic position control at every stand, absolute value automatic gauge control (AGC) for correcting deviation of thickness gauge readings from the set values and monitoring AGC using the actual thickness being measured by X-ray thickness meters installed at the delivery side of each stand from the mill F4 and thereafter.[7]

The gauge control system is outlined in **Fig. 7** and the mill modulus variable control system in **Fig. 8**. Furthermore, a strip thickness chart of the endless hot strip rolling partially with 1.0 mm thick parts is shown in **Fig. 9**. It can be observed from the chart that the thickness is kept within $\pm 30\,\mu m$ all over the product to the end points. There is no fluctuation in thickness at the points of flying gauge changes and excellent control has been actualized.

3.4 Gauge and Tension Control in the Finishing Mill

The joining parts of the sheet bars are heated by the joining machine, and therefore, are at a higher temperature than the mother material parts. This causes sudden drops in the rolling load accompanied with fluctuations

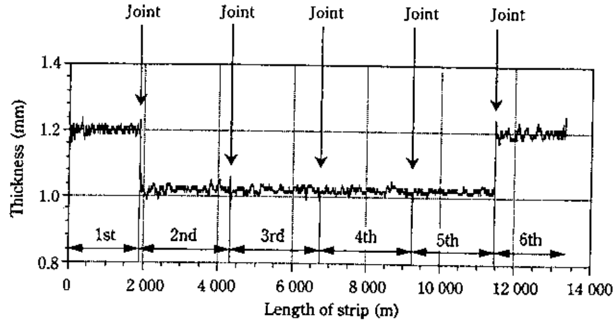


Fig. 9 Strip thickness chart of endless hot strip rolling measured X-ray thickness meter at F7 delivery point (strip thickness: 1.2 → 1.0 → ··· → 1.0 → 1.2 mm)

in the tension. Furthermore, these parts are weaker in strength than the mother material parts and could possibly break. Therefore, it is extremely important to achieve the target thickness and to steadily stabilize the product.[8]

In order to steadily stabilize joining parts where temperature fluctuation is large, the mill modulus control (MMC) described in the preceding article and mass-flow control which suppresses tension fluctuation resulting from changes in mass-flow between stands are effective. Furthermore, by speeding-up the response using AC motors for the finishing mill and by installing low inertia loopers, the controllability of the tension between stands improves and more stable rolling can be realized. In order to suppress fluctuations in the tension at the rolling of joining parts, the control system was designed with two control loops. One of them is the tension control loop to feed tension back to the speed control system for the main motor of the mill and the other is the looper angle control loop which feeds the looper angle back to the looper angle speed control system. In order to make the controllability of the looper angle better in response than controllability for looper angle, internal model control (IMC) was added.[9] A schematic diagram of the looper angle and tension control system is shown in **Fig. 10**. With respect to the control and flatness, a pair of cross mills having a high crown controllability and a powerful work roll bender were adopted for every stand, thus it was made possible to highly accurately control the strip crown over a wide range. The crown and flatness control system is outlined in **Fig. 11**. The cross angle and work roll bending force are set-up according to the rolling load estimation and roll profile. Fluctuations of the crown and flatness due to load changes are suppressed by load linked control of the bender. **Figure 12** shows changes in the strip crown over a range of 25 mm on the edge during endless hot strip rolling of ten sheet bars and **Fig. 13** shows the results of measurements taken for endless hot strip rolled sheets using a profile meter provided at the delivery side of the finishing mill. It can be observed from these figures that a sta-

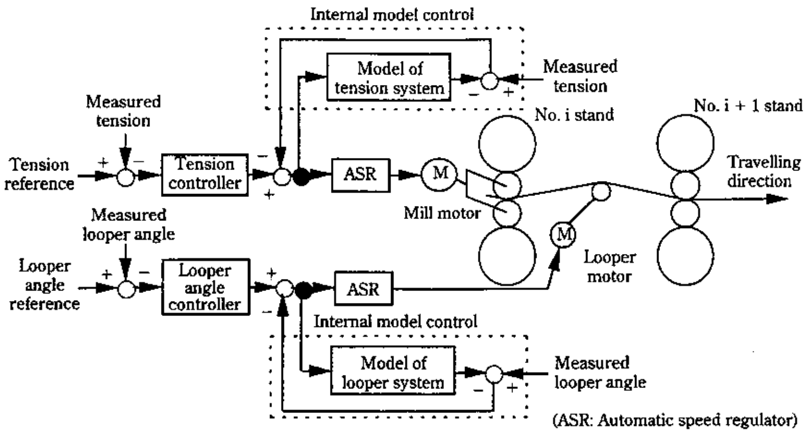


Fig. 10 Schematic diagram of tension and looper angle control system

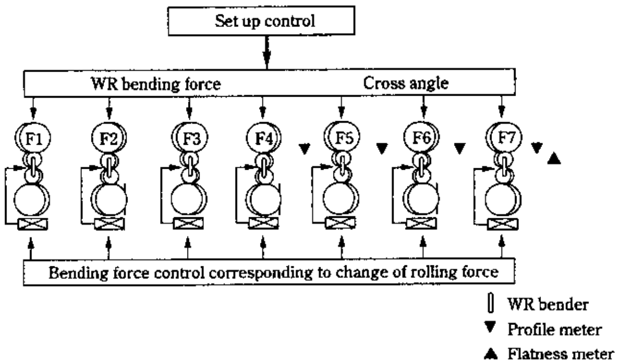


Fig. 11 Outline of crown and flatness control system

ble crown and profile have been achieved although the strip crown gradually decreases as a result of the thermal expansion of the rolls.

3.5 High-speed Shear and Coiler Control

The maximum coiling speed of the leading end of strip for batch rolling is about 800 m/min, however, for endless rolling it reaches 1 200 m/min. In order to shear-cut ultra-thin strips of 0.8 mm thick at the thinnest at the predetermined position under this high-speed stabilization condition, various kinds of control including shearing point trucking control, strip tension control before and after shearing, alternate coiler changing control with two units and stopping control at the tailing end and

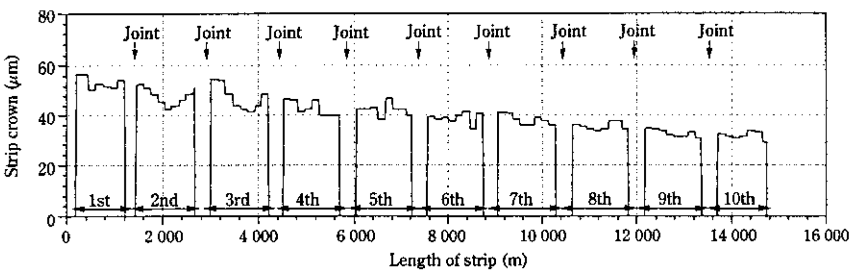


Fig. 12 Changes in strip crown during endless hot strip rolling measured by profile meter at F7 delivery point (strip thickness: 1.66 → 1.26 → · · · → 1.26 → 1.66, width: 1 220 mm)

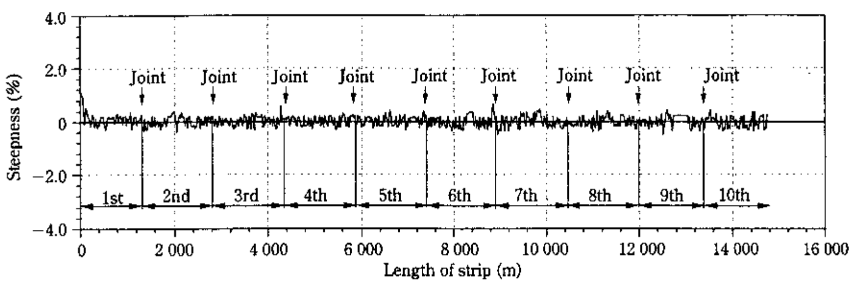


Fig. 13 Steepness chart at F7 delivery point (strip thickness: 1.66 → 1.26 → · · · → 1.26 → 1.66, width 1 220 mm)

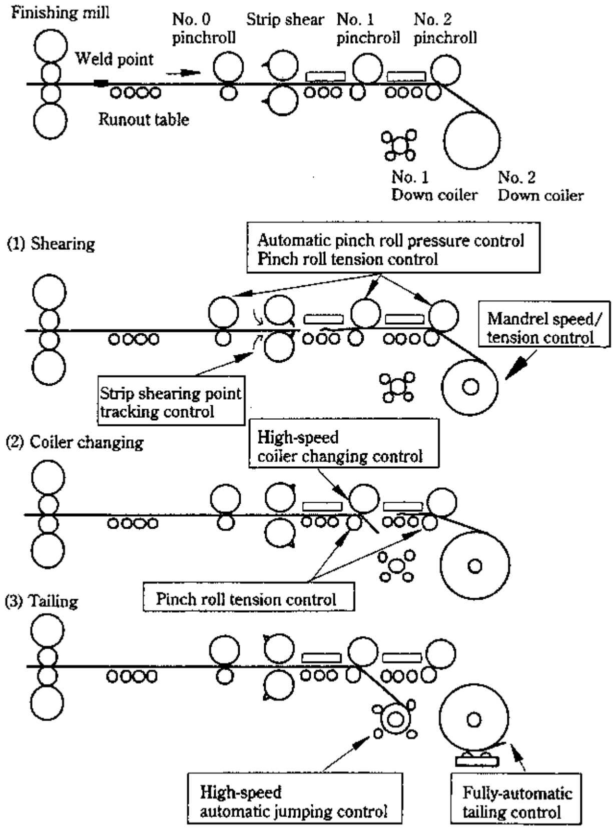


Fig. 14 Process control of high-speed shear and coiler in endless hot strip rolling

fixed position become important. Furthermore, the leading end of the succeeding strip passes the position of the coiler within several tens of milliseconds after the trailing end of the preceding strip, therefore, there is no room for operators to intervene in coiler changing in endless rolling and fully automatic operation is indispensable. Operators were needed to be involved in the proper operation of pinch rolls of coilers in the past, however, complete automatization of coilers with no manual work has been realized by adopting a hydraulic servo press-down system.[10] The major control systems for high-speed shearing and coiling are shown in **Fig. 14**. A cycle time of 40 s has been achieved for changing coilers with these control systems.

4 Closing Remarks

The world-first endless hot strip rolling has been realized by developing endless rolling process control technologies. By completing this rolling process, defects in size and profile at the leading and tailing ends have been decreased, improving the quality aspects and the ± 30 μm on-gauge ratio has been dramatically improved from 96% to 99.5% in strip thickness accuracy. In addition to the above, various troubles in rolling have been decreased. Furthermore, stable production of thin-wide steel strips with a thickness of 1.2 mm and a width of 1 600 mm and of ultra-thin steel strips of thinner than 1.2 mm thick has become possible. Such products could not be stably produced by conventional batch rolling. Production of steel plates having new material constants has also become possible by means of lubricated rolling and/or force-cooled rolling with this endless hot strip rolling process.

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