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Synopsis :

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The body can be viewed from the next page.

# Development of Hot Rolling Technology for Improving Strip Profile and Flatness*1

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## 1 Introduction

With a rising need for higher yield, process streamlining, and automatization at steel users in recent years, a supply of steel sheets that meet these particular aims is strongly desired. Against such backdrops, quality requirements of hot rolled strip has turned more rigorous, with higher accuracy demanded on not only steel properties, but also on such dimensional and shape requirements as thickness, width, flatness, and profile (as shown in **Fig. 1**, a widthwise thickness distribution of sheet, comprising strip crown indicating a center height of sheet, high spot resulting from local wear of roll, and edge drops). To meet these requirements, new and sophisticated techniques have been developed one after another and conventional hot strip mills are in a transition into a new age.

As for thickness and width accuracy, many hot strip mills have obtained satisfactory results by using the hydraulically-operated automatic control systems for gage and width as the systems exceed conventional electric systems in the speed of response and action.

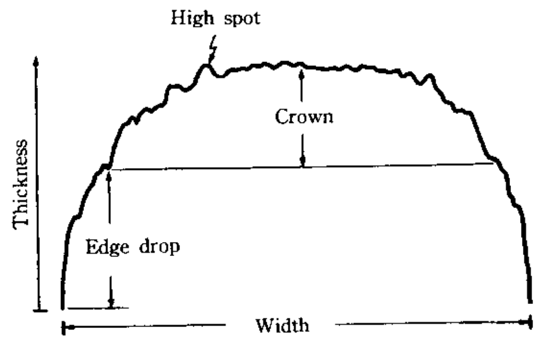


**Fig. 1** Definition of strip profile (crown, edge drop and high spot)

For flatness control, highly reliable and accurate shape meters have been developed to make automatic control operable by using signals from the meters for adjusting the hydraulic pressure of the work-roll bender on the final stand of finishing mill, thereby controlling the work-roll deflection.[1)] Thus, the flatness control technique up to the finishing mill delivery side is approaching the completion. However, these techni-

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ques are insufficient to ensure the flatness required by users. It is also important to control changes in flatness which arise during cooling process which follows the delivery end of the finishing mill. Techniques to achieve this are also being developed.[2)]

As for strip profile, no substantial progress has been made until very recently in crown and profile control because conventional rolling mills had no mechanism to permit efficient control measures and because a slow development of sensors for a high-accuracy measurement of the profile of sheets under rolling.

Basically, "dead flat" (crown-free) hot-rolled and cold-rolled steel sheets are required by users for automobile parts, motor cores, and tinplate cans, etc. In the case of hot-rolled strip to be cold rolled, however, it is necessary to control the strip crown to optimum values during hot rolling in order to obtain good flatness during threading and after cold rolling. For this reason, the optimum hot strip crown shown in **Fig. 2** differs from steel grade to steel grade and from application to application. In this figure, the strip crown is defined as the difference in sheet thickness between at the cetner of the strip width and at 25 mm from the strip edge, and denoted by $Cr_{25}$. The high spot greatly affects the flatness of cold-rolled steel sheets and must be controlled below a certain tolerance.

Because a hot strip mill composed of ordinary 4-high mills is not provided with an effective crown control device, changes in strip crown of about 100 $\mu$m occur in one rolling campaign due to changes in the roll profile over time caused by thermal expansion, work-roll wear, and changes in the roll deflection resulting from changes in the thickness and width of the strip.[3)] In the conventional hot strip mill, therefore, it is impossible to maintain the required strip crown shown in Fig. 2 to satisfy users' needs. Furthermore, the local roll wear that occurs at a strip edge causes high spots. It is therefore necessary to substantially reduce the rolling schedule by restricting the rolling order in terms of the strip width and the number of strip rolled of the same width. This has been a great obstacle to synchronising the processes before and after hot rolling. The development of a rolling mill which can effectively control the crown, high spot and edge drop of the hot-rolled strip has thus been long sought after.

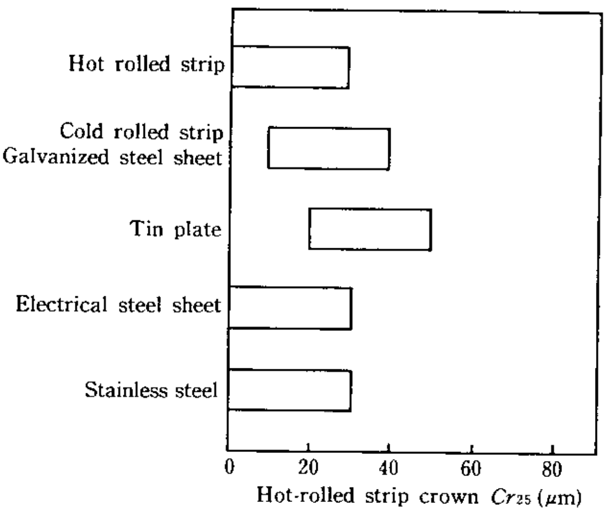



**Fig. 2** Suitable hot rolled strip crown for products use

In recent years, various new rolling mills have been put into practical use in some hot strip mills to increase the capacity to control the profile and relax the limitations on rolling schedules.

Kawasaki Steel recently installed a tapered-crown work-roll shifting mill (K-WRS mill: Kawasaki Steel work-roll shifting mill),[4)] the company's own development, and the HC mill (High-crown-control 6-high mill) at No. 1 hot strip mills of Chiba Works and at hot strip mills of Mizushima Works respectively. Products with a good profile which meet users' requirements have been obtained and stable operations achieved. This paper presents an outline of the results. In the Mizushima hot strip mill, it has become possible to supply products of excellent flatness to users through a closed-loop flatness control system comprising a flatness meter and a finishing stand work-roll bender, and through a flatness control using width direction cooling control on the runout table. This flatness control technique and the results obtained are also decribed in this paper.

## 2 Profile Control in Hot Strip Mills

### 2.1 Problems with Conventional Profile Control Methods

In finish rolling of conventional hot strip mills, a draft schedule comprising heavy reduction in the upstream stands and light reduction in the downstream stands has usually been adopted, with flatness control conducted by a work-roll bender of the downstream stands, especially for the final stand. The profile of the hot-rolled strip alters according to changes in the work-roll profile resulting from roll wear and thermal crown. Therefore, for hot-rolled products that must satisfy stringent dimensional and flatness accuracies, good profiles have been obtained so far by optimizing the initial crown of the work rolls, and by adopting a rolling schedule starting with wide strip followed by less wide strip, and by limiting the rolling order in the rolling schedule.

As previously mentioned, requirements of strip flatness and profile are getting increasingly severe year by year. Since the latter half of the 1970's, various improvements have been made in rolling methods by the conventional 4-high mill owing to the development and introduction of on-line flatness meters and profile meters.

In terms of draft scheduling in the finisher, the total rolling force changing method[3] and the draft schedule changing method[5] have been developed to control the elastic deformation of rolls due to the rolling load and serve to maintain at constant the strip crown in a rolling campaign.

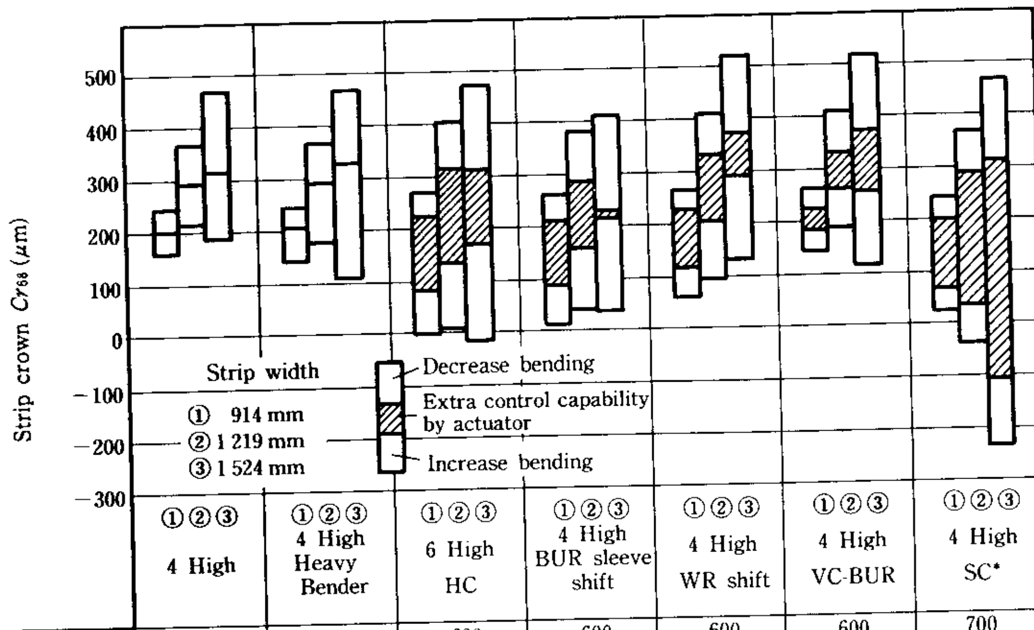
In terms of hardware, the strip crown and edge drop have been reduced by a rolling method which uses rolls of different diameter[6], in which a single roll drive is adopted to reduce the elastic deformation of rolls by decreasing the rolling load; a heavy-duty work-roll bender[7] of the double bearing chock type; trapezoidal-crown work rolls[8] which reduce the edge drop due to their geometrical effect; and stepped backup rolls[9] which improve the effect of the work-roll bender because they have backup rolls with their barrel shorter than those of work rolls.

However, satisfactory results have not been obtained through the use of any of these methods and, in particular, it has been impossible to control the high spot which is a local profile abnormality. Therefore, there has been a demand of a mill with a greater capacity to control strip profile and flatness.

### 2.2 New Profile Control Method

The 6-high HC mill[10] in which the roll bender effect is improved by shifting the intermediate rolls to the axial direction, has been adopted in many cold strip mills. Since the beginning of the 1980's, HC mills equipped with a work-roll shifting mechanism have also been introduced into hot strip finishing mills in view of their application to the schedule-free rolling that substantially relaxes the limitations on rolling schedules.[11] Moreover, the development and introduction of equipment-related techniques are being actively carried out—for example, a VC roll[12] in which sleeve is shrink-fitted to backup roll and an oil chamber installed between the sleeve and the arbor to control the expansion of the sleeve by the oil pressure; a work-roll shifting mill in which the functions of a 6-high HC mill are achieved in a 4-high mill; the work-roll shifting mill developed by Kawasaki Steel (K-WRS mill)[4], in which the work rolls have a crown tapered on one side to have the effect of the trapezoidal-crown roll meeting the changes in the strip width, and the crown, edge drop, and high spot can be simultaneously controlled; and a cross roll (SC) mill[13], in which the roll gap is axially changed by crossing the top and bottom rolls alternately in the rolling direction.

The crown control capabilities of various mills mentioned above are shown in **Fig. 3.**[14] The cross roll mill has excellent crown control capability. However, in addition to its complex structure, this mill is unable to control the high spot or improve the functioning of the roll bender during rolling. Although the VC roll mill effectively controls flatness, it has a low profile control




| | 4 High | 4 High Heavy Bender | 6 High HC | 4 High BUR sleeve shift | 4 High WR shift | 4 High VC-BUR | 4 High SC* |
|---|---|---|---|---|---|---|---|
| WR dia. (mmϕ) | 700 | 700 | 600 | 600 | 600 | 600 | 700 |
| Bending force (t/chock) | ±95 | +143~−95 | ±60 | ±60 | ±60 | ±60 | ±95 |
| Shift stroke (mm) | – | – | $\delta \geqq 0$ | $\delta \geqq 0$ | $\delta \geqq 45$ | – | – |
| Cross angle | – | – | – | – | – | – | 0~1° |
| BUR crown | 0 | 0 | – | 0 | 0 | 0~250 (μm) | 0 |

*calculated by the authors

**Fig. 3** Comparison of crown control capability between newly developed crown control mills and conventional 4-high mill

**Table 1** Specifications of hot strip mills before refreshment

| Mill | Number of stands | Roll size | Products | Product's size |
|---|---|---|---|---|
| No. 1 hot strip mill in Chiba Works | 6 | WR 596~700 $\phi \times$ 1 422 $L$<br>BUR 1 118~1 255 $\phi \times$ 1 372 $L$ (mm) | Mild steel<br>High carbon steel<br>Low alloy steel<br>Silicon steel<br>Stainless steel<br>(Ferrite phase) | Thickness: 1.2~12.7 $t$ (mm)<br>Width: 610~1 310 $W$ (mm) |
| No. 2 hot strip mill in Chiba Works | 7 | WR 647~755 $\phi \times$ 2 032 $L$<br>BUR 1 413~1 495 $\phi \times$ 1 032 $L$ (mm) | Mild steel<br>High carbon steel<br>Silicon steel<br>Stainless steel<br>(Austenite phase) | Thickness: 1.2~19.0 $t$ (mm)<br>Width: 700~1 880 $W$ (mm) |
| Hot strip mill in Mizushima Works | 7 | WR 700~815 $\phi \times$ 2 300 $L$<br>BUR 1 470~1 630 $\phi \times$ 2 300 $L$ (mm) | Mild steel<br>High carbon steel<br>Low alloy steel<br>Silicon steel<br>Stainless steel | Thickness: 1.2~25.4 $t$ (mm)<br>Width: 700~2 200 $W$ (mm) |

capability and can not control the edge drop and high spot. The 6-high HC mill has high profile control capability over a wide range from narrow to wide strip and can be applied to the schedule-free rolling. The 4-high work-roll shifting mill has a sufficient profile control capability for narrow strip. This can be further increased in the K-WRS mill, where a tapered crown is given to the work rolls.

Incidentally, the range of crown control may be limited in these new mills for profile control due to tolerances on flatness. It is important, therefore, to adopt a mill type and a mill arrangement that allow ample allowance for the control of profile and flatness.

The 6-high HC mill with a work-roll shifting mechanism and the 4-high work-roll shifting mill are functionally superior to other mills when their overall profile control covering the strip crown, edge drop, and high spot and their suitability to the schedule-free rolling are taken into consideration.

At Kawasaki Steel, the following profile-controlling mills have been adopted in consideration of the finishing mill specifications shown in **Table 1**.

(1) No. 1 hot strip mill at Chiba Works

This hot strip mill rolls narrow strip. The trapezoidal-crown work roll of the company's own development has been used and it has been ascertained that this work roll is effective in reducing the strip crown and edge drop. Furthermore, there has been an accumulation of technical known-how from the actual operation. The tapered-crown work-roll shifting mill (K-WRS mill) with functions expanded to cope with strip width changes was adopted in the third to fifth stands of the finisher. Flatness control is conducted on the final stand. **Table 2** gives the specifications of the K-WRS mill adopted in the No. 1 hot strip mill at Chiba Works.

(2) Hot strip mill at Mizushima Works

This hot strip mill produces wide strip of various steel grades and dimensions. On account of this, the 6-high HC mill was adopted in the fifth to seventh stands of the finisher. The strip profile and flatness are also controlled. **Table 3** gives the specifications of the HC mill adopted in the Mizushima hot strip mill.

(3) No. 2 hot strip mill at Chiba Works

This hot strip mill also produces wide strip of various steel grades and dimensions. It would be difficult to remodel this mill into a 6-high HC mill. Furthermore, as a result of a technical examination, it was ascertained that K-WRS mill has almost the same crown control capability as in the 6-high HC mill by increasing the amount of shift stroke and adopting a heavy-duty bender. Therefore, the company plans to adopt the K-WRS mill in the fifth to seventh stands of the finisher of this hot strip mill.

## 3 Application of K-WRS Mill to Chiba No. 1 Hot Strip Mill

### 3.1 Principle of Control of K-WRS Mill

K-WRS mill is an improvement over a rolling method using trapezoidal-crown work rolls originally developed to reduce the strip crown and edge drop in the No. 1 hot strip mill at Chiba Works. In the K-WRS mill, work rolls with a crown tapered on one side are axially shifted to adapt to changes in the strip width. At the same time, high spot is controlled by making the work-roll wear uniform. This mill was designed in such a way as to permit schedule-free rolling.

The strip-profile control function of the K-WRS mill is based on

(1) the geometrical effect of the tapered crown of the work rolls,

**Table 2** Specifications of K-WRS mill in the No. 1 hot strip mill of Chiba Works

| Roll size | | Max. work-roll shift | | Max. work-roll bending force |
|---|---|---|---|---|
| WR | BUR | Stroke | Force | |
| 597~700 $\phi\times$1 700 $L$ (mm) | 1 118~1 255 $\phi\times$1 372 $L$ (mm) | 275 mm | 100 tf | 53 tf/chock (increase) |

**Table 3** Specifications of HC mill in hot strip mill of Mizushima Works

| | | |
|---|---|---|
| Roll dia. | WR | 685~ 585 $\phi\times$2 380 $L$ |
| | IMR | 675~ 540 $\phi\times$2 300 $L$ |
| | BUR | 1 340~1 190 $\phi\times$2 300 $L$ |
| IMR shift stroke | | 0~750 mm |
| WR shift stroke | | ±150 mm |
| Hydraulic screw down | | Cylinder: 930 $\phi\times$20 st<br>Max. rolling force: 2 600 tf/std<br>Max. screw down speed: 4.0 mm/s<br>Frequency response: 20 Hz (phase delay: 90°) |
| Max. work-roll bending force | Increase | 75 tf/chock |
| | Decrease | 75 tf/chock (for only upper roll) |
| Mill motor | | DC 2 800 kW×3/std |

(2) making roll wear and thermal crown uniform by shifting the work rolls.

As schematically shown in **Fig. 4**, there are two work-roll shifting methods:

(1) the taper adjusting method in which the effective taper length (*EL*) is kept constant to mainly control the strip crown and edge drop.

(2) the cyclic shifting method, the principal purpose of which is to ensure that the distribution of roll wear is uniform.

The use of these methods depends on the strip profile requirements. **Figure 5** shows a comparison of the crown changes within one rolling campaign between these two work-roll shifting methods and the conventional rolling method by a 4-high mill. Strip crown obtained by these two methods are smaller than those obtained by the conventional method and it can be seen that the strip crown is controlled to within certain limits.

### 3.2 Profile Control Capability of K-WRS Mill

An experiment was conducted on an actual single stand to investigate the relationship between the effective taper length (*EL*) and the strip crown. The results of this experiment are shown in **Fig. 6**. It is expected that the strip profile can be controlled over a wide range by optimizing the effective taper length and applying this control method to multiple stands.

As shown in **Fig. 7**, the wear contour of the tapered part of the work roll maintains its initial contour even if rolling is conducted with a constant effective taper length. It is therefore apparent that the profile control

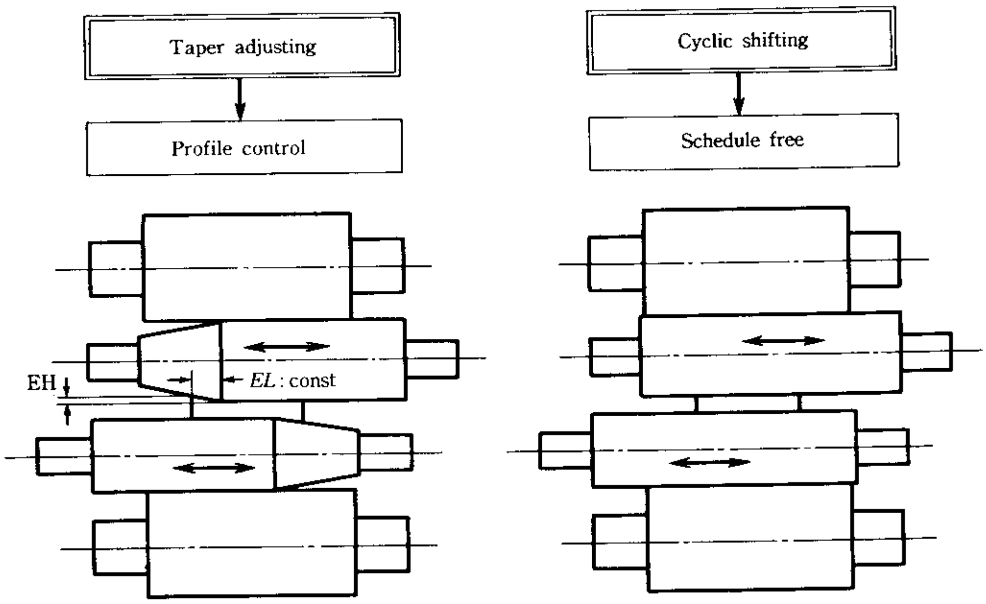



**Fig. 4** Schematic diagrams of work-roll shifting methods in K-WRS mill

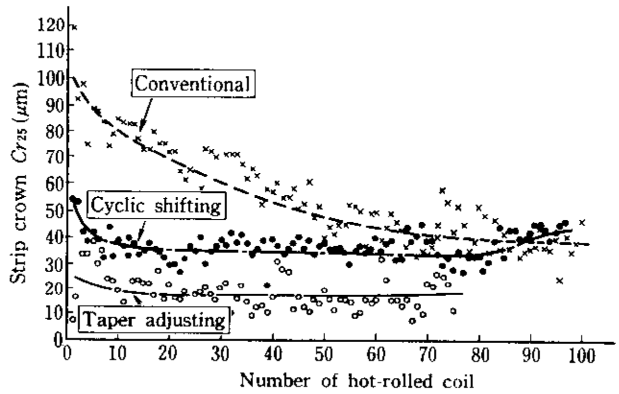



**Fig. 5** Strip crowns obtained by taper adjusting method and cyclic shifting method in K-WRS mill and conventional rolling method

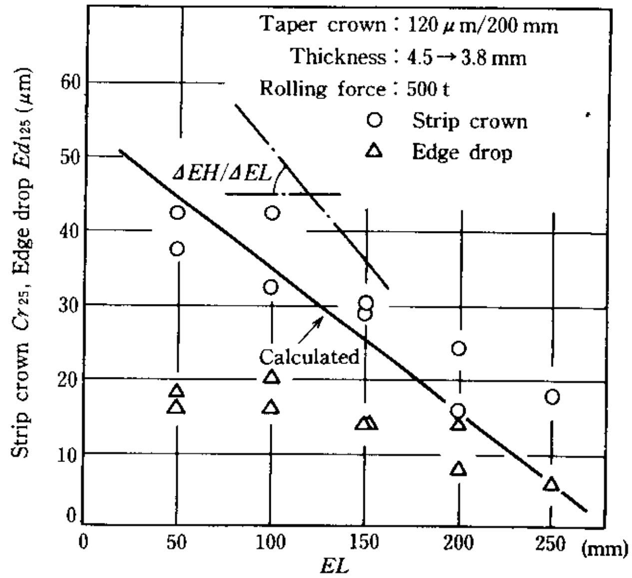



**Fig. 6** Effect of *EL* on crown and edge drop in single stand of K-WRS mill

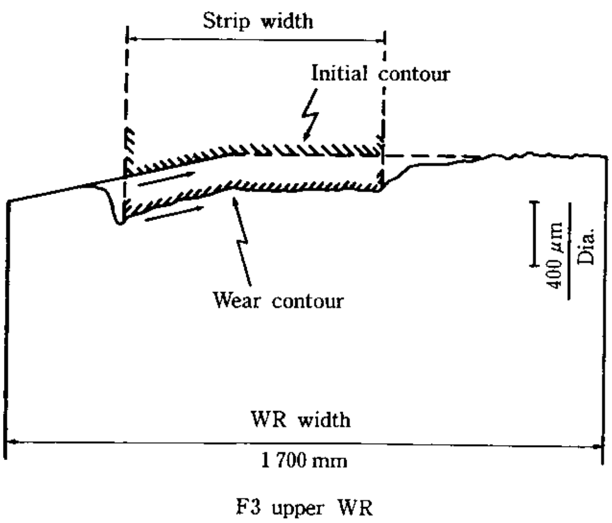



**Fig. 7** Typical example of wear contour of work-roll after hot rolling

capability of the mill does not deteriorate even if the number of strip rolled increases.

**Figure 8** shows schematic diagrams of the conventional 4-high mill, the 4-high mill with trapezoidal-crown work rolls, and the K-WRS mill together with typical profiles of hot strips rolled by these mills. It can be seen that a good profile control can be obtained in a narrow strip mill by adopting the K-WRS mill.

### 3.3 Operation Results

Results of strip profile control by the K-WRS mills in the No. 1 hot strip mill at Chiba Works are described in the following for each type of product.

#### 3.3.1 Tinplate and cold-rolled sheet

The cyclic shifting method is adopted when strip sheets of the same width are rolled frequently. The taper adjusting method is adopted when small crowns are required as with tinplates for drawing and ironing. **Figure** 9(a) shows a typical profile of a hot-rolled strip for tinplate for drawing and ironing. This hot-rolled strip displays small crown change in one rolling campaign and is free of high spots.

In tinplates, high spots in the hot coil cause surface defects due to coiling in the cold rolling process and sticking during annealing. This poses a severe problem. However, it can be solved by introducing the K-WRS mill. It is also possible to mass-produce tinplates with small crown, such as materials for drawing and ironing and materials ordered with a TMW (theoretical minimum weight).

#### 3.3.2 High-carbon steel and low-alloy steel sheets

With these steel grades, so far, the strip crown and edge drop have been reduced by using trapezoidal-crown rolls. As is apparent from the profile example shown in Fig. 9(b), changes in the strip width can also be met by the taper adjusting method on the K-WRS mill and the crown can be controlled to 40 μm or less in one rolling campaign.

#### 3.3.3 Stainless steel sheets

In stainless steel sheets, the yield stress during hot rolling is large and the rolling load is high. Therefore, the strip crown and edge drop in stainless steel sheets are larger than those in ordinary steel sheets and reduction of the strip crown and edge drop has been a great subject to overcome. As shown in Fig. 9(c), the strip crown can be controlled to 40 μm or less to meet almost all specifications by introducing the K-WRS mill and adopting the taper adjusting method. It was feared that in the hot rolling of stainless steel sheets the surface roughening of work rolls due to the shifting of the rolls might impair the surface properties of the product. Under the taper adjusting method, however, this has not been

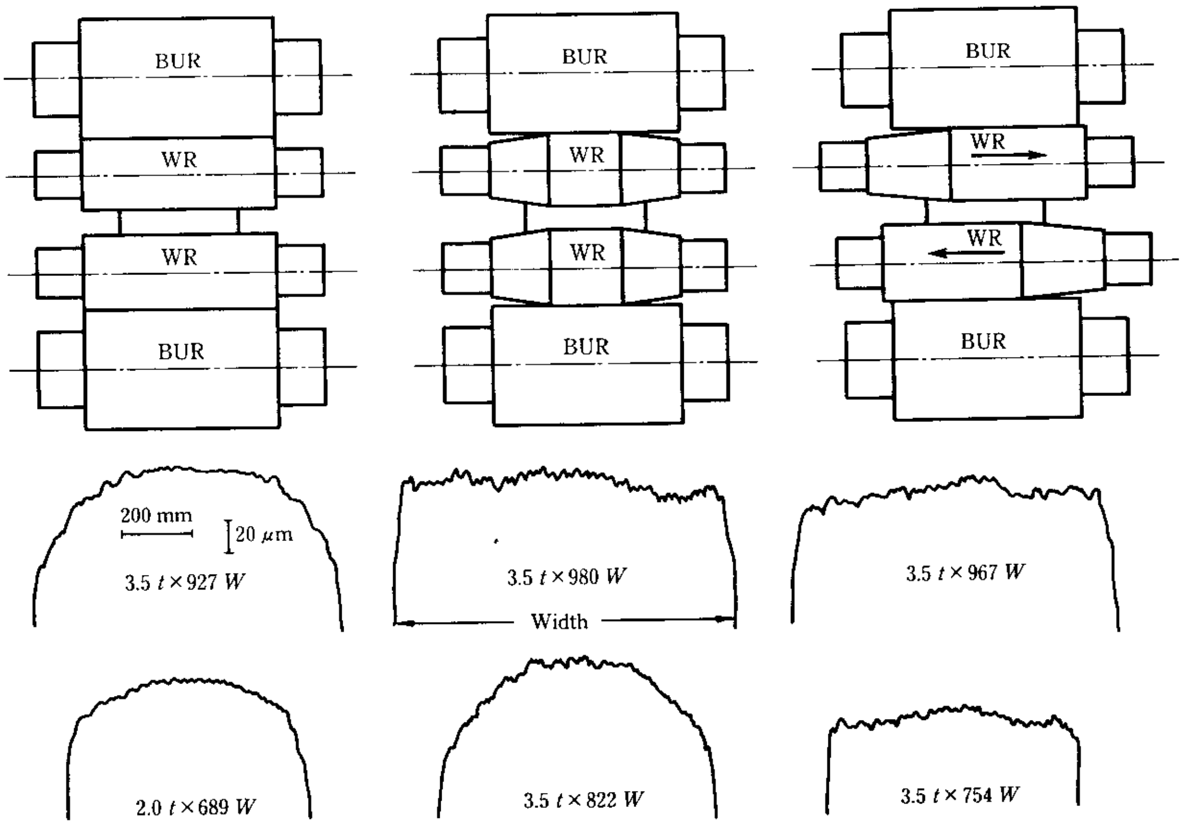
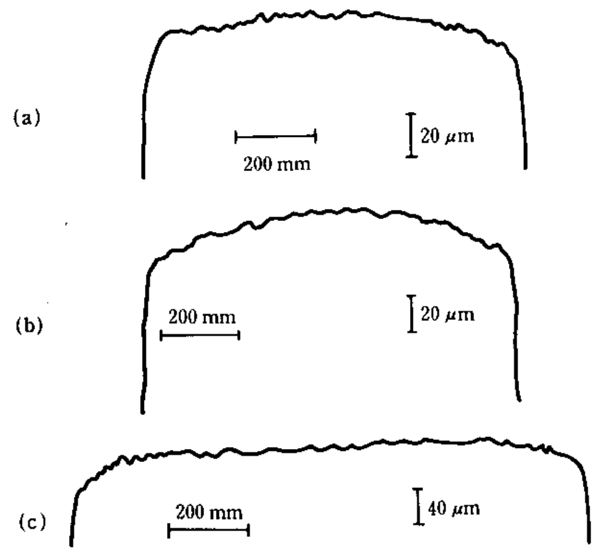



**Fig. 8** Improvement of strip profile by K-WRS mill




a: Tin plate for drawing & ironing use (2.0t× 960 W)
b: High carbon steel (1.8t× 968 W)
c: Stainless steel (3.0t× 1265 W)

**Fig. 9** Typical example of hot-rolled strip profile by taper adjusting method in K-WRS mill

a problem.

#### 3.3.4 Other special steel sheets

In electrical steel sheets which are stacked after cutting, some strip sheets must meet demanding crown and edge drop requirements as well as severe edge buildup requirements. For the former strip, the strip crown can be controlled to 0 to 30 μm by adopting the taper adjusting method. In the latter case, optimum profiles can be obtained by cotrolling edge buildup at 60 μm or less using the cyclic shifting method.

As mentioned above, profiles have been substantially improved for almost all steel grades and sizes at Chiba No. 1 hot strip mill by adopting the K-WRS mill and by developing the rolling technology for the mill.

## 4 Application of HC Mill to Mizushima Hot Strip Mill

### 4.1 Principle of Profile Control in HC Mill

**Figure 10** gives a comparison of the principle of profile control between the HC mill and the conventional 4-

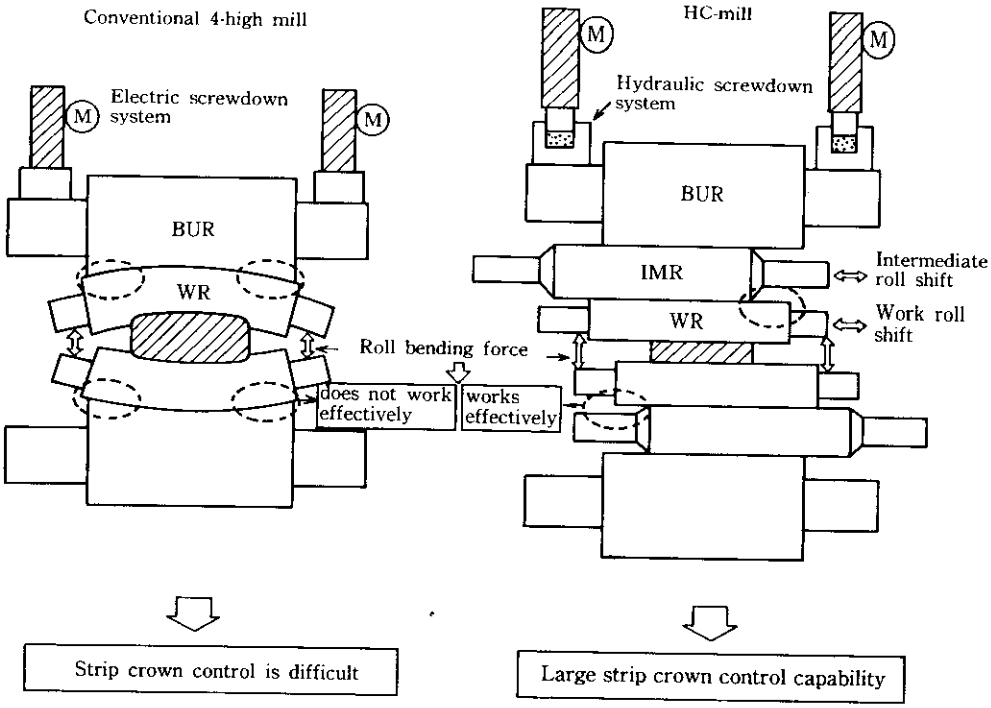



**Fig. 10** Comparison of crown control mechanism between conventional 4-high mill and HC mill

high mill. In the 4-high mill, deflection occurs in the work rolls and backup rolls as shown in the figure due to the roll-separating force from the material being rolled, and the strip receives a convex profile. Up to now, a work-roll bender which bends the rolls in the opposite direction to the roll deflection due to the roll-separating force has been used to reduce the amount of deflection. However, the effect of the work-roll bender is slight because the work rolls and backup rolls are in contact with each other along the full length of the roll barrel. Therefore, the work-roll bender has little effect on the strip crown.

In the HC mill, intermediate rolls shiftable in the direction of roll barrel are installed between the top and bottom work rolls and backup rolls. Noncontact areas between the work rolls and the intermediate rolls are formed at the barrel ends of the work rolls by shifting the intermediate rolls to opposing directions according to the strip width. As a result, the amount of work-roll deflection due to the roll-separating force decreases while the effect of the work-roll bender increases substantially. The amount of work-roll deflection can be freely controlled by shifting the intermediate rolls and the force of the work-roll bender. The strip crown can be controlled over a wide range.

Furthermore, the addition of a shifting mechanism to the work rolls permits the local wear and thermal crown of the work rolls to be distributed in the direction of the roll barrel, thus preventing high spots. The HC mill has a great crown control capability owing to the intermediate-roll shifting and the effect of the work-roll bender and functions to prevent high spots by work-roll shifting. This mill can thus perform a comprehensive profile control. Moreover, this mill can greatly assist the establishment of schedule-free rolling techniques, such as continuous rolling of strip of the same width and rolling from wide to narrow strip by changing width.

### 4.2 Examination of Specifications for Application to Actual Mills

#### 4.2.1 Crown control capability and number of stands

**Table 4** shows the strip crown control capability of the HC mill as calculated from five combinations of typical product sizes and steel grades at the Mizushima hot strip mill. The crown control capability of a single stand represents a case where the maximum amount of control capability is displayed on the final stand (F7) of the finisher regardless of changes in flatness. Although it is apparent that adequate control capability can be obtained in all cases, it is necessary to apply the HC mill to multiple stands in order to control the strip crown so as to maintain good flatness.

According to a study[15] on the number of finisher stands to which the HC mill is applied and the strip crown control capability in which the strip flatness is taken into consideration, the strip crown control capability almost attains its maximum when the HC mill is applied to three or four downstream stands. The larger the number of stands to which the HC mill is applied,

**Table 4** Strip crown control capability of HC mill ($\mu$m)

| Case | Products | Amount of crown control[a)] | | |
|---|---|---|---|---|
| | | F7 single stand | F5, 6, 7, HC mill[b)] | F4, 5, 6, 7 HC mill[b)] |
| 1 | Mild steel 3.2 $t$ × 2 100 $W$ | 194 | 102 | 136 |
| 2 | Mild steel 3.2 $t$ × 1 200 $W$ | 184 | 115 | 131 |
| 3 | High-strength steel 2.3 $t$ × 1 200 $W$ | 140 | 82 | 104 |
| 4 | High-strength steel 2.3 $t$ × 1 600 $W$ | 175 | 79 | 94 |
| 5 | Mild steel 6.0 $t$ × 950 $W$ | 128 | 94 | 106 |

a) Calculation condition for crown control:
IMR shift stroke: $HC\delta$ = Max ~ −50 mm
Roll bender : 0~65 tf/chock
WR diameter : 650 mm
IMR diameter : 650 mm
BUR diameter : 1 320 mm

b) The flatness was assumed as follows:
Inter-stand steepness = ±2%
Final-stand steepness = 0%

the higher this capability will become. Table 4 gives a comparison of the strip crown control capability between a case where the HC mill is applied to the three downstream finisher stands and a case where it is applied to the downstream four stands at the Mizushima hot strip mill. An interstand steepness of 2% and a final-stand steepness of 0% were adopted as flatness change tolerances. In all cases, the strip crown control capability was higher with four stands than with three stands. However, the difference was small. When the HC mill is applied to three stands, the strip crown can be controlled by 80 $\mu$m or more in almost all cases. Therefore, changes in the strip crown in the same rolling cycle resulting from the thermal crown and wear of rolls can be thoroughly compensated for and the optimum strip crowns for each application, as shown in Fig. 2, can be obtained at any position in the rolling cycle. Other factors such as investment and construction term were considered together and it was decided to apply the HC mill to the three stands F5, F6 and F7 of the finisher.

Incidentally, the maximum shift stroke for the intermediate rolls was set at 750 mm so that rolling with $HC\delta$ (position of the intermediate roll end relative to the strip end) of 0 mm could be performed with strip of up to 800 mm in width.

#### 4.2.2 Shift stroke of work rolls

An integrated system is planned in order to optimize the material distribution between the continuous caster and the hot strip mill based on hot charge rolling. In this system, it will be necessary not only to relax limitations on the tonnage of continuously rolled strip of the same width due to high spots at strip edges, but to apply schedule-free rolling techniques in the broader sense. The latter will include rolling techniques involving width changes from wide to narrow strip. Rolling with a width change of at least 300 mm is required. Therefore, ±150 mm was selected as the work-roll shift stroke to disperse roll wear over a length of 300 mm in the direction of the roll barrel.

#### 4.2.3 Roll diameter distribution

The overall performance of the HC mill depends greatly on roll diameters. Because the six rolls had to be installed in the existing housing, optimum roll diameter distribution among the backup rolls, intermediate rolls, and work rolls was determined after a comprehensive examination,[16)] taking account of the machine strength, roll and power consumptions, dimension control, and stability of straight strip travel.

Work rolls: In terms of crown control capability and rolling energy, the smaller the roll diameter the better. However, the roll diameter must be at least 585 mm, in consideration of the strength of the work-roll neck and spindle. Furthermore, it became clear from an analysis of the stability of straight strip travel that this stability decreases abruptly when the roll diameter is less than 600 mm. Therefore, roll diameters of between 585 and 685 mm were selected.

Intermediate rolls: The roll diameter must be at least 515 mm in view of the limitation of Hertz stress between the work rolls and intermediate rolls. In terms of surface pressure, the larger the roll diameter the better. The intermediate-roll diameter is greatly restricted by the sizes of the work rolls, backup rolls, and housing. However, diameters of 540 to 675 mm were selected to obtain the largest possible diameter.

Backup rolls: In terms of machine strength, the larger the roll diameter the better. The roll diameter must be at least 1 180 mm from the standpoint of the fatigue strength of the bearing necks. On the other hand, small rolls diameters are advantageous in terms of operating cost because of their small unit consumption. Consequently, roll diameters of from 1 190 to 1 340 mm were selected to obtain the smallest possible diameter within the restrictions of machine strength.

#### 4.2.4 Hydraulic screwdown system

Requirements for gage accuracy have also become increasingly severe. With electric screwdown systems, there is a limit to the control of gage variations in the rolling direction of the strip, and it has been impossible to guarantee rigid accuracy requirements of ±3% in normal operation. Moreover, a deterioration in the stability of straight strip travel was feared because the strip crown decreases with the adoption of the HC mill and the mill's stiffness to obtain a symmetric roll gap geometry between the drive and the work side decreases when the intermediate rolls are shifted. It was therefore necessary to control strip meandering. Consequently, it was decided to install hydraulic screwdown systems in the stands from F5 to F7. The main specifications of the hydraulic screwdown system, such as response, screwdown speed, and permissible load, were determined in full consideration of gage control performance, meandering control performance, and suitability to heavy reductions on the downstream stands.[17)]

#### 4.2.5 Other specifications

Renewal and expansion of both hardware and software were carried out: the mill motor power of stand F7 was increased from 5 600 to 8 400 kW to adapt to the rolling with heavy reductions on the downstream stands; process computers were adopted as were a DDC system suitable for various types of control; and full automation was adopted in the changing and transfer of rolls which had become complicated because of the adoption of the HC mill.

### 4.3 Operation Results

After one year of remodeling work, the HC mill at the Mizushima hot strip mill was brought into operation in September 1983. Various experiments have since been carried out to check the performance of the mills and it has been found that the basic performance of the mills is as originally planned. Studies are being continuously made to improve the performance of the mills. Operation results obtained to date are described in the following.

#### 4.3.1 Strip crown control capability

(1) Effect of crown control in a single stand
**Figure 11** gives a comparison between calculated and measured strip crowns when the intermediate-roll shift stroke and roll bender force are changed only on stand F7. It is apparent from the figure that the present HC mill possesses the planned strip crown control capability.

(2) Effect of crown control in three stands
**Figure 12** shows changes in the strip crown when the intermediate-roll shift stroke and roll bending force are changed simultaneously on stands F5 to F7. It can be seen that the strip profile can be changed over a wide range from the conventional convex profile to an almost flat profile. It is apparent from the gradients of this figure that the effect of intermediate-roll shift is an about 0.1 $\mu$m change in crown for each 1 mm change in the shift stroke. The larger the intermediate-roll shift stroke, the more noticeable the effect of the roll bending. In the case of this strip size, a strip crown control capability of about 30 $\mu$m was attained through the combined application of intermediate-roll shift and the increase bending. It has been further confirmed that the wider the strip width, the higher the strip crown control capability of the HC mill.

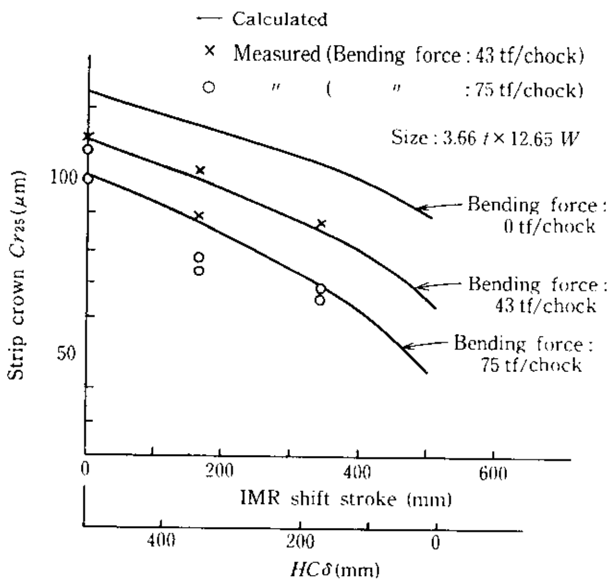



**Fig. 11** Comparison between calculated and measured strip crown at F7 stand after hot rolling

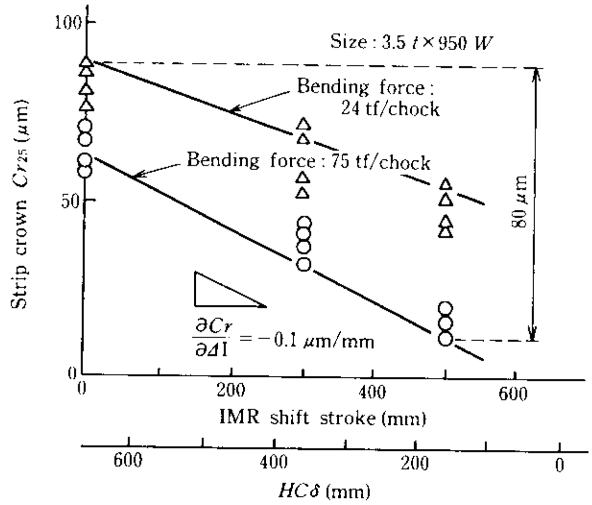



**Fig. 12** Effect of IMR shift stroke in F5–F7 stands on hot-rolled strip crown

(3) Changes in crown in one cycle
**Figure 13** shows changes in the crown and profile in one rolling cycle when crown control was carried out on the HC mill. In the conventional 4-high mill, the strip crown was 120 to 130 $\mu$m just after the start of a rolling cycle and 30 to 40 $\mu$m just before the end of the cycle. Variations in the strip crown of from 90 to

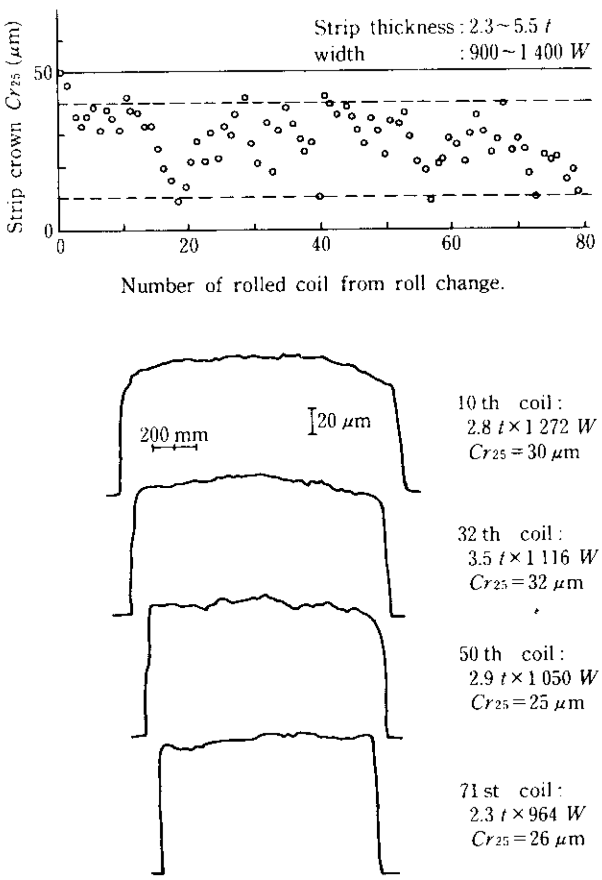
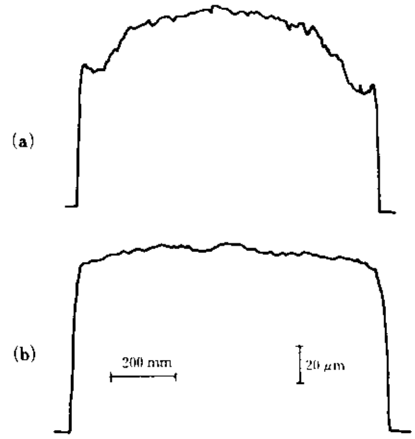



**Fig. 13** Change of strip crowns and profiles through rolling cycle




a: 4-high mill without WR shift
(after 30 same width coils, 2.1t×950 W)
b: HC mill with WR shift
(after 50 same width coils, 2.1t×950 W)

**Fig. 14** Comparison of profile after a lot of same width coils rolling between conventional 4-high mill and HC mill

100 μm were thus unavoidable in one rolling campaign. In the HC mill, however, crown variations can be controlled to between 10 and 40 μm. As a result, it has become possible to easily make products which have an almost rectangular profile with scarcely any crown at any time desired in the rolling campaign.

### 4.3.2 Effectiveness in high-spot prevention

**Figure 14**(b) shows an example of the effect of work-roll shift on the prevention of high spots. There is no sign of high spots at edges observed in the strip profile even after continuous rolling of 50 coils 2.1 mm in thickness and 950 mm in width. This is a noticeable improvement, because in the conventional 4-high mill high spots were formed at strip edges as shown in Fig. 14(a) after the continuous rolling of 30 coils of the same size. **Figure 15** shows a comparison of the work-roll wear profile between the 4-high mill (stand F4) and the HC mill (stand F7). In stand F4 without work-roll shift, the wear profile is of a box type in which local wear occurred in the areas of the roll corresponding to the strip edges. In stand F4 on which work-roll shift was conducted, however, the roll shows a clean tapered wear profile without local wear. Thus, the effect of work-roll shift obtained was as expected.

### 4.3.3 Effect of hydraulic screwdown system

The gage accuracy in the longitudinal direction of the strip was noticeably improved due to the adoption of a hydraulic AGC (automatic gage control) system with a high response speed. **Figure 16** shows a comparison of gage accuracy between the conventional electric AGC system and the hydraulic AGC system adopted in the HC mill. The effect of hydraulic AGC is clearly observed and cyclic gage variations due to skid marks

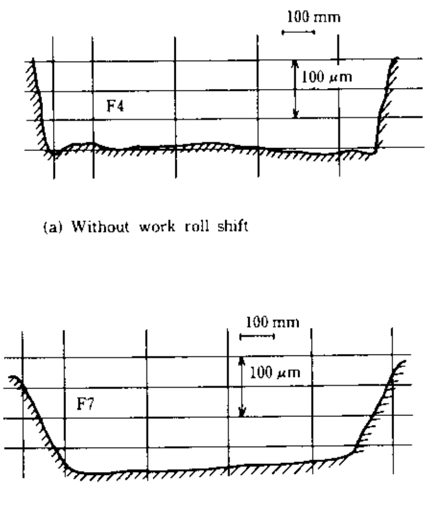



**Fig. 15** Comparison of work roll wear contour between 4-high mill (F4) and HC mill (F7)

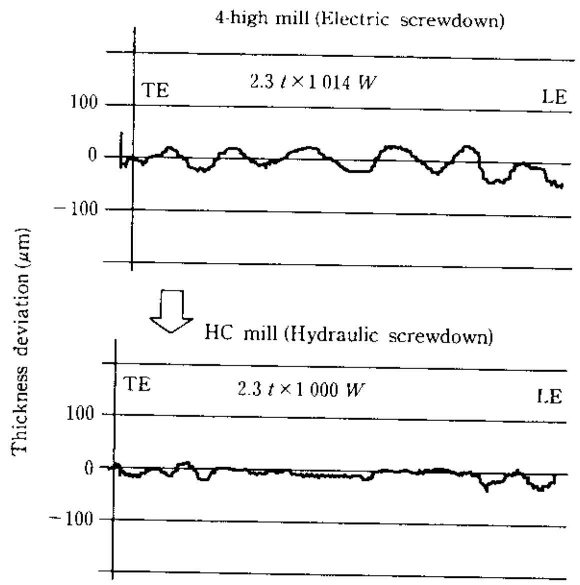



**Fig. 16** Comparison of gage accuracy between 4-high mill with electric screwdown and HC mill with hydraulic screwdown

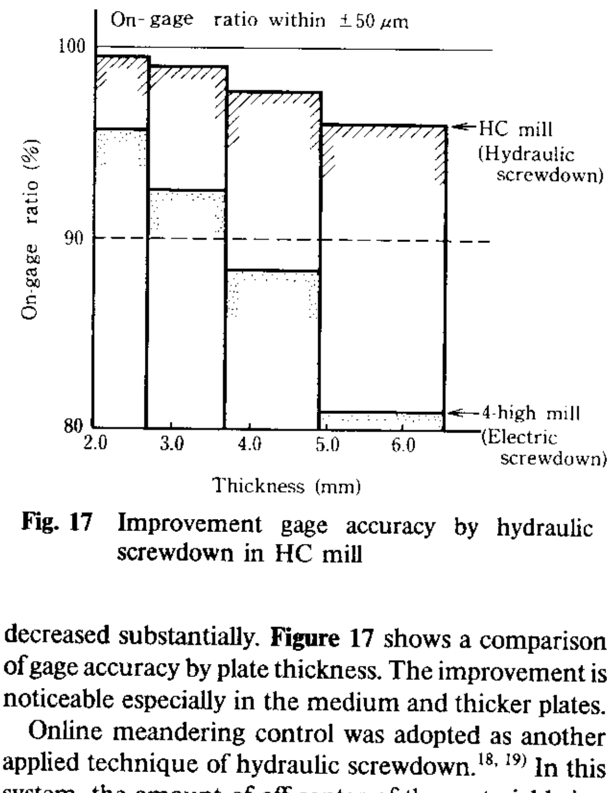



**Fig. 17** Improvement gage accuracy by hydraulic screwdown in HC mill

decreased substantially. **Figure 17** shows a comparison of gage accuracy by plate thickness. The improvement is noticeable especially in the medium and thicker plates.

Online meandering control was adopted as another applied technique of hydraulic screwdown.[18, 19] In this system, the amount of off-center of the material being rolled is translated into difference in the rolling load between the right and the left load cell, and hydraulic leveling reductions is automatically controlled according to the rolling load difference. It has been confirmed that this online meandering control is very effective in preventing the pinching of the trailing end of a thin strip.

As mentioned above, it was ascertained that the Mizushima hot strip mill performs almost as planned as regards strip profile control capability, effectiveness in high-spot prevention, and effective gage control by hydraulic gage control. Thus, a production system capable of thoroughly meeting users' quality requirements was established.

## 5 Flatness Control

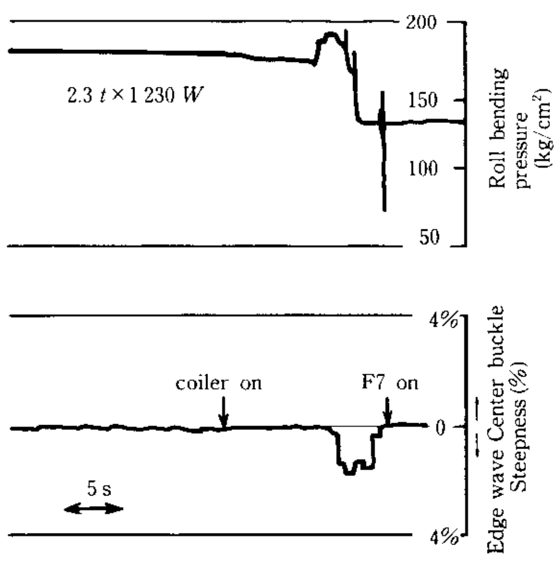
In addition to strip profile control, production of hot-rolled strip with good flatness is one of the most important problems of hot rolling. To obtain good flatness in products, it is important to establish the following techniques:

(1) Flatness control techniques in the finisher
(2) Flatness control techniques in the cooling process on the runout table.

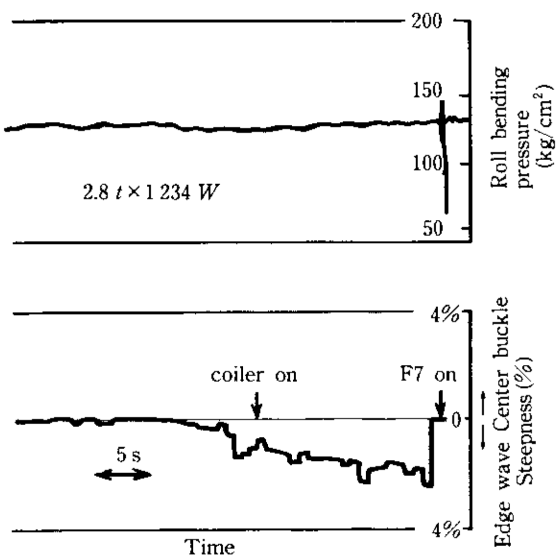
At Mizushima's hot strip mill, excellent flatness control techniques have been developed and put into practical use with excellent results. An outline of these techniques is described in the following.

(1) Flatness control in finisher

A flatness meter of the water column type[20] capable of highly accurate quantitative measurement of flatness on the delivery side of the finisher was successfully developed. In this flatness meter, nozzles are arranged in from 3 to 5 places (3 places at the Mizushima hot strip mill) in the width direction in such a way that water streams are injected against the bottom surface of the strip. The strip steepness is continuously measured by converting the vertical motions of the strip on the runout table into changes in the electric resistance of water columns from the nozzles. This device has excellent measurement accuracy ($2\sigma = \pm 0.22\%$) and maintainability under the adverse conditions caused by water drops and steam. The flatness control in the 4-high mill has been conducted using a closed loop flatness control system[1] developed by combining this shape meter, the roll bender, and a system for draft scheduling in the finisher. Examples of feedback flatness control in the 4-high mill are given in **Fig. 18**. It can be seen that edge waves at the strip end are automatically altered to a flat shape. Efforts are being made to develop a crown and flatness setup system for the HC mill in order to achieve the target values of interstand flatness and the flatness and crown on the delivery side of the finisher. Furthermore, in the rolling direction, a closed loop control is in operation for dynamically controlling the roll bender on the final stand by feeding back signals from the flatness meter and a feedforward control for preventing flatness changes due to rolling load changes. Incidentally, this flatness control system permits optimum automatic gain setting suited to intermediate-




(a) With flatness control




(b) Without flatness control

**Fig. 18** Effect of feedback flatness control on strip flatness in 4-high mill

roll shifting positions because the effect of the roll bender depends greatly on the shifting position.

(2) Flatness control in cooling process

Even if the flatness on the delivery side of the finisher is controlled sufficiently, edge waves often occur after cooling due to nonuniform temperatures in the width direction of the strip in the cooling process after finish rolling. To control such flatness changes in the cooling process, a device for controlling the coiling temperature in the width direction, as shown in **Fig. 19**, was installed in the upper cooling device for hot run coolant.

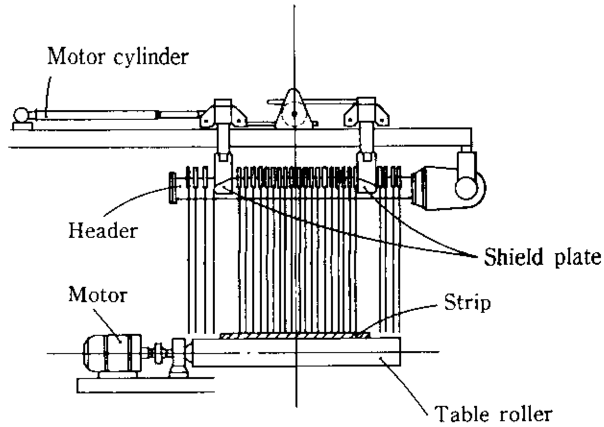



**Fig. 19** Schematic diagram of cooling device with shield plate on runout table

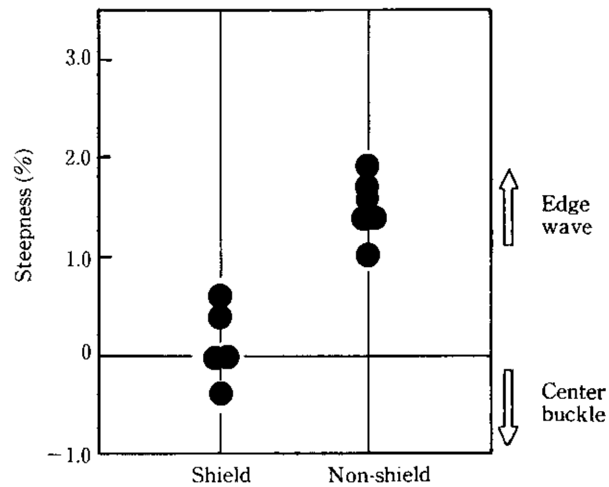



**Fig. 20** Comparison of flatness after cooling between shield and non-shield

It has been confirmed that this edge wave resulting from nonuniform temperatures in the width direction (temperature drop at strip edges) is formed by the strip edge buckling that occurs when compressive stresses generated in the overcooled parts of edges in the cooling process exceed critical buckling stress.[2,21] This device for controlling the coiling temperature in the width direction shields some of the cooling water sprayed onto strip edges, in order to prevent this overcooling of the edges by hot run coolant. **Figure 20** shows the effect of this coiling temperature control device on the steepness after cooling. It is apparent that the flatness after cooling is markedly improved by using this device.

As mentioned above, the flatness control in the finisher has been virtually achieved because a flatness meter, which has so far been the greatest bottleneck in flatness control, was put into use, and a strong actuator called HC mill was installed. Furthermore, it has flatness control, was put into use and a strong actuator called HC mill was installed. Furthermore, it has become possible to prevent flatness changes in the cooling process by controlling the coiling temperature in the width direction. Thus, the techniques for ensuring good flatness required by users have been established.

## 6 Conclusions

Kawasaki Steel has installed K-WRS mills at the No. 1 hot strip mill of Chiba Works and HC mills at the hot strip mill of Mizushima Works and these are operating smoothly. Both of the new mills effectively control strip-profile and can achieve strip crowns of 40 $\mu$m or less for most products. The results which were expected have been obtained in these mills.

Furthermore, the company has developed flatness control techniques in the cooling process on the runout table by controlling the coiling temperature in the width direction in addition to flatness control at the finisher by a combination of flatness meter and work-roll bender. These techniques were applied to the hot strip mill at Mizushima ensuring good flatness in finished products.

Consequently, the company has established techniques for stably producing hot-rolled strip which is excellent in gage accuracy, profile, and flatness and which can meet severe quality requirements.

The company intends to establish the schedule-free rolling techniques necessary for linking the continuous casting process to the hot rolling process by further developing the above-mentioned techniques.

Incidentally, the company also intends to introduce the K-WRS mill at the No. 2 hot strip mill of Chiba Works.

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