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Edge-Drop Control of Hot and Cold Rolled Strips by a Tapered-Crown Work Roll Shifting Mill*


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In the rolling of hot and cold rolled strip, one of the essential tasks is a minimization of edge drop, which is a sharp reduction in the transverse thickness profile at strip edges. The authors made an experimental study of deformation behavior at strip edges, followed by an investigation into the characteristics of edge drop control on a tapered-crown work roll shifting mill by using a laboratory mill and commercial cold and hot strip rolling mills. The results of finding: (1) The edge drop is caused by three dimentional material flow which occurs at the strip edge, and is largely affected by changes in the work roll profile resulting from roll flattening, (2) in the cold rolling tandem mill, edge drops can be markedly corrected by applying a one-side-tapered crown work roll shifting mill used at one stand upstream, and (3) in the hot strip mill, the one-side-tapered crown work roll shifting mill is also found effective in improving edge drops.

1 Introduction

The longitudinal thickness accuracy of hot and cold rolled steel strip has been greatly improved by using automatic gage control with quick-response hydraulic screwdown devices and AC mill motors. The current problem is the thickness accuracy of hot and cold rolled steel strip in the nonsteady acceleration and deceleration regions of rolling speed.

For transverse thickness accuracy, the body crown, except near the strip edges, can now be controlled by using such crown control mills as the 6-high HC (high-crown) mill and the pair-cross mill. Furthermore, high spots caused by the local wear of rolls can be prevented by shifting the work rolls in their axial direction. The remaining problem is to control a sharp decrease in thickness at points 0 to 100 mm from the strip edges, which is called edge drop.

Based on an analysis of the elastic deformation of rolls, K. Saxl has clarified that the edge drop occurs because of a sharp change in the flattening deformation of the work rolls, and suggested that the edge drop could be improved by tapering the barrel end from the portion corresponding to the zone a little inward from the edges of the material being rolled.[1] To examine the effect of the flattening deformation of rolls, Suzuki et al. rolled plate-like plasticine by varying the hardness of rubber rolls, and investigated the three-dimensional deformation behavior at the strip edges.[2] Adachi et al. used trapezoidal-crown work rolls with tapered edges on the final stand of the finisher of a hot strip mill, and suggested that it might be possible to reduce the crown and edge drop by using these rolls.[3] The authors have put a taperedcrown work roll shifting mill into practical use by further developing these ideas, and used this mill

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in a hot strip mill[4] and a cold strip mill[5] to control the crown and edge drop.

In this report, the deformation behavior at the strip edges was investigated by studying the edge drop during strip rolling, and the edge-drop control characteristics by the tapered-crown work roll shifting mill. The results of the application of this mill to commercial production process are described.

2 Behavior of Metal Flow at Strip Edges During Cold Rolling

2.1 Experimental Method

The deformation behavior at the strip edges during cold rolling was investigated by using a commercial reverse rolling mill under the experiment conditions shown in **Table 1**. A hot-rolled strip of low-carbon steel with a thickness of 2.6 mm and a strip crown (the thickness difference between the middle of the strip and a point 25 mm from the edge) of 0 μm was used as the test material. The rolling conditions employed were (1) a reduction in the first pass of 10–40%, (2) 5-pass rolling at 30% reduction/pass, and (3) a work-roll bending force of 0–490 kN/chock. An investigation was made into the effects of the reduction ratio in the first pass and of the work-roll bender on the deformation behavior at the strip edges, and into the change of deformation with each pass. Before rolling in the first pass, a marking line was scribed widthwise to investigate the behavior of transverse metal flow and the width change before and after rolling.

Table 1 Experimental conditions in 80″ reversing mill

Material		Low C steel
Entry thickness	(mm)	2.6
Delivery thickness	(mm)	0.44
Width	(mm)	930
Crown after hot rolled	(μm)	0
WR diameter	(mm)	546 ϕ
WR barrel length	(mm)	2 032
Rolling conditions		
(1) Reduction at 1st pass	(%)	10, 20, 30, and 40
(2) Rolling pass schedule		5 pass rolling (30%/pass)
(3) WR bending force	(kN/chock)	0, 245, and 490

2.2 Experimental Results

The relationship between the reduction during the first pass and the edge drop is shown in **Fig. 1**. The edge drop in this figure is represented by the strip thickness difference between a point 50 mm from the strip edge and a point 10 mm from it, and the edge-

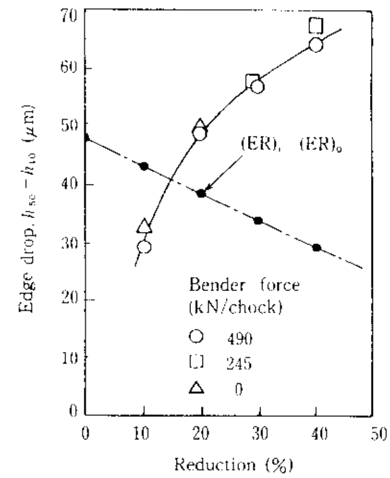

Fig. 1 Relation between reduction and edge drop at first pass

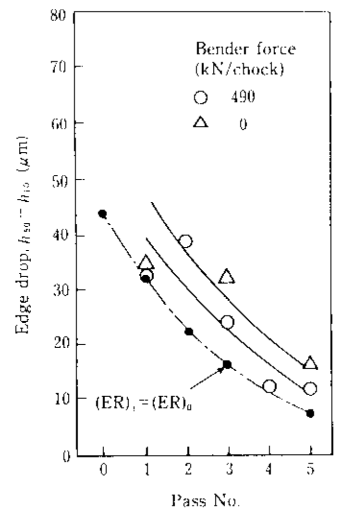

Fig. 2 Relation between pass number and edge drop

drop ratio (ER) is given by Eq. (1).

$$(ER_x)_i = \{(h_{50})_i - (h_x)_i\}/(h_{50})_i \cdots\cdots\cdots\cdots (1)$$

where h_{50}: Strip thickness at a point 50 mm from the edge

h_x: Strip thickness at a point x mm from the edge ($x = 10$ mm)

Suffix i: After the ith-pass of rolling ($i = 0$ for the mother strip)

A constant edge-drop ratio indicates that the edge-drop ratio of the strip after rolling is equal to that of the mother strip, and this case is given by Eq. (2).

$$(ER_x)_i = (ER_x)_0 \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

From Fig. 1, the edge drop increases with increasing reduction, and the edge-drop ratio at a reduction of about 15% is equal to that of the mother strip. The effect on edge drop by the work-roll bender is as small as a few micrometers or less. **Figure 2** shows the change in edge drop when 5-pass rolling was conducted. The edge drop decreases with increasing number of passes. When the crown on the mother strip is 0 μm, the edge drop shows a change similar to that observed when the edge-drop ratio is constant.

2.3 Examination of the Mechanism Producing Edge Drop

An examination was made of how far from the strip edge occurred metal flow of the material during cold rolling. **Figure 3** shows the difference between the measured strip crown C_h^{meas} at each transverse position after 1-pass, 3-pass and 5-pass rolling, and the calculated value C_h^{cal} from a constant crown ratio. C_h^{cal} is given by Eq. (3).

$$C_h^{cal} = C_H^{meas}(1 - r) \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

where: C_H^{meas}: Measured crown of mother stirp

r: Total reduction

If the difference between measured crown value C_h^{meas} and calculated value C_h^{cal} at a constant crown ratio is zero, deformation would occur at a constant crown ratio. Deformation occurred with a constant crown ratio at a point about 50 mm from the strip edge after the first pass, at a point 30 mm from the strip edge after the third and fifth passes, and in the center of the strip, where the mother strip crown has most effect. In the zone toward the strip edge, metal flow is likely to occur during cold rolling, the cold rolling conditions being the governing factors. In addition, the thinner the sheet, the more limited is the metal flow to the edge. From these results, the body crown of the cold-rolled steel sheet is unequivocally determined by the mother strip crown. However, it is apparent that edge drop can be controlled during cold rolling.

Figure 4 shows the relationship between the amount of flattening deformation of the work roll and the edge drop. The amount of flattening deformation E_P is calculated from Hitchcock's equation, as in Eq. (4).

$$E_P = \frac{C_0}{8} \cdot P \cdot \ln\{2D_W/(H - h + C_0 \cdot P)\} \cdots (4)$$

where E_P: Amount of flattening deformation of the work roll

P: Rolling load per unit width

D_W: Work-roll diameter

H: Entry strip thickness

h: Delivery strip thickness

C_0: Constant ($C_0 = 16(1 - \nu^2)/(\pi E)$)

As has so far been said, the amount of edge drop increases linearly with increasing degree of flattening deformation.

Figure 5 shows the relationship between the edge drop and the width spread. B_T represents the width spread over the total width, and B_{50} represents the width spread in the range from the edge to a point 50 mm in from the edge. The width spread increases

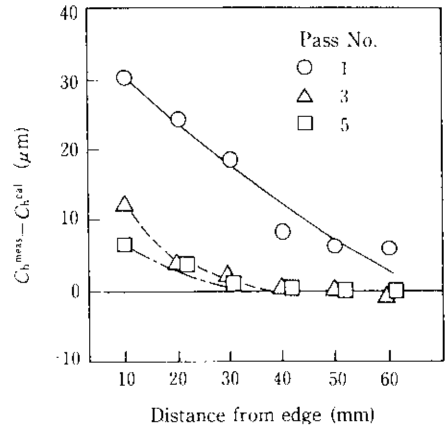

Fig. 3 Change in $C_h^{meas} - C_h^{cal}$ along width direction from strip edge (C_h^{meas}, measured strip crown; $C_h^{cal} = C_H^{meas}(1 - r)$, calculated strip crown; C_H^{meas}, strip crown of mother strip; and r, reduction)

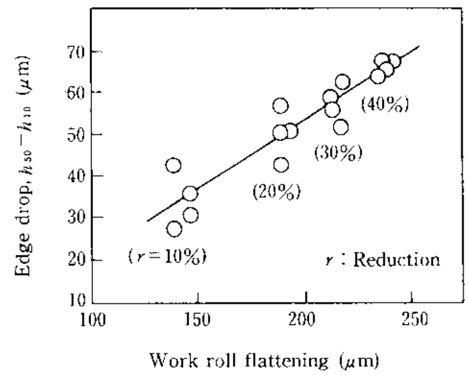

Fig. 4 Relation between work roll flattening and edge drop at first pass

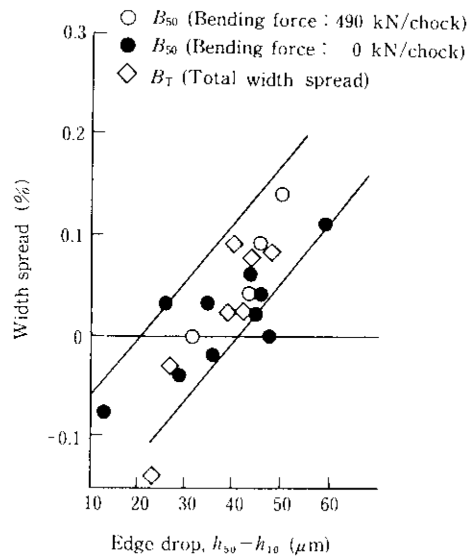

Fig. 5 Relation between width spread and edge drop at first pass

with increasing edge drop, and the greatest width spread occurs in the range from the edge to a point 50 mm in from the edge.

Therefore, it can be understood that the edge drop would be improved by rolling that causes less width spread, rolling that causes less flattening deformation of the rolls, or by giving a roll curve suited to the effect from roll flattening.

3 Edge-Drop Control Characteristics with a Tapered-Crown Work Roll Shifting Mill

After deriving a roll curve for the work rolls that would compensate for a sharp change in the flattening deformation of the rolls at the edges of the strip, the authors further developed the studies by K. Saxl and Adachi et al., evolved a rolling method with shifting, tapered work rolls capable of being used for materials of all steel grades, widths and thicknesses, and investigated the effectiveness of this rolling method.

3.1 Control Characteristics for Cold Rolling

The edge-drop control characteristics in a one-side tapered crown work roll shifting rolling was first studied by using a small-scale laboratory mill, and then investigated using a commercial rolling mill.

3.1.1 Experimental conditions

The experimental conditions employed with the laboratory mill are shown in **Table 2**. Work rolls of 310-mm diameter, 300-mm barrel length and $\tan\theta = 1/250$ taper were used; the material strip had a yield stress of 300 MPa and a width of 150 mm. As shown in **Fig. 6**, the work-roll taper position (EL) is regarded as positive when the taper starting point is inward from the edge of the strip, and rolling was conducted in an EL range of −5 to 30 mm

Table 2 Experimental conditions in laboratory mill

Material		Low C steel
Entry thickness	(mm)	2.3
Delivery thickness	(mm)	0.5
Width	(mm)	150
WR diameter	(mm)	310 ϕ
WR barrel length	(mm)	300
WR taper		$\tan\theta=1/250$
WR taper position		EL = −5~30 mm
1st pass reduction	(%)	42
2nd pass reduction	(%)	42
3rd pass reduction	(%)	35
Tension	(MPa)	140/80
Speed	(m/min)	5

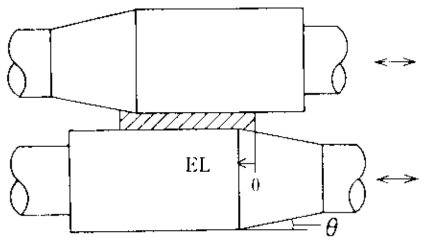

Fig. 6 Schematic diagram of work roll shifting mill

Table 3 Experimental conditions in tandem cold mill

Material		Low C steel
Entry thickness	(mm)	2.3
Delivery thickness	(mm)	0.5
Width	(mm)	1 100
WR diameter	(mm)	360 ϕ
WR barrel length	(mm)	1 480
WR taper		$\tan\theta=1/400$
Rolling speed	(m/min)	50 (at No. 4 stand)

Table 4 WR taper position EL in tandem cold mill (mm)

	Stand			
	No. 1	No. 2	No. 3	No. 4
Case A	30	30	30	15
Case B	30	30	30	−10
Case C	30	−10	−10	−10
Case D	−10	−10	−10	−10

The experimental conditions employed in the commercial mill are shown in **Tables 3** and **4**. The experiment was carried out on a 4-stand cold rolling mill, all four stands being equipped with shifting tapered-crown work rolls. The work-roll diameter was 360 mm, the barrel length was 1 480 mm, and the taper was $\tan\theta = 1/400$. In case A, rolling was conducted with the one-side-tapered crown work rolls used on the No. 1, No. 2, No. 3 and No. 4 stands. In case B, rolling was conducted with the tapered-crown work rolls being used on the No. 1, No. 2 and No. 3 stands. In case C, rolling was conducted with the tapered-crown work rolls being used only on the No. 1 stand. In case D, rolling was conducted with ordinary flat work rolls on the No. 1, No. 2, No. 3 and No. 4 stands.

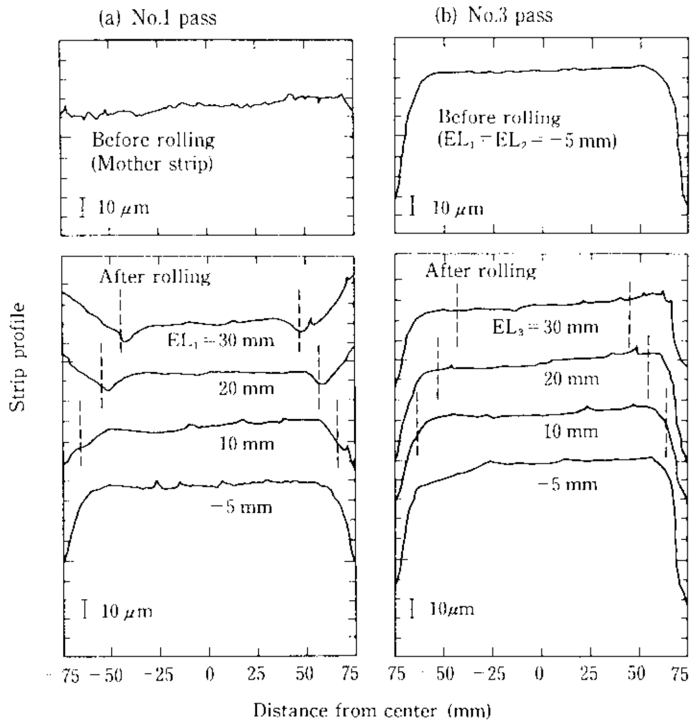

Fig. 7 Effect of taper position (EL) on cold rolled strip profile in small scale laboratory mill

3.1.2 Experimental results

Figure 7 shows the strip thickness distribution in the transverse direction when taper position EL was varied. The strip thickness distribution before the first pass is shown in Fig. 7 (a), no edge drop being apparent in the material before rolling. This is because the edge-drop portions of the hot-rolled coil were cropped. The thickness distribution after the first pass shows the generation of edge drop for $EL \leqq 10$ mm. With greater EL, however, the edge drop improves gradually, and edge showing an upward inclination for $EL \geqq 20$ mm. The strip thickness distribution before and after the third pass is shown in Fig. 7 (b). The material before rolling had gone through the first and second passes for $EL = -5$ mm (corresponding to rolling with flat work rolls), and the edge drop had formed at a point about 20 mm from the strip edge. After the third pass, the edge drop about 10 mm from the edge is no better even for $EL \geqq 20$ mm, except for being slightly reduced at the edges. In the preceding section, it was shown that the formation of edge drop is caused by the metal flow of material at the strip edges. It is apparent, however, that because the degree of metal flow differs according to strip thickness, the behavior of the edge drop also varies depending on the strip thickness.

Based on these results, changes in the edge-drop ratio at points 7.5 mm and 2.5 mm from the strip edge ($ER_{7.5}$ and $ER_{2.5}$) were reconsidered.

Figure 8 shows a comparison between edge-drop ratios $ER_{7.5}$ and $ER_{2.5}$ after each pass with taper position EL as a variable. For $ER_{7.5}$, the effect of taper position EL displays itself after the first and second passes, while

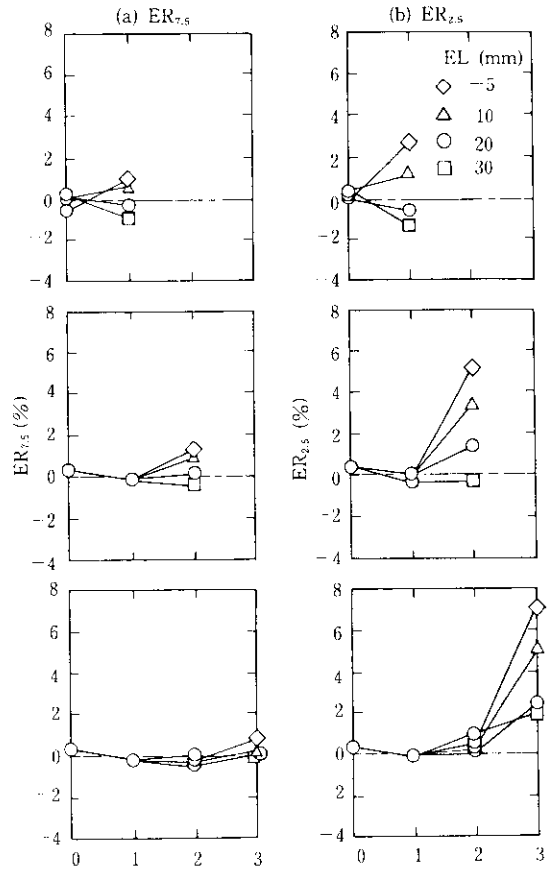

Fig. 8 Effect of taper position (EL) on edge drop ratio (ER) of cold rolled strip in small scale laboratory mill

this effect is scarcely apparent after the third pass. For $ER_{2.5}$, however, the effect of EL is great even after the third pass. This shows that the edge drop can be improved by setting the taper position a little inward from the strip edge on the first stands of a tandem mill, and by setting it nearer the strip edge on the subsequent stands.

The edge-drop control characteristics in a commercial 4-stand tandem mill were then investigated. The strip thickness profile at a point 50 mm from the edge is shown in **Fig. 9**. It is apparent that the edge drop at the end the strip edges could likewise be improved by using one-side-tapered crown work rolls on all stands of the mill. Changes in the edge drop on each stand are shown in **Fig. 10**. From the edge drop at a point 17 mm from the strip edge ($h_{50} - h_{17}$), it is apparent that the effect of the tapered crown work rolls displayed itself on the No.1 stand, while it is not apparent on the subsequent stands. For the edge drop at 7.5 mm from the strip edge ($h_{50} - h_{7.5}$), the effect of the tapered crown work rolls is apparent not only on the No. 1 stand, but also on the No. 2 stand. For the edge drop at a point 3 mm from the strip edge ($h_{50} - h_3$), the further downstream the tapered crown work rolls are used, the greater the improvement is. Conversely, when the tapered crown work rolls were used only on the No. 1 stand, the improvement in the No. 1 stand is greatest; this effect, however, decreases due to metal flow at the edge of the strip in the downstream stands, with the result that the edge drop after rolling on the No. 3 stand is equivalent to that observed when flat work rolls were used.

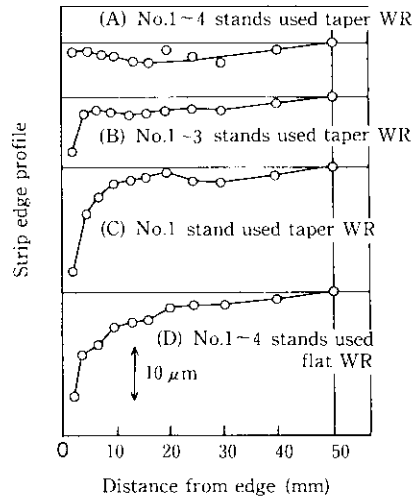

Fig. 9 Effect of taper work roll on edge profile of cold rolled strip in tandem cold mill

It is apparent that tapered-crown work rolls must be used on all stands if the edge drop at the extreme edges is to be controlled, while these work rolls can be installed only on the first stand if the edge drop is to be controlled to a certain extent inward from the strip edges.

3.2 Control Characteristics in Hot Rolling

In hot rolling where the strip thickness is large and the deformation resistance low, sufficient edge-drop control can be expected by using tapered crown work rolls only on a latter stand unlike with cold rolling. The following is the control characteristics when tapered crown work rolls were used in the No. 5 stand of a 6-stand finisher in a commercial hot strip mill.

3.2.1 Experimental method

The experimental conditions are shown in **Table 5**, with the work-roll diameter 678 mm, the taper $\tan\theta = 0.03/100$, and the length of the tapered part 550 mm. The slab was finished on the No. 5 stand

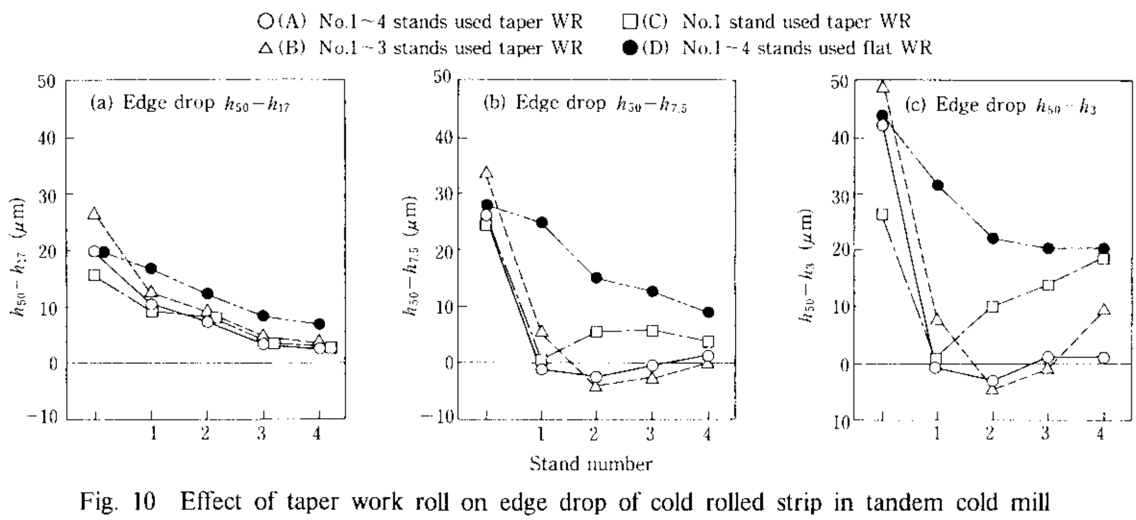

Fig. 10 Effect of taper work roll on edge drop of cold rolled strip in tandem cold mill

Table 5 Experimental conditions in hot strip mill

Material		Low C steel
Entry thickness	(mm)	4.5
Exit thickness	(mm)	3.2, 3.8
Width	(mm)	927
WR diameter	(mm)	678
WR barrel length	(mm)	1 422
WR taper		tan θ=0.03/100
WR taper position		EL=50∼250 mm

without using the roll pass of the No. 6 stand, and was reduced from a thickness of 4.5 mm to 3.8 mm or 3.2 mm. The strip width was 927 mm, and the strip crown C_{h25} (thickness difference between the middle of the width and a point 25 mm inward from the edge) on the entry side of the No. 5 stand was 60–70 μm. Rolling was conducted by varying EL for each strip, with the strip profile measured by an on-line profile meter.

3.2.2 Experimental results

The effect of work-roll taper position EL on the strip profile for a delivery thickness of 3.8 mm is shown in **Fig. 11**. The thickness deviation decreases with increasing EL, and a strip profile close to the flat condition was obtained. The relationship between work-roll taper position EL and the edge drop $(h_{125} - h_{25})$ is

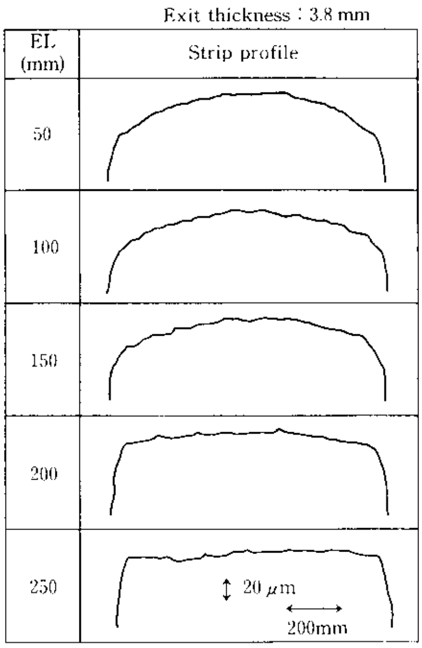

Fig. 11 Effect of taper position (EL) on hot rolled strip profile

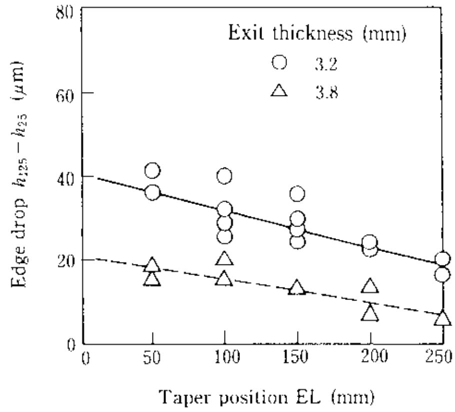

Fig. 12 Effect of taper position (EL) on edge drop of hot rolled strip

shown in **Fig. 12**. The edge drop decreases linearly with increasing EL. When a comparison is made with the same taper position EL, the edge drop is larger for a strip thickness of 3.2 mm than that for 3.8 mm. This is because the rolling load was higher for the 3.2-mm strip thickness than that for 3.8 mm, with the result that the flattening deformation was larger for the 3.2-mm-thick strip. In such cases, larger tapers are required.

4 Production Experience of Tapered-Crown Work Roll Shifting Mill

The results of edge-drop control by a tapered crown work roll shifting mill for strip production are next discussed.

Figure 13 shows the effect of edge-drop control when tapered-crown work roll shifting mills were used in all stands of the 4-stand cold rolling mill at Mizushima Works. The edge drop $(h_{100} - h_{12.5})$ is 17 μm without edge-drop control, while it is reduced to within 5 μm, about 1/3, by using the present rolling mills.

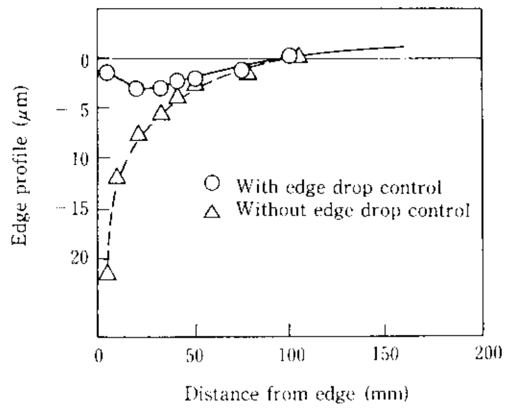

Fig. 13 Effect of edge drop control at tandem cold strip mill

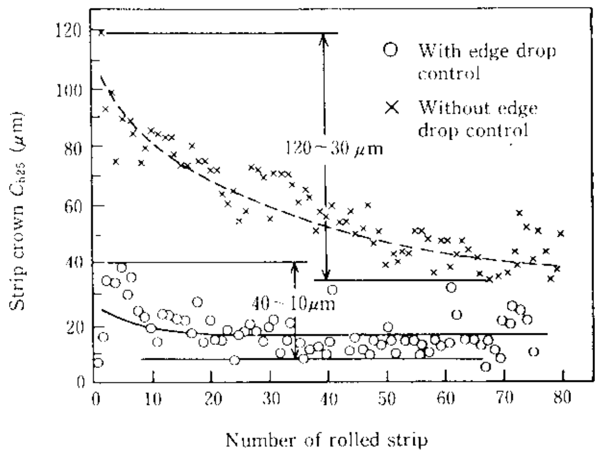

Fig. 14 Effect of edge drop control at the No. 1 Hot Strip Mill

Figure 14 shows the improvement in the strip crown C_{h25} achieved when tapered-crown work roll shifting mills were used in three stands (F3, F4 and F5) of the 6-stand finisher in the No. 1 Hot Strip Mill at Chiba Works. The strip crown is reduced by about 80−20 μm when controlled with the present rolling mills, and changes within the cycle are also small.

5 Conclusions

The deformation behavior of material near the edges of hot and cold rolled strip was investigated, and a tapered crown work roll shifting mill was developed from the results of the investigation. The edge drop control characteristics of this rolling mill were examined by laboratory experiments, and its effectiveness was proved. This rolling mill was then used in a commercial cold strip mill and a commercial hot strip mill.

(1) The results of the cold rolling experiment show that, even during strip rolling, three-dimensional metal flow occurs near the strip edges, affecting the formation of the edge drop. This three-dimensional metal flow reaches the middle of the strip in the transverse direction when the strip thickness is large, while it occurs only at the edges when the strip is thin.

(2) The edge drop has an almost linear relationship to the amount of flattening deformation of the work rolls, and increases with increasing flattening deformation. In other words, edge drop is caused by an abrupt change in the amount of flattening deformation in the region of the work roll corresponding to the edge drop position and three-dimensional metal flow.

(3) The effect of taper position EL on the edge drop during cold rolling is strong during the initial passes with large strip thicknesses, while it is limited to only near the edges in the latter passes with small strip thicknesses.

(4) The optimum number of stands in which tapered-crown work rolls should be used in a tandem cold mill depends on the position across the strip at which edge drop is to be controlled. When edge drop needs to be controlled only at the edges, it is necessary to use one-side tapered crown work rolls in all stands.

(5) The edge drop in the hot strip mill can be improved by using tapered crown work rolls only on the latter stands.

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