KAWASAKI STEEL TECHNICAL REPORT
No.1 (September 1980)

Flatness and Profile Control in Hot and Cold Rolling of Steel Strip

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The body can be viewed from the next page.

Flatness and Profile Control in Hot and Cold Rolling of Steel Strip*

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One of the most important and principal qualities required of hot- and cold-rolled steel strip is good flatness and profile. Practical and theoretical studies into control systems on flatness and profile of the strip and their applications in full scale four-high mills have led to the following conclusions and to the establishment of control method.
(1) A hot-rolled strip having such uniformed internal property as that from continuously cast steel is desirable to get a cold rolled strip with good flatness. And a hot-rolled strip having convex crown of 30 ~ 60 μ without surface abnormalities leading to ridge (so-called high spot) is suitable to get a good flatness and profile of cold-rolled strip. Furthermore, some cold rolling conditions are discussed in order to optimize work-roll camber, rolling schedule and roll bending force in cold rolling.
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1 Preface

Users' specifications for dimensions and flatness of steel strip have been getting increasingly severe year after year. Along with a growing trend of TMW (Theoretical Minimum Weighing) type contracts, requirement for thickness accuracy is getting severer not only in the rolling direction but also in the cross direction, namely, the profile. This is also true of the flatness, with requirement getting more rigid for the thinner products, thus making the control more difficult.

Various types of profile and shape sensors have been developed for installation in operating mills, with success in actual operation although there remain some problems of edge accuracy detection, temperature and quality corrections, etc.

On the other hand, efforts for improving flatness have been made in the area of equipment and methods, including the development of a new six-high rolling mill with advanced control functions. In the four-high mills, however, flatness control is still dependent on the use of optimal roll camber, roll bender, roll coolant, etc.

A rolling material always involves uneven distribution of mechanical properties in both rolling and cross directions because of variations in chemical composition and rolling temperatures. There is also growth of roll thermal crown and wear during rolling. In the case of four-high rolling mill, the correcting functions mentioned above are not sufficient for correcting factors affecting flatness.

This paper summarizes the results of operation experiments for flatness and profile control of cold- and hot-rolled strip on actual four-high rolling mills, theoretical investigation results and technologies developed on the basis of these practical and theoretical studies.

2 Flatness and Profile Control in Cold Rolling Process

2.1 Flatness Control

The influences of various factors such as hot-rolled strip properties and cold-rolling conditions are described here with emphasis on cold-rolled strip for plating, which requires severe flatness quality and a difficult control.

The flatness index, crown and edge drop are defined as shown in **Fig. 1.** The index is the average value for $L = 1\ 000$ mm. C_H and C_h mean the crown before and

* Originally published in Kawasaki Steel Technical Report, **11** (1979) 1, pp.78–88 (in Japanese)
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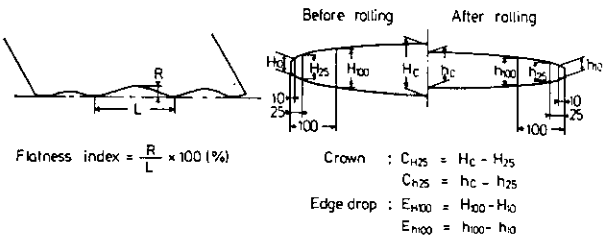


Fig. 1 Definition of flatness and cross profile of rolled strip

after rolling, respectively. C_{H25}, for example, means the difference $(H_C–H_{25})$ im thickness between at the center, H_C, and a point 25 mm from the edge, H_{25}, and C_{H50} means $(H_C–H_{50})$. Edge drop E_{H100} means $(H_{100}–H_{10})$ which is the difference in thickness between 100 mm from the edge and 10 mm from the edge. These values are obtained by averaging the right and left side values.

2.1.1 Influence of hot-rolled strip properties

First, the influences of the hot-rolled strip internal properties are described by using ordinary rimmed steel and continuously cast steel[1].

Fig. 2 shows the hardness (H_RB) distribution in the cross direction of a hot-rolled rimmed steel (C: 0.08 wt%) steel at finisher delivery temperatures of 780 °C and 850 °C. With a delivery temperature of 780 °C, the portion corresponding to the center layer zone is rolled at above Ar_3 transformation point to generate micro structure, while the portion corresponding to the rim zone is rolled at under Ar_3 transformation point to show a rapid decrease of hardness caused by micro-structure generation. With a delivery temperature of 850 °C, portions corresponding to both rim and central zones are rolled at above the Ar_3 transformation point to show a relatively even hardness distribution as a result of uniform micro-structure generation along the whole width. The edge portions show slightly higher hardness values because of deformed structure by quenching during coiling. Thus the uniformity of mechanical properties of a hot-rolled strip depends on the hot rolling temperature. **Fig. 3** shows the relation between the finisher delivery temperature in hot rolling and the flatness index of edge wave after cold rolling in a six-stand mill. The edge wave defect region corresponds to cases where the rim zone is rolled at below the critical point Ar_3 causing a decrease in hardness. When the whole width of the strip is rolled at above the transformation point or at below the transformation point, the mechanical properties are uniform as mentioned above, so the edge wave is improved appreciably. This is also true with capped steel, and the flatness index of edge wave can be reduced to one-half by making internal properties uniform through selection of the appropriate hot rolling temperature.

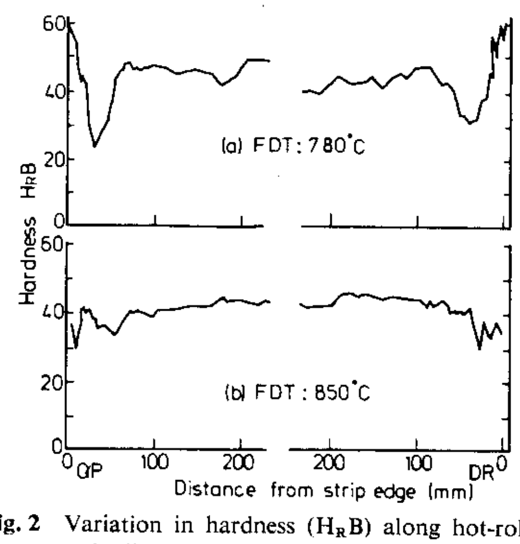


Fig. 2 Variation in hardness (H_RB) along hot-rolled strip distance from edge for rimmed steel

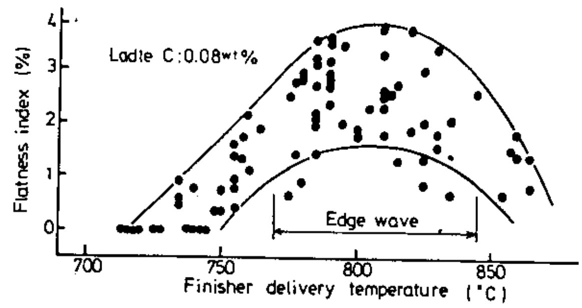


Fig. 3 Relation between the finisher delivery temperature in hot rolling and flatness index of edge wave for cold-rolled rimmed steel strips

Since killed steel, including continuously cast steel, has no rim zone, the internal properties are made uniform and shape after cold rolling is relatively good. **Fig. 4** shows the hardness distribution near the edge

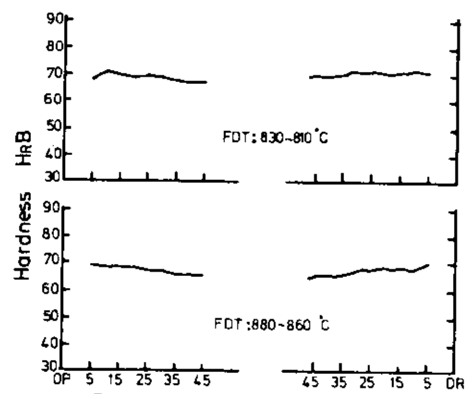


Fig. 4 Variation in hardness (H_RB) along hot-rolled strip distance from edge for continuously cast steel

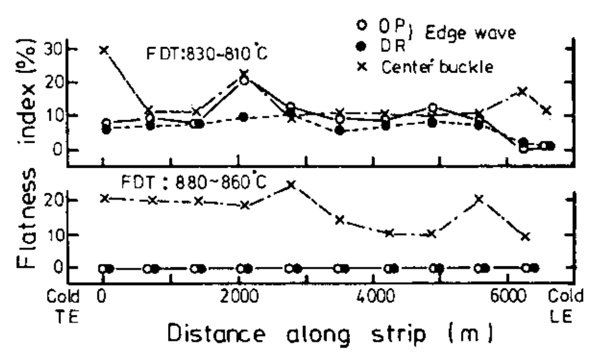


Fig. 5 Flatness index of cold-rolled strip for continuously cast steel

of continuously cast steel with finisher delivery temperatures of approximately 820 °C and 870 °C. The distribution is almost uniform without any appreciable hardness decrease. The hardness as a whole is higher than that of rimmed steel, and is higher for an FDT of approximately 820 °C than for an FDT of approximately 870 °C because of the remaining transformed structure. **Fig. 5** shows the flatness index measured after cold rolling in these cases. As compared with rimmed steel, it is apparent that edge wave is far better. At 870 °C, edge wave can be controlled to almost 0 %. Center buckle gets worse as rolling proceeds, because this is the result of growth of the roll thermal crown.

Next, the influence of the hot-rolled strip profile on the flatness index of a cold-rolled strip is described. Capped steel is used as the rolling material and is hot-rolled at a finisher delivery temperature of 860 °C for four gauges to finish the hot-rolled strip with the crown limited to 0 ~ 120 μ. The strip is then cold-rolled on a four-stand mill under a fixed schedule. **Fig. 6**

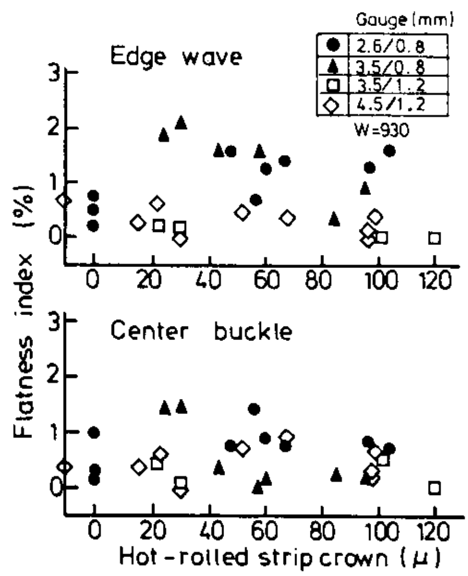


Fig. 6 Relation between crown of hot-rolled strip and flatness index of cold-rolled strip

shows the relation between the crown of a hot-rolled strip and the flatness index of a cold-rolled strip. The crown of a hot-rolled strip does not affect the flatness of a cold-rolled strip. Edge wave defects are more apparent in thinner gauges, while center buckle shows almost no significant difference. Since a large convex crown tends to cause ear of passing strip and a concave crown tends to give rise to edge wave, the crown of hot-rolled strip desirable in actual operation is considered to be 30 ~ 60 μ. Local ridges, called high spots, are undesirable because the corresponding positions are formed as coarse structure which causes local elongation[2] or adhesion after coiling and annealing. Since hot-rolled strip flatness is easily corrected in the preceding stand of a cold rolling mill, its influence on the flatness of a cold-rolled strip is small. However the hot-rolled strip flatness must be kept within the desirable range determined by operating conditions as it becomes a cause of threading troubles such as ear.

2.1.2 Effects of control factors in cold rolling process

As control factors of the flatness of a cold-rolled strip, initial roll camber, entry and exit tensions, rolling load, roll bending force and roll coolant flow rate are considered. As viewed stand by stand, controls in later stands have more influence on final product flatness. The influence of roll camber on flatness is fairly large[3]. The initial camber depends on the rolling material and control objects (for example, edge wave and center buckle). Taking a thin strip for plating for example, use of tapered work roll reduced in size from near the edge greatly reduces edge wave. It also decreases the edge drop.

In a four-high rolling mill, control by the roll bender is generally adopted, but it is almost powerless for

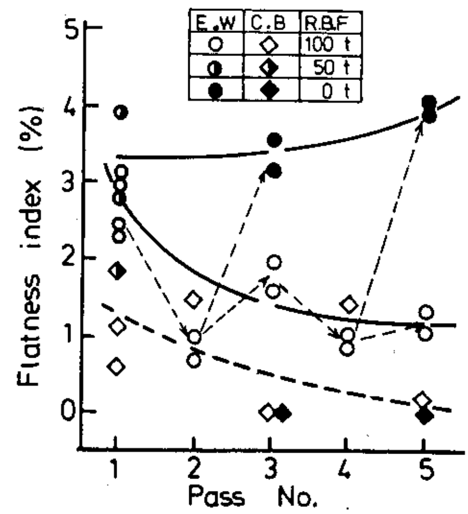


Fig. 7 Effect of roll bending force on flatness of cold-rolled strip at each rolling pass

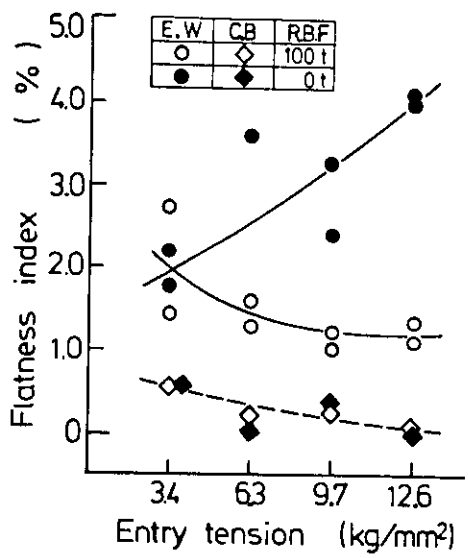


Fig. 8 Effect of entry tension at finish stand of 4-stand tandem mill on flatness of cold-rolled strip

thin strip with non-uniform internal properties and a high rolling load[1]. **Fig. 7** shows the control effect of the roll bender in each pass in rolling capped steel with uniform internal properties to 0.4 mm with a reduction ratio of 30 % per pass in a reversing mill. The flatness control by the roll bender is almost ineffective for center buckle but is effective for edge wave, and the effect is larger in later passes. This means that flatness control by the roll bender is most desirable in the final stand. **Fig. 8** shows the control effect of the roll bender for different entry tension. It shows the control effect on flatness obtained by changing the entry tension at the last pass, and tells us that the control effect on edge wave increases as tension increases. This effect is not observed with regard to center buckle.

Both the entry and exit tensions are effective for control of edge wave but not effective for center buckle control[4]. The rolling load is an important factor as it not only affects determination of the initial roll camber but also makes flatness control difficult if it varies largely within a coil.

2.2 Profile Control

The crown and edge drop forming mechanism has been studied using a reversing mill and the influence of rolling conditions such as draft schedule and of hot-rolled strip properties has been studied using a four-stand rolling mill[5,6].

2.2.1 Profile forming mechanism in cold rolling

Fig. 9 shows the difference between the actually measured crown (C_{meas}) and the calculated crown in proportion to constant crown ratio ($C_{cal} = C_H(1 - r)$) along strip width in the 1st, 3rd and 5th passes. The

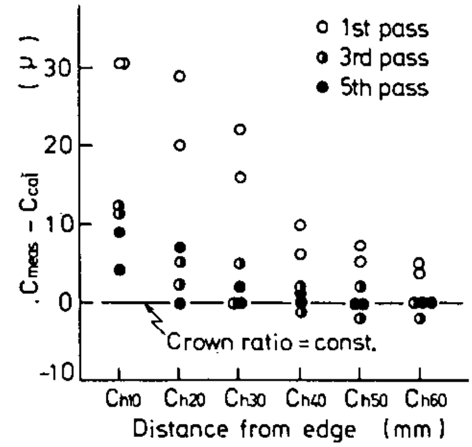


Fig. 9 Difference between measured crown (C_{meas}) and calculated crown (in proportion of crown ratio. . . . . C_{cal}) along strip width

strip was rolled in 5 passes from 2.6 mm to 0.4 mm. If the difference is 0, it means deformation in proportion to a constant crown ratio. Deformation with nearly a constant crown ratio is observed for more than 50 mm from the edge in the 1st pass and for more than 30 mm from the edge in the 3rd and 5th passes, where metal flow in the direction of the width is small and the crown of the hot-rolled strip is predominant. At the portion nearer to the edge, the measured crown is larger, indicating metal flow during cold rolling. Therefore, the crown of a cold-rolled strip is primarily determined by the crown of a hot-rolled strip, and the edge drop is determined by cold rolling conditions.

2.2.2 Crown control

Fig. 10 shows the relation between the crown ratio (H_{25}/H_C) of a hot-rolled strip and the crown ratio (h_{20}/h_C) after cold rolling to 0.8 mm and 1.2 mm. As seen from the figure, the crown after cold rolling is

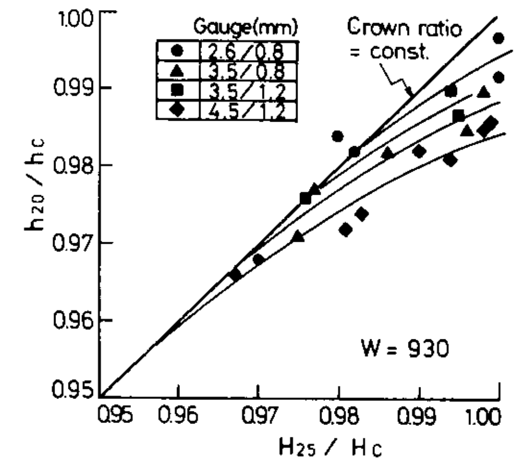


Fig. 10 Relation between crown ratio (h_{20}/h_C) after cold-rolling and crown ratio (H_{25}/H_C) after hot-rolling

almost proportional to the crown of the hot-rolled strip, thereby indicating primary dependence on the crown of the hot-rolled strip. The crown after cold rolling is smaller as the finishing thickness and total reduction by cold rolling get smaller. As the crown ratio (H_{25}/H_C) after hot rolling approaches 1.0, the crown after cold rolling deviates from the line with 45° gradient.

It is also clarified that the crown after cold rolling cannot be controlled by changing the reduction distribution in the cold rolling process[5].

2.2.3 Edge drop control

Since the edge drop of cold-rolled strip is influenced by metal flow during rolling as mentioned above, it can be improved by changing the cold rolling conditions. One of the factors which dominates metal flow is work roll flattening. **Fig. 11** shows the relation between work roll flattening and edge drops of cold-rolled strips when a 2.6 mm hot-rolled strip is cold-rolled in a reversing mill with a reduction ratio of 10 ~ 40 %. As flattening increased, the edge drop become larger. Some difference of metal flow caused by the difference of reduction exists, but the tendency is the same because the difference is also affected by work roll flattening. **Fig. 12** shows the relation between edge drops of cold-rolled strips and total reduction in the latter 2 stands in a four-stand tandem mill when 2.8 mm thick hot-rolled strips are cold-rolled to thickness of 0.8 mm. Edge drops of cold-rolled strips are improved as the total reduction in the latter 2 stands decreases. In a tandem mill, edge drops of cold-rolled strips are greatly influenced by the rolling conditions such as reduction ratio and rolling load in these latter stands.

Width change also affects edge drops. As width broadens, the edge drop becomes larger[6]. Width reducing caused by increasing the tension between stands may be helpful in decreasing the edge drop.

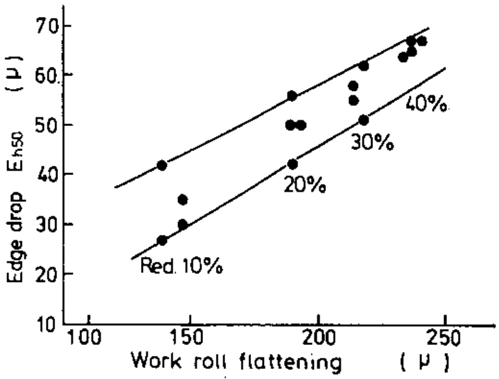


Fig. 11 Relation between work roll flattening and edge drops E_{h50} of cold-rolled strips

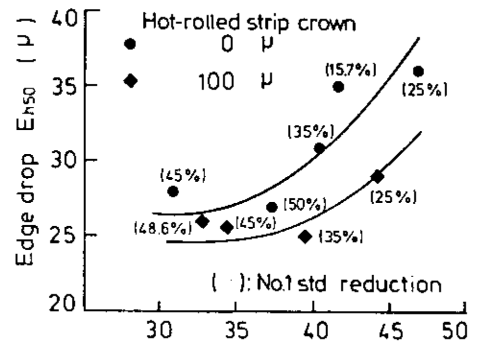


Fig. 12 Influence of total reduction of latter 2 stands in 4-stand tandem mill on edge drops of cold-rolled strips

3 Flatness and Profile Control in Hot Rolling Process

3.1 Flantness Control

An important problem in flatness control of hot-

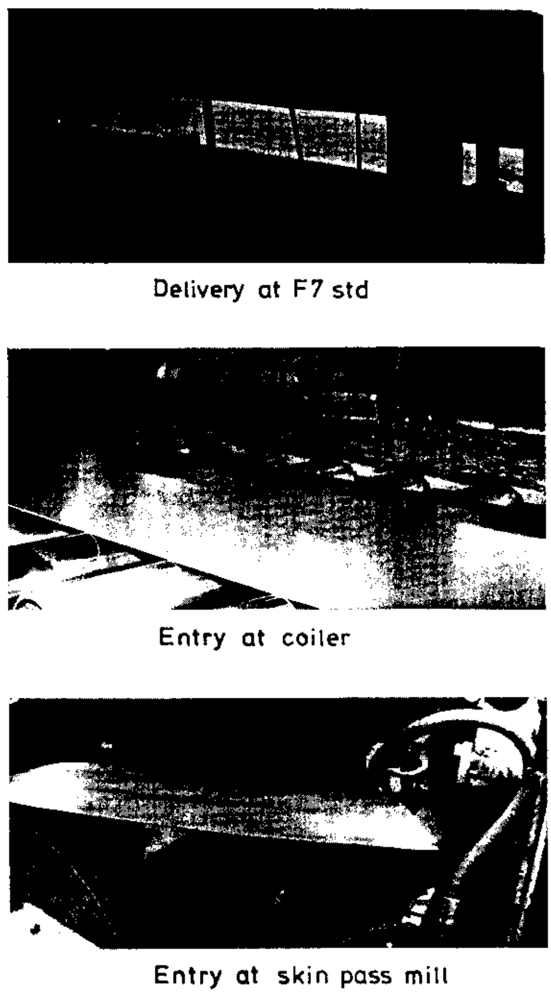


Photo. 1 Change of hot-rolled strip flatness with subsequent process

rolled thin strips is accurate grasping of flatness change brought about by temperature change in the hot rolling process. As shown in **Photo. 1**, the flatness changes depending on the process steps, such as in delivery at the final stand, entry at the coiler and after full cooling[7]. It is necessary to determine and control the flatness on the delivery side of the finishing stand so that the flatness after full cooling will be good.

Generally the flatness of a finished hot-rolled strip is controlled by optimal use of the reduction ratio to make the crown ratios constant and by the work roll bender at latter stands, especially at the final stand. **Fig. 13** shows theoretical calculation results of the effects of the roll bending force at each finisher stand on the flatness of a hot-rolled strip product with reference to the F7 stand of a seven-stand finisher when 26 mm thick, 960 mm wide plate is hot-rolled to 2.3 mm with the roll bender of each stant changed from 0 to 100%. As mentioned above, the figure shows the greater flatness control effects of roll bending force at latter stands, especially the final stand.

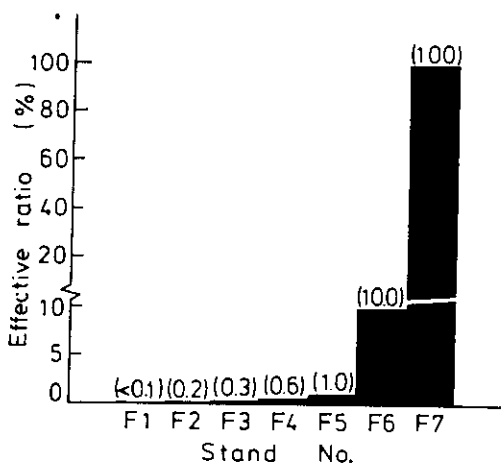


Fig. 13 Effect of roll bending force at each finisher stand on flatness of hot-rolled strip product

In the crown control experiment by changing the reduction distribution at an actual hot rolling mill described in **3.2.2**, the flatness was improved when making the crown proportion nearly constant at the entry and exit of the final stand ($C_h = C_H(1 - r)$). Edge wave was observed for $C_h > C_H(1 - r)$ and center buckle was observed for $C_h < C_H(1 - r)$.

3.2 Profile Control

As mentioned above, optimum results in the hot-rolled strip profile is important in controlling the cold-rolled strip flatness and profile. Here roll wear, thermal crown change and rolled strip crown change in a four-high rolling mill are described. Moreover, a constant crown control method and a edge drop control method are discussed.

3.2.1 Roll wear and thermal crown

Generally rolling schedules for hot-rolling finishers lay stress on thickness and temperature control. Reduction is generally distributed much heavier in preceding stands and lighter in latter stands. **Fig. 14** shows progress of wear, thermal crowns and surface profiles of work rolls immediately after rolling in a hot rolling cycle of seven-stand finisher under such reduction distribution measured for the F1-(preceding stand), F4-(intermediate stand) and F7-(latter) stands. Ordinary rimmed steel was rolled to a finishing thickness of 3.2 ~ 2.6 mm. In the rolling schedule, the strip width in a cycle was changed from 900 mm to 1 200 mm and then to 900 mm.

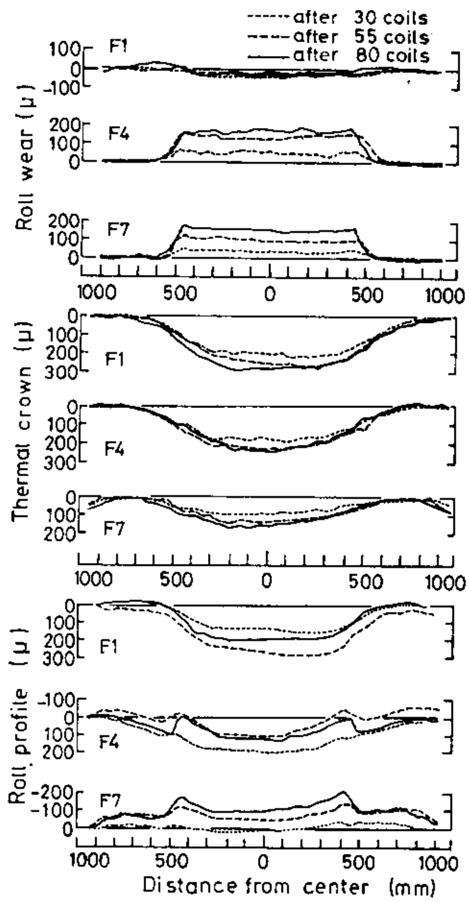


Fig. 14 Growth of wears, thermal crowns and surface profiles of work rolls immediately after rolling in a hot rolling cycle

An adamite roll is used in the F1-stand, and almost no wear was observed because of skin black scale layer formation. In the F4- and F7-stands using nickel grain rolls, the rolls were worn in the strip passing point almost in a rectangular shape. The progress of wear after rolling one cycle (80 coils) is approx. 175 μ at the F4-stand and 150 μ at the F7-stand. With regard to thermal crown, it is distributed parabolically along the width and is approximately 275 μ at the F1-stand, 225 μ at the F4-stand, and 150 μ at the F7-stand after rolling one cycle. The work rolls immediately after rolling in a hot rolling cycle show composite profiles in which thermal crowns are added to by subslantial wear. Therefore, the strip profile gradually changes from the convex profile to the rectangular profile as shown in **Fig. 15.** Thus thermal crowns greatly affect strip profiles except at edges, or strip crowns, and wear greatly affect edge profiles or edge drops. Strip crown C_{h25} changes from 100 μ to 20 μ a cycle.

The experiment using an actual mill also clarified the difficulty of reducing thermal crowns of rolls and controlling them to constant values[8].

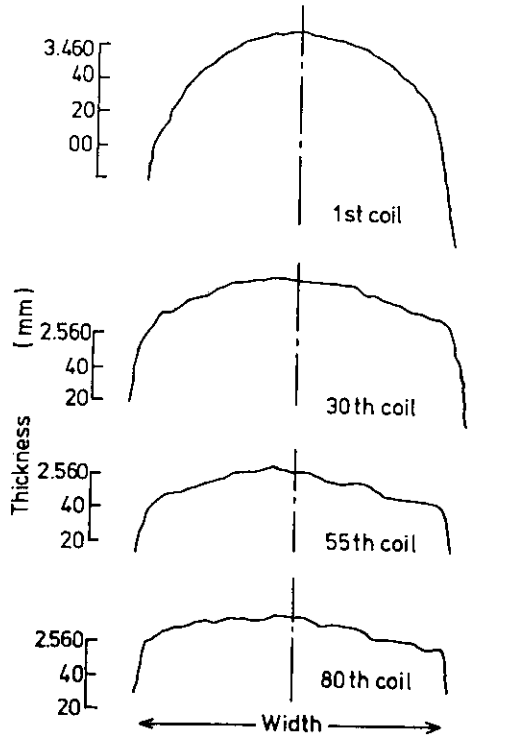


Fig. 15 Change of strip profiles in a hot rolling cycle

3.2.2 Crown control

Effective control of crowns to constant optimum values by changing the reduction distribution also considering the strip flatness control is explained below[7] using a 7-stand finisher. This method changes the reduction distribution at the finisher along with the progress of rolling to compensate for the roll thermal crown change, taking into consideration the fact that the strip profile is determined by metal flow in the latter stands and the fact that the flatness can be controlled by the rolling condition at the final stand. Three reduction modes as shown in **Table 1** are used. Mode A adopts heavy reduction in the former stands and light reduction in the latter stands. Mode B adopts almost equal reduction in the F1 ~ F6 stands. Mode C adopts light reduction in the former stands and heavy reduction in the latter stands. In all three modes, the crown ratios between on the entry side and on the delivery side at the F7-stand are made almost equal. **Fig. 16** shows the calculated results of hot-rolled strip crown C_{h25} at each finisher stand when 26 mm thick 900 mm wide strip is rolled to 3.2 mm in the three modes described above. The calculated strip crown difference between mode A and mode C is

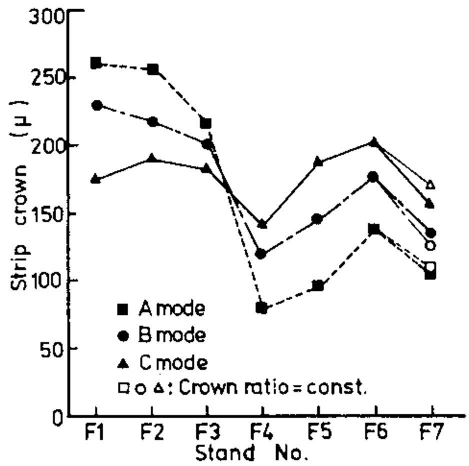


Fig. 16 Calculated results of hot-rolled strip crown at each finisher stand due to change of rolling schedules

Table 1 Rolling schedules in order to control the crown and the flatness of hot-rolled strip

(%)

Mode \ Stand	F1	F2	F3	F4	F5	F6	F7	Note
A	36.3	34.9	32.0	23.3	21.7	21.2	10.7	Latter stands: Light reduction
B	29.7	28.3	30.0	23.7	28.4	27.2	14.7	Many stands: Equal reduction
C	20.5	23.7	27.9	31.8	32.3	27.0	17.3	Latter stands: Heavy reduction

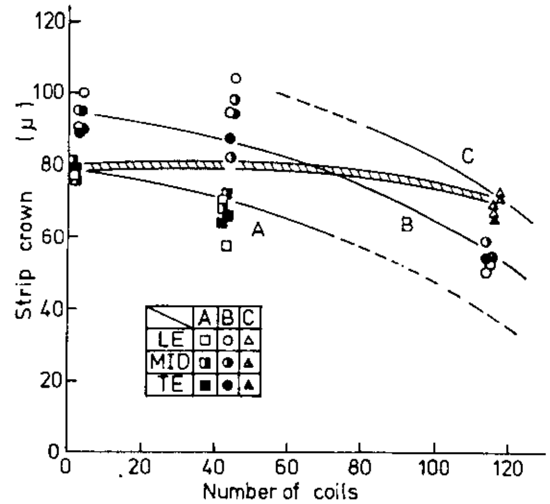


Fig. 17 Comparison of hot-rolled strip crowns due to change of rolling schedules

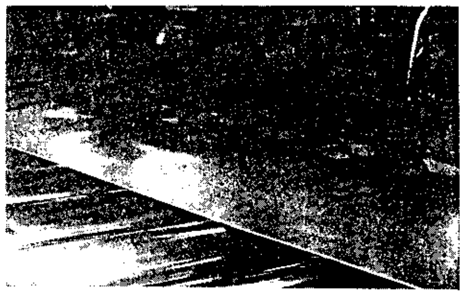
approximately 55 μ. It indicates that the strip crown change due to roll thermal crown can almost be compensated for.

Fig. 17 shows the comparison of crowns of hot-rolled strip rolled on a seven-stand finisher according to the following schedule:

Leading stage of a cycle:	925 mm wide rolling material in modes A and B in **Table 1**
Middle stage of a cycle :	1 215 mm wide rolling material in modes A and B
Last stage of a cycle :	925 mm wide rolling material in modes B and C

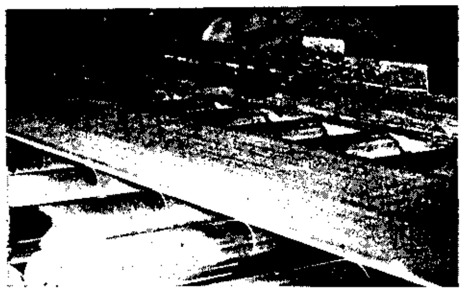
The strip crown difference between two modes is approximately 15 μ for 925 mm width, and approximately 25 μ for 1 212 mm width. By changing the reduction distribution modes from A to B and to C in a cycle with the progress of rolling, the crown can be controlled to a constant value. Optimum crown can be achieved by making the initial work roll camber to a convex shape. As shown in **Photo. 2**, the strip flatness immediately before coiling is almost always good for each model. **Fig. 18** shows the change of strip crown C_{h25} when low carbon rimmed steel is hot-rolled for one cycle by a conventional schedule and by the new schedule as mentioned above. In the conventional schedule the change is from 100 μ to 20 μ while the change in the new schedule is between 60 μ and 30 μ. The result fully satisfies the target crown. When the crown change by mode change is large, it is recommended that you increase the frequencies of mode change.

As mentioned above, we have developed a tech-



Mode A

Mode B



Mode C

Photo. 2 Observation of hot-rolled strip flatness (before coiling) on each schedule shown in **Table 1**

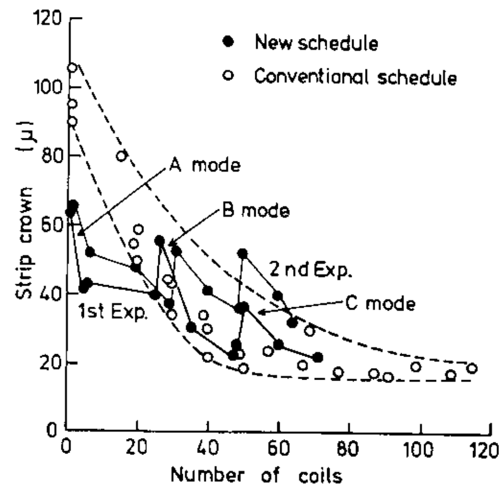


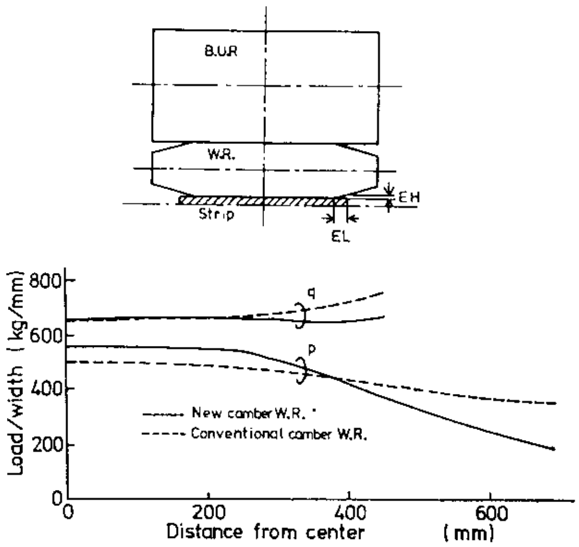
Fig. 18 Effect of new rolling schedule on hot-rolled strip crown

nique to control rolled strip crowns in the target range by compensating for the change of the roll thermal crowns by gradual change of reduction distribution in hot-rolling mill finisher stands which also enables us to have more flatness control.

3.2.3 Edge drop control

It has been stated that use of trapezoid-cambered work roll is effective in reducing edge wave in cold-rolled strip. Since metal flow is likely to occur in the latter stands in hot rolling, edge drop control is also possible[9]. **Fig. 19** shows the trapezoid-cambered work roll setting diagram and theoretically calculates distributions of contact load (p) between backup roll and work roll and contact load (q) between work roll and rolled strip in comparison between the trapezoid-cambered work roll and ordinary flat roll.

Calculating conditions are as follows:



q : Contact load between work roll and rolled strip
p : Contact load between back-up roll and work roll

Fig. 19 Schematic diagram of new trapezoil-cambered work roll and distribution of contact load per width

Effective crown (EH) $= 50\ \mu$
Effective length (EL) $= 200$ mm
Rolling condition : 920 mm wide material rolled from 4.6 mm to 3.8 mm in thickness

When a trapezoid-cambered work roll is used, contact load p at roll edges, which causes unnecessary bending moment to work roll, decreases and contact load q becomes uniform. As a result, a deflection of work roll is small and a flattening at the strip edge portion is offset by the tapered portion. Thus the surface profile

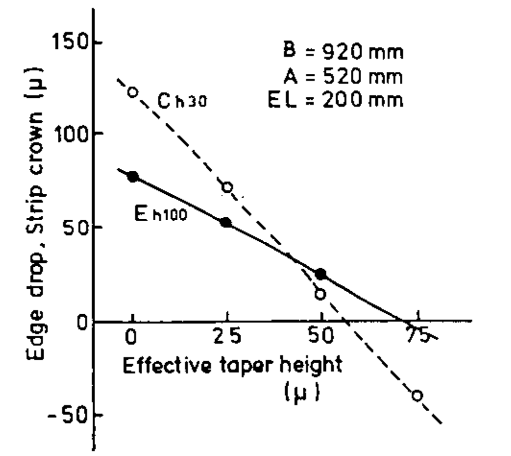


Fig. 20 Calculated results of effective taper height (EH) dependence on edge drop and crown of hot-rolled strip

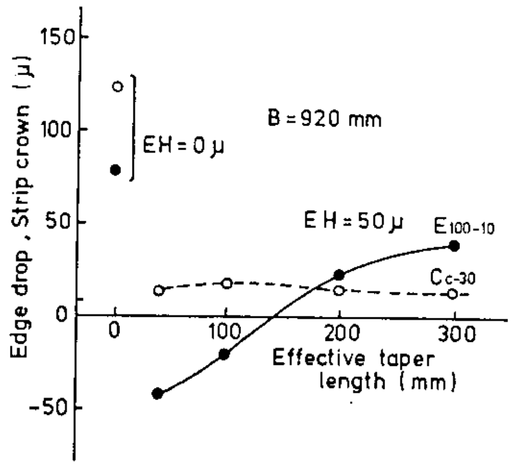


Fig. 21 Calculated results of effective taper length (EL) dependence on edge drop and crown of hot-rolled strip

of work roll becomes uniform, and edge drop is reduced widely. **Fig. 20** shows the calculated results of effective taper height (EH) influence on edge drop (E_{h100}) and crown (C_{h50}) when assuming effective length EL $= 200$ mm. **Fig. 21** shows the calculated results of effective length (EL) influence on edge drop (E_{h100}) and crown (C_{h50}), assuming effective crown EH $= 50\ \mu$. The edge drop and crown decrease almost linearly as EH increases. When EL increases, the crown remains constant but edge drop increases.

Fig. 22 shows the effect of new trapezoid-cambered work roll installed at the final stand of a 6-stand finisher on the edge drop of strips in one cycle rolling for low carbon rimmed steel, as compared with the edge drop change in the conventional method. Edge drops in the $100 \sim 120\ \mu$ zone in the initial period by the conventional methods, are decreased to $40 \sim 60\ \mu$ by

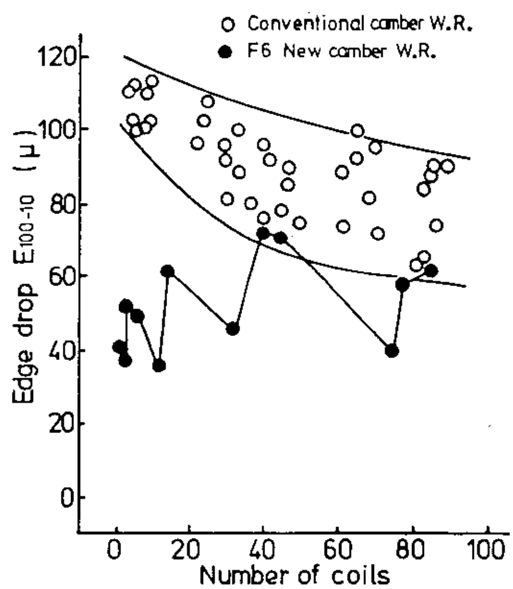


Fig. 22 Effect of new trapezoid-cambered work rolls on edge drop of hot-rolled strip

the new method. Since flatness control in actual operation must be done at the final stand, trapezoid-cambered work rolls are installed at the F4-and F5-stands mainly for rolling such materials as high carbon steel, which have high deformation resistance, thus leading to large edge drops. The effective taper height (EH) and effective taper length (EL) are so determined as to become optimum for rolling material which has a specially large edge drop in an initial stage of rolling cycle.

4 Conclusion

Flatness and profile control of cold- and hot-rolled strip, experiment results on four-high mills, theoretical calculation results and techniques developed from these studies are summarized. From the above results, the following points have been deduced:

(1) Uniformity of hot-rolled strip's internal properties is the most important factor affecting the flatness of cold-rolled strip. The second most important factor is optimal use of the initial work roll camber in a cold rolling mill. After a maximum possible improvement in strip flatness by these factors, control can be made by adoption of roll benders, coolant and tension adjustment.

(2) Since metal flow in cold rolling occurs only within a limited distance (less than several tens millimeters) from edges, the crown of a cold-rolled strip is primarily determined in proportion to the crown of the hot-rolled strip used. Edge drop can be controlled and improved by rolling with light reduction rates at the latter stands so as to reduce flattening of work rolls.

(3) The hot-rolled strip flatness can be controlled at the last one or two stands. As the flatness varies according to the temperature change in the downstream processes, flatness control must take this point into consideration.

(4) The hot-rolled strip crown can be controlled within a target range by compensating for the work roll thermal crown change through changes of reduction distribution along with the rolling progress in the rolling cycle. By making crown ratios almost equal between on the entry side and on the derivery side at the final stand, flatness can be controlled simultaneously.

(5) Reduction of the hot-rolled strip edge drop is possible by adoption of trapezoid-cambered work rolls. In actual operation, they are installed at the final one or two stands. Flatness can be controlled by making the crown ratios almost equal between on the entry side and on the delivery side at the final stand.

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