KAWASAKI STEEL TECHNICAL REPORT
No.3 (September 1981)

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Synopsis :
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Metal shaping behavior has been investigated to improve slab rectangularity in slab rolling. A newly developed rolling method called "Bite and Back" can sufficiently serve the purpose by giving a rectangular shape to both leading and tail ends of slabs, while minimizing crop loss due to overlap in the longitudinal section.

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1 Foreword

The availability rate of the slabbing mill has recently been lowered as a result of an increase in the continuous casting ratio. Under such circumstances, various steel mills are vying with one another in developing and improving operation techniques, so that slab yield in slabbing can be made closer to that in continuous casting.

"Overlap" and "fish tail" account for most of the losses, in terms of quantity, that occur in the slabbing process. "Overlap" is double folding in the thickness direction, and "fish tail" is a concave shape at the center in the width direction as shown in **Fig. 1.** Both result in the rejection of these slab portions of poor rectangularity (hereinafter generally called "crops"), and such crops sometimes reach as much as 6 to 7% of the total weight of the ingot. Therefore minimization of these crop losses by means of a decrease in the overlap length and by maintaining proper rectangularity at both leading and tail ends of the slab are needed to improve slab yield.

Past remedial measures against these crop losses included correction of the ingot shape[1,2], optimization of the pass schedule[3], and correction of the shape and dimensions of the recessed bottom plate of ingot mold[4], all of which were aimed at improving slab yield. These processes, however, were limited by restraints of facilities or problems in ingot casting conditions.

Therefore the authors have examined in detail the basic deformation behaviors of the unsteady portion by means of model experiments and developed a new slabbing method[5-7] (hereinafter referred to as "Bite and Back" rolling) which will give a higher slab yield with existing equipment.

This technique is now being used in the actual mill process at No. 2 slabbing mills of Chiba and Mizushima Works with remarkable success. This "Bite and Back" rolling method is reported below.

2 Deformation Behavior at Leading and Tail Ends by One-pass Rolling

The portion which is cut off from a rolled slab as defective is ordinarily determined by the overlap formed in the thickness direction. Consequently, it is important to minimize the length of this portion, if it is desired to improve the slab yield. Since this deformation at the slab end is of a 3-dimensional nature, no theoretical analysis but only experimental studies have been made on it[8,9]. The authors also made model experiments using a 1/10-scale steel ingot to clarify the effects exercised by ingot dimensions and draft per pass upon the overlap length in the conventional rolling operation.

The crop formation mechanism in the conventional slabbing method is briefly explained below. When

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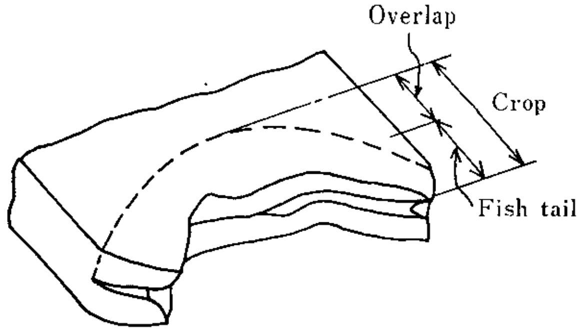


Fig. 1 The shape of slab end and definition of terms used

Table 1 Experimental conditions

Model ingot (1/10 scale of 18 t steel ingot)	Dimensions	(1) $t_0 \times 60 W_0 \times 250\ l$ (t_0=98, 108, 118 mm)
		(2) $t_0 \times 118 W_0 \times 250\ l$ (t_0=40, 60, 80 mm)
	Material	Low manganese killed steel
Draft (Δt)		3, 6, 10 mm/pass
Rolling temperature		1 000±50°C
Roll diameter		120 mm
Rolling speed		7 m/min

steel ingot is to be rolled into a slab by a universal rolling mill with horizontal and vertical rolls, several passes in the initial rolling are made with horizontal rolls in the width direction for peeling the primary scale off the surface of the ingot and removing taper from the ingot. At this time the slab end becomes concave and the fish tail begins to grow. At the same time, a regional increase in thickness called "dog bone" occurs in the thickness direction. Later, the steel under rolling is rotated by 90° and proceeds to be rolled in the thickness direction by horizontal rolls. In this case as in widthwise rolling, the slab end becomes a concave shape, the overlap begins to grow, and a "dog bone" is rolled, resulting in further expanding the fish tail which occurred in the preceding process. Later, with more than 10 times of reverse rolling by horizontal and vertical rolls, the above phenomena are repeated until a slab of a desired thickness and width can be obtained at the sacrifice of a marked increase in crops.

In view of the above, the conditions of the model experiments were set up by estimating the ingot dimensions and rolling reduction at each pass given to the ingot in an upright position in the width direction at an initial roll-period and at each pass given to the ingot after 90° rotation in the thickness direction.

2.1 Experiment Method

One-pass rolling was performed under the rolling conditions shown in **Table 1**, and the crop length was measured according to the definition in **Fig. 2**.

2.2 Results of Experiment and Discussion

2.2.1 Crop lengths at both sides in width direction

Thickness reduction develops concave crops at both sides of the slab in the width direction, because of the easy metal flow at the free ends on the sides, under any conditions of ingot thickness and draft per pass, as shown in **Fig. 3**. These crop lengths at the leading and tail ends show different behaviors; namely, at the

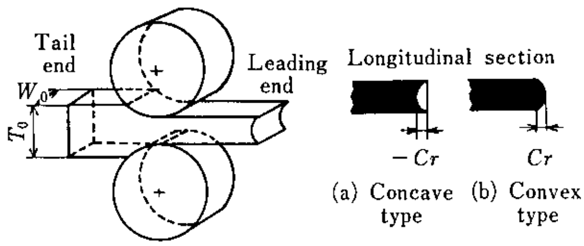


Fig. 2 Definition of crop length

leading end, the crop length increases as either the draft per pass or the ingot thickness increases. When the ingot thickness (118 mm) is more or less equal to the roll diameter (120 mmϕ), which is the possible condition at the initial period of actual rolling, the length along which force is applied to the material is smaller than the thickness; and therefore the thickness at which material deformation occurs is more or less the same as the length to which force is applied. In other words, contact length [= (roll radius × draft)$^{1/2}$] during the initial period of rolling is 24 mm for a draft of 10 mm, and the region of this thickness, 24 mm from the surface only is subjected to vertical deformation, and therefore, the metal flow at the surface layer region becomes larger than that near the center, thereby increasing the length of the concave crop. Also in slab rolling, an increase in draft aggravates shear deformation and elongates the crop length. At the tail end, crop length increases, as ingot thickness increases, and when the ingot thickness exceeds 98 mm, the draft per pass and the crop length have a linear relation. When the thickness drops to 80 mm and 60 mm, the increase in crop length reaches its saturation point at a draft of about 8 mm; and when ingot thickness further drops to 40 mm, crop length grows maximum at a draft of about 5 mm, beyond which crop length decreases.

If the cases of draft per pass ΔT = 6, 8, and 10 mm as shown in **Fig. 3** are re-plotted with ingot thickness

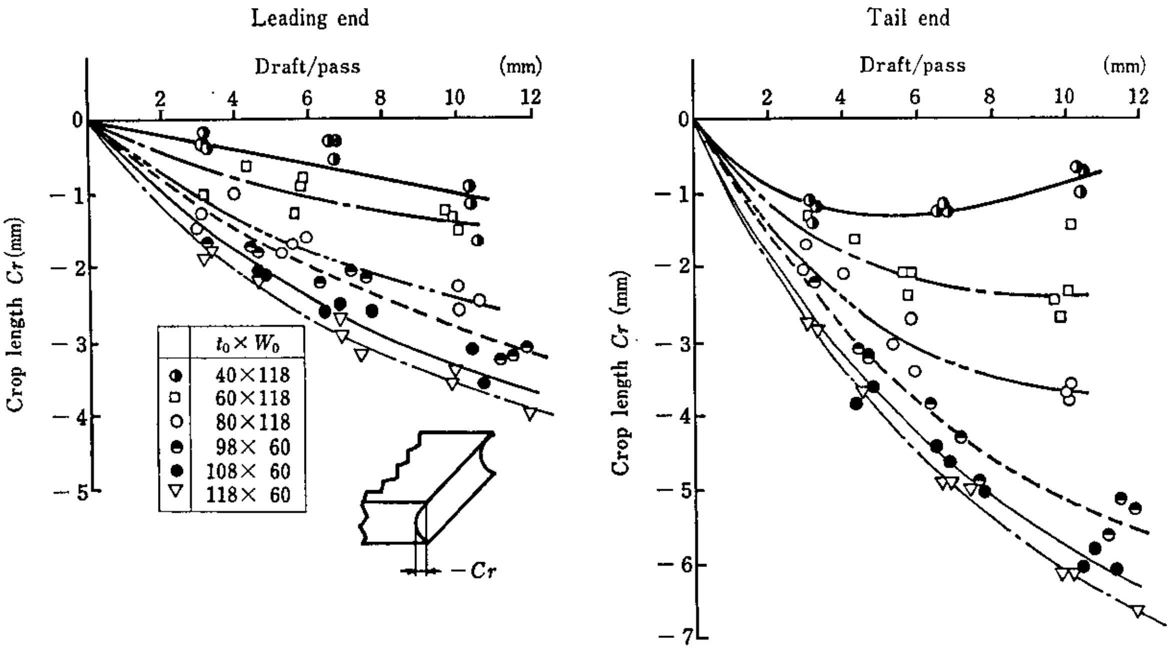


Fig. 3 Effects of ingot thickness and draft on the crop lengths at the leading and the tail ends of slab

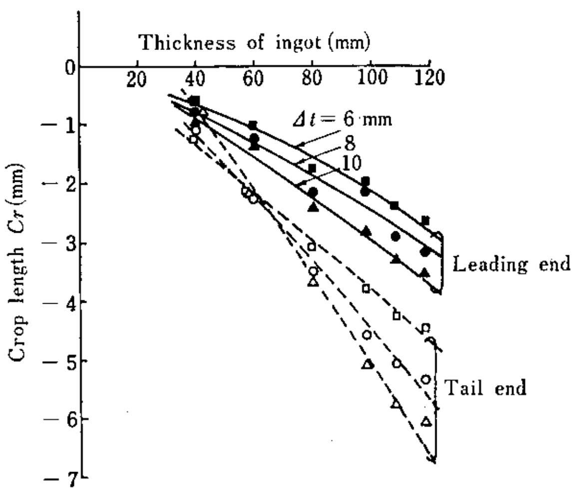


Fig. 4 Effects of ingot thickness and rolling direction on the crop lengths at the sides of the leading and the tail ends of slab

on the X-axis and with rolling directions as parameters, crop length will be as shown in **Fig. 4**. At any draft per pass, crop length at the tail end becomes larger than that at the leading end when ingot thickness exceeds 60 mm, but no conspicuous difference occurs when ingot thickness drops to 40 mm, and when draft per pass is increased to the maximum value of 10 mm, crop length at the tail end seems to become shorter than that at the leading end. It is also observed that the difference in crop length between the leading and the tail ends becomes more conspicuous as ingot thickness increases. This can be explained by formation of a metal sink at the entry side of the contact portion between the roll and the ingot surface as rolling operation progresses and by releasing this metal sink at the tail end which is free of constraint.

2.2.2 Crop length along longitudinal plane at center in width direction

In general, the crop shearing position is determined by the crop formed at the center in the width direction; therefore, it is important to minimize this crop length. The relation between crop length along the longitudinal plane at the center in the width direction, ingot thickness, and draft is shown in **Fig. 5**. At the leading end, metal protrudes at any draft per pass when ingot thickness is 40 mm and forms a convex crop showing a linear relation between the crop length and draft. The reason for this is that when the thickness is 40 mm, the contact length each becomes 24 mm for a draft of $\Delta t = 10$ mm, as explained in detail in Section 2.2.1, so that deformation will reach the near center of ingot thickness, and simultaneously, width spread at the center will be more constrained than at the ends, resulting in extension of metal flow in the longitudinal direction and formation of a large convex crop. At an ingot thickness of more than 60 mm, a concave crop is formed and, as draft increases, the crop length reaches a point of inflection where the crop length decreases or seems to saturate. This point of inflection shifts to the lower draft side, as ingot thickness decreases. On the tail end, crop length be-

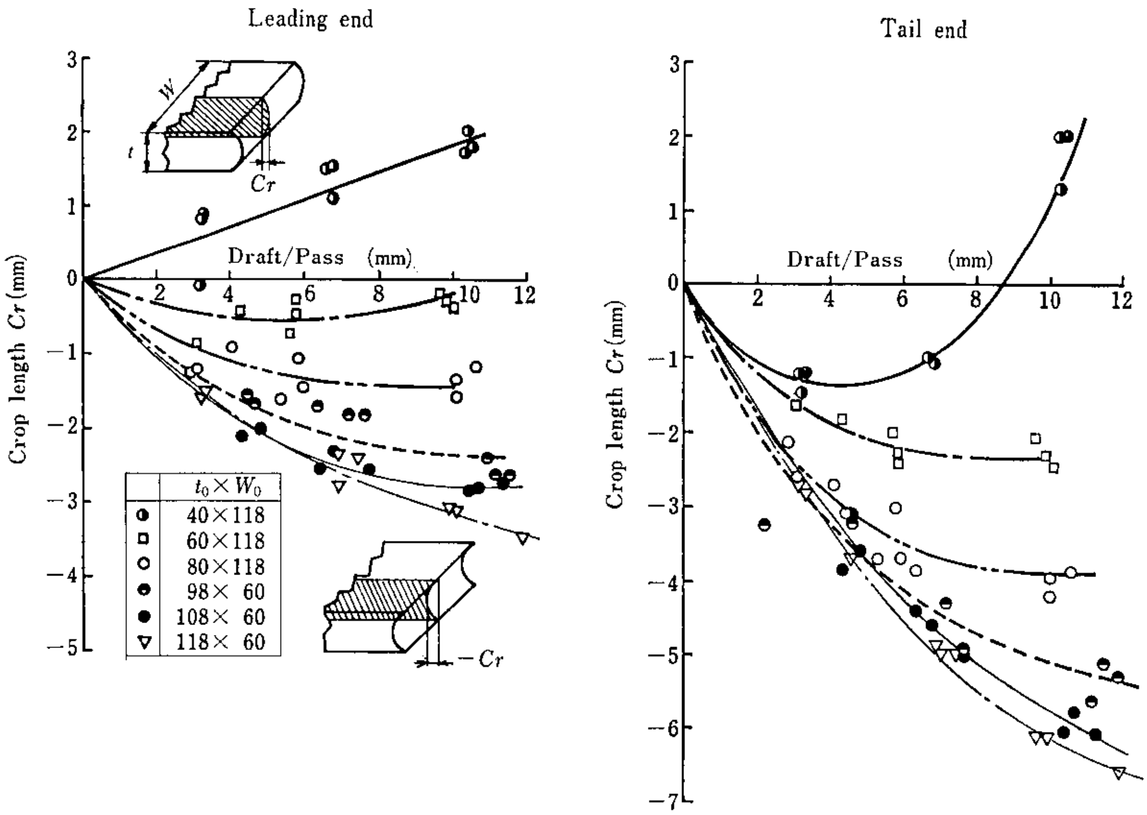


Fig. 5 Effects of ingot thickness and draft on the crop lengths at the width-centers of the leading and the tail ends of slab

comes nil, when ingot thickness is 40 mm and draft is about 8.7 mm. If the draft is increased, metal at the center will protrude and the length of the convex crop will increase. At a thickness of 60 or 80 mm, crop length increases as draft per pass increases, but the crop growth ceases at a draft of about 7 mm. When ingot thickness exceeds 98 mm, crop length increases as draft increases, within the draft range of 12 mm.

If the cases of draft per pass $\Delta t = 6$, 8, and 10 mm as shown in **Fig. 5** are re-plotted with ingot thickness on the X-axis and with rolling directions as parameters, **Fig. 6** is obtained. When ingot thickness is as large as 120 mm equivalent to the thickness at the initial period of actual rolling practice, crop length at the tail end is longer than at the leading end, and crop length at any location becomes larger as draft increases. The relations between ingot thickness and draft (Δt) at which crop length on the leading end becomes nil are 58 mm at $\Delta t = 10$ mm, 55 mm at $\Delta t = 8$ mm and 53 mm at $\Delta t = 6$ mm. In order to cause metal at the center to protrude for overlap prevention, a draft of 6 to 10 mm may be applied at an ingot thickness of 58 mm and under. On the other hand, if metal on the tail side is to be protruded, a draft of 10 mm and over is required at an ingot thickness of 40 mm.

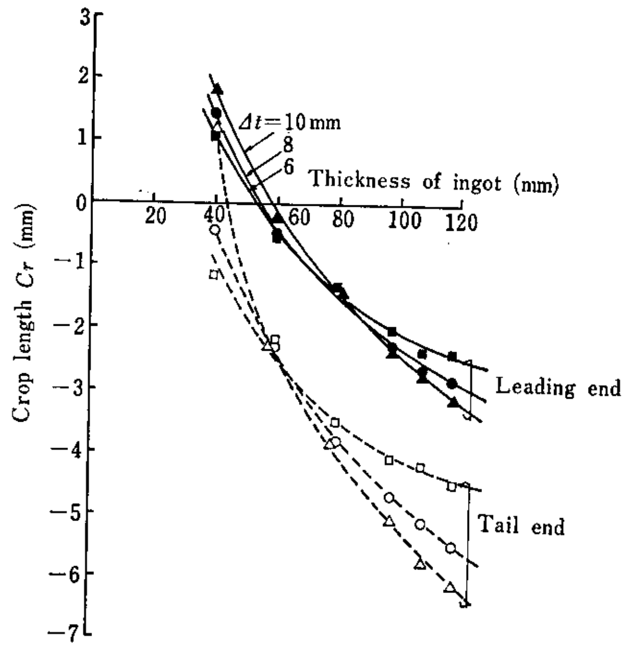


Fig. 6 Effects of ingot thickness and rolling direction on the crop lengths at the width-center of the leading and the tail ends of slab

3 "Bite and Back" Rolling Method

From the experimental studies mentioned in Chapter 2, the following major remedial measures for slab rectangularity have been obtained:

(1) In view of the fact that crop length in the thickness direction at the center of the width direction becomes nil or a convex crop is formed, when ingot having a thickness of 59 mm (1/10 scale of actual measurement of 590 mm) or below is subjected to ultra-high reduction rolling, reduction rolling of the leading and tail ends down is performed to about 59 mm at a stroke in the thickness direction (at short sides) by using horizontal rolls, at the initial period of rolling.
(2) From the fact that crop length on the leading end becomes shorter than on the tail end, it is so arranged that regions involved in formation of crops on both ends of an ingot will always come to the leading end in the rolling reduction.
(3) From the fact that crop length becomes shorter as ingot thickness decreases, the width rolling at the initial period in the conventional rolling method is used as thickness rolling.

The "Bite and Back" rolling techniques have been developed so that the above results can be effectively achieved. The details of this rolling method is given below.

3.1 Rolling Method

Fig. 7 shows how "Bite and Back" rolling is performed. In this figure, deformation only at one side is explained. First, set the rolls at a desired gap (T_1) as shown in (a) and the leading portion of an ingot, then stop and reverse roll rotation. Next, feed back the material to make recessed portions. Then, shift rolls and feed the material without reduction as shown in (b). Set rolls at a proper gap (T_2) and roll the portion not yet rolled in the reverse direction as shown in (c) so that the hatched areas ηA_1, ηA_3, A_4, and A_5, which may develop into a crop at the tail end, are absorbed at recess A_2. The above is the fundamentals of the "Bite and Back" rolling. It is intended, by properly executing this rolling method in both thickness and width directions, to prevent the occurrence of crops, improve slab rectangularity after rolling and minimize overlap rejection, thereby achieving enhanced yield.

Fig. 8 shows the principles of decreasing the length of the crop formed in the thickness direction as an application example of the "Bite and Back" rolling method.

(1) Light reduction rolling in the width and thickness directions for taper removal.
(2) As shown in (b), reduce the ingot thickness at both ends at a stroke with several passes of "Bite and Back" rolling until the thickness of the recessed portion becomes 0.65 times the original ingot thickness (T_0), so that the crop that occurs in the thickness direction near the center of the width direction will be convex-shaped or eliminated.
(3) As a result of rolling in (2), both sides in the width direction form concave crops which can be rectified by proper "Bite and Back" rolling in the width direction.
(4) Then, roll the portion not yet rolled in the thickness and width directions, and cause the recesses

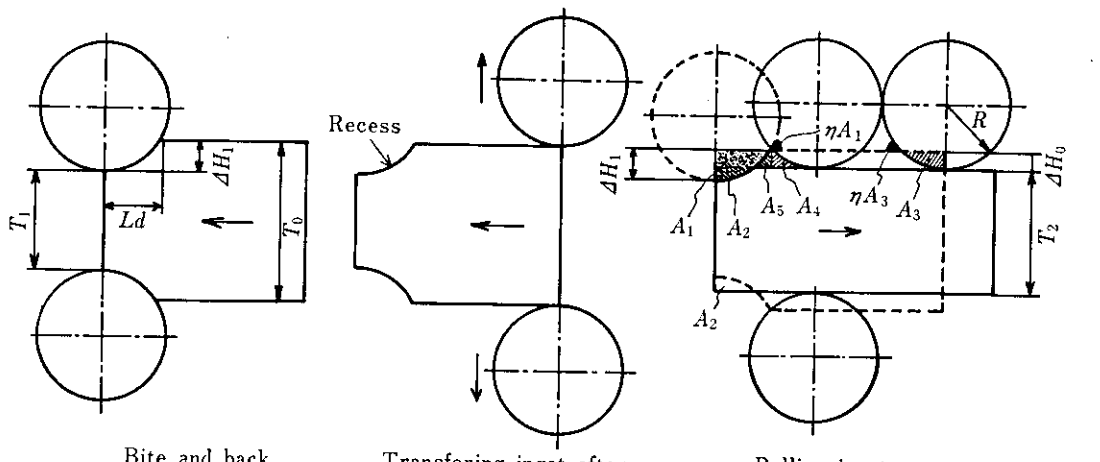
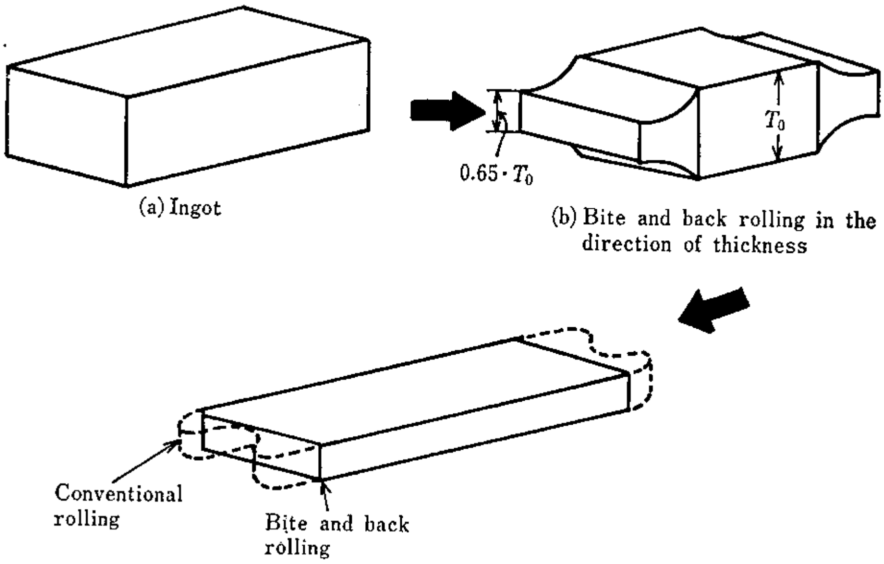


Fig. 7 Explanation of bite and back rolling process



(c) Plan view pattern of slab

Fig. 8 Bite and back rolling in the thickness direction

at both ends to absorb metal which is considered to grow into a crop when the slab passes through the tail end, thereby preventing non-uniform deformation at both the leading and tail ends, until proper slab rectangularity is obtained as shown in (c).

Prior to conducting experiments, proper dimensions of the recess are considered below from the geometrical point of view. Metal which is going to flow into the recess by rolling the un-rolled portion from the reverse direction is considered in terms of area (mm²) to be ηA_1, ηA_3, A_4, and A_5; and in order for the recess which has been formed into area A_2 beforehand to absorb all the quantities of the above-mentioned metal, the following eq. (1) must be satisfied:

$$A_2 = A_4 + A_5 + \eta(A_1 + A_3) \cdots\cdots\cdots\cdots (1)$$

These areas can be obtained geometrically and approximated by the following eqs. (2) to (6):

$$A_1 \fallingdotseq \frac{2}{3}\Delta H_1\sqrt{2R\cdot\Delta H_1} \quad \cdots\cdots\cdots\cdots (2)$$

$$A_2 \fallingdotseq \frac{2}{3}(\Delta H_1 - \Delta H_0)\sqrt{2R(\Delta H_1 - \Delta H_0)} \quad \cdots\cdots\cdots\cdots (3)$$

$$A_3 \fallingdotseq \frac{2}{3}\Delta H_0\sqrt{2R\cdot\Delta H_0} \cdots\cdots\cdots\cdots (4)$$

$$A_4 \fallingdotseq \frac{1}{3}\Delta H_0\sqrt{2R\cdot\Delta H_0} \cdots\cdots\cdots\cdots (5)$$

$$A_5 \fallingdotseq \frac{1}{3}\Delta H_1\sqrt{2R\cdot\Delta H_1} + \frac{2}{3}(\Delta H_1 - \Delta H_0) \times \sqrt{2R(\Delta H_1 - \Delta H_0)} - (\Delta H_1 - \Delta H_0) \times \sqrt{2R\cdot\Delta H_1} \cdots (6)$$

A_1: Total area of recesses formed by "Bite and Back" rolling (mm²)

A_2: Area which absorbs metal flowing into the recess by rolling unrolled portion from the reverse direction (mm²)

A_3: Area which is subjected to initial deformation when unrolled portion is reduced from the reverse direction (mm²)

$A_4, A_5, \eta A_1, \eta A_2$: Areas in the recess into which metal flows by rolling the unrolled portion from the reverse direction (mm²)

η: Correction factor

ΔH_0: Draft during reverse direction rolling (to be determined by the capacity of rolling mill and actual dimension 30 to 60 mm) (mm)

ΔH_1: Adequate draft during "Bite and Back" rolling (mm)

R: Roll radius (mm)

By substituting eqs. (2) to (6) for eq. (1), the following eq. (7) is obtained.

$$2(1-\eta)\Delta H_1^{3/2} - 3\Delta H_0\cdot\Delta H_1^{1/2} - (1+2\eta)\times\Delta H_0^{3/2} = 0 \quad \cdots\cdots\cdots\cdots(7)$$

Here, numerical calculation is made under conditions of no swelling or no sagging of metal, that is, $\eta = 0$, and draft at the proper recess, ΔH_0, is approximately obtained as shown in the following eq. **(8)**:

$$\Delta H_1 \doteqdot 1.866\Delta H_0 \quad \cdots\cdots\cdots\cdots(8)$$

In order to prove the validity of eq. **(8)** by model experiments of steel, "Bite and Back" rolling is performed by using ΔH_1 obtained by eq. **(8)**. The result shows that the recess is not completely filled up with metal. When the value of ΔH_1 is changed to obtain the conditions under which the recess will be completely filled up with metal and η is obtained from eq. **(7)**, a figure of -0.475 is obtained. This figure means that metal during rolling does not swell but sags at the roll-stop position. At this time, eq. **(8)** is modified into the following eq. **(9)**:

$$\Delta H_1 \doteqdot 1.034\,\Delta H_0 \quad \cdots\cdots\cdots\cdots(9)$$

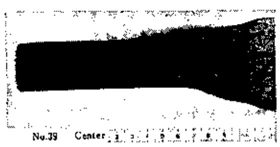
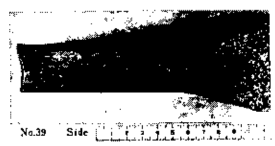
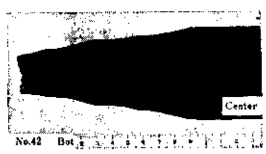
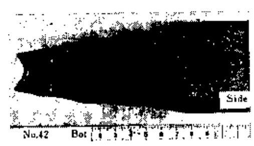
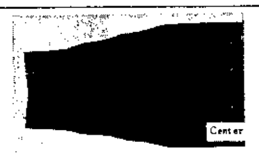
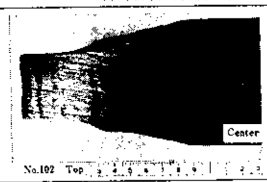
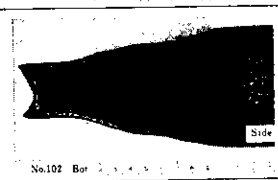
Proper biting-stop length, Ld, is obtained by eq. **(10)**:

$$Ld = (2R\cdot\Delta H_1)^{1/2} \quad \cdots\cdots\cdots\cdots(10)$$

On the basis of this calculation result, succeeding model experiments and mill experiments were conducted. Incidentally the proper recess dimension for actual-mill experiments was obtained as follows: Assuming that $R = 610$ mm and rolling reduction from the reverse direction $\Delta H_0 = 60$ mm, proper rolling reduction at the recess $\Delta H_1 = 62$ mm, and proper biting-stop length $Ld = 275$ mm.

Table 2 Rolling conditions

Ingot size (mm) Thickness	Ingot size (mm) Width	Draft/pass (mm)	Number of bite and back rolling	Final thickness (mm)
60	118	15	2	30
		5.5	5	32.5
80	118	10	3	50
		10	4	40

(a) $t_0 \times W_0$	(b)	(c)	Location of width direction: Center	Location of width direction: Side
60 × 118	15 (30)	2		
	5.5 (32)	5		
80 × 118	10 (50)	3		
	10 (40)	4		

(a) Ingot size (b) Draft and finish thickness (mm)
(c) Numbers of bite and back rolling

Photo. 1 Longitudinal sections of the bite and back rolled slabs

3.2 Confirmation Experiments by Using a Model

Prior to actual mill rolling, model experiments were conducted for confirming the effectiveness of "Bite and Back" rolling.

As the first step, efforts were made to clarify the effects of draft per pass and the number of "Bite and Back" rollings exercised upon the slab end rectangularity obtained by "Bite and Back" rolling in the thickness direction. The rolling conditions are shown in **Table 2**.

Photo. 1 shows appearance of crops formed at the center of the width direction and at side edges. As can be seen from this photo., a small number of large rolling reduction is more preferable to a large number of small drafts in eliminating the crop length at the center of the width direction, when ingot thickness of 60 mm is to be reduced by rolling into a slab of 30 mm in thickness; and the crop length at side edges also seems to become shorter.

By considering rolling of actual steel ingot, 80 mm-thick ingot was given 3 and 4 times each of "Bite and Back" rolling with a decrement of 10 mm, and rolled into 50 and 40 mm in thickness. It can be found that rolling down to 40 mm in thickness gives a better crop shape at the center in the width direction and gives a nearly rectangular slab than rolling down to 50 mm in thickness. Crop shapes on the width sides will give concave shapes under all conditions. These concave crops can be corrected if "Bite and Back" rolling in the width direction is properly incorporated in the "Bite and Back" rolling in the thickness direction.

As the second step, a rolling schedule was prepared which embodied the idea of the above-mentioned proper reduction method, and experiments were conducted to confirm the validity of the "Bite and Back" rolling method. For comparison, the one-direction rolling method and the conventional rolling method were also used. Here, model ingot in the rectangular shape with 80 (t) × 118 (w) × 250 (ℓ) mm was rolled into a rectangular slab 36 mm thick and 97 mm wide. Slab thickness and width were limited by the dimensions of auxiliary facilities for the experimental rolling (reheating furnace, vertical rolls and table rollers). The results are shown in **Photo. 2**. The photo. indicates that compared with the conventional rolling method, the "Bite and Back" rolling method largely removes the fish tail formed in the width direction and the overlap formed in the thickness direction, thereby experimentally proving that higher yield can be obtained. The sslab yield obtained by the "Bite and Back" rolling method is 2.3% more than by the conventional rolling method.

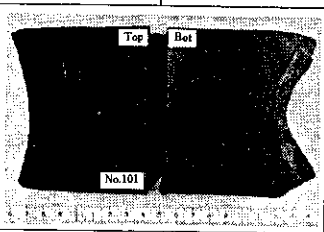
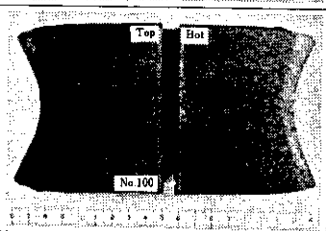
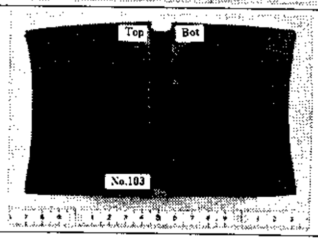
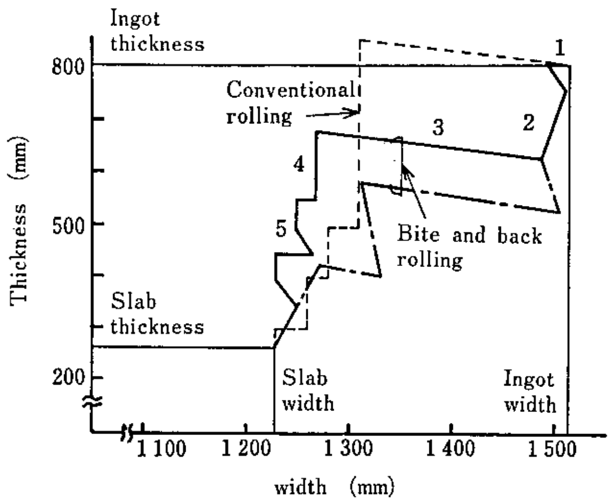
Rolling method	Crop shape: Leading end / Tail end	Overlap	Yield of slab (%)
One way rolling		Center  Side 	95.8
Reverse rolling		Center  Side 	95.6
Bite and back rolling		Center  Side 	97.9

Photo. 2 Comparison of crop shapes in one direction, reverse, and bite and back rollings of slabs

3.3 Mill Experiment

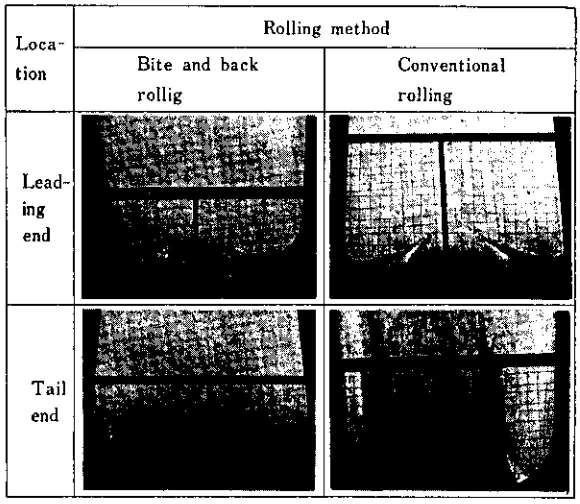
For comparative studies on crop shapes at the leading and tail ends and on width accuracy, an experiment was conducted by rolling 6 pieces of 21 t capped steel ingot by "Bite and Back" rolling and conventional rolling into 3 levels of the total width rolling reductions of 136, 286, 416 mm, respectively, while maintaining the thickness draft at a more or less constant value. **Fig. 9** shows an example of rolling schedule used in this mill experiment. In this figure the case of the total-width draft of 286 mm is indicated. **Photo. 3** shows the rectangularity of the slab resulting from the rolling schedule of **Fig. 9**. **Photo. 3** proves that compared with conventional rolling, "Bite and Back" rolling gives a much smaller metal flow from the width direction end and greatly improves slab rectangularity. Slab yield given by "Bite and Back" rolling shows a remarkable improvement of 3.0 to 3.8% over that by conventional rolling at any reduction ratio of width to



Stage	Operation	Description
1	Initial reduction	Min. reduction for removal of primary scales and elimination of ingot taper in directions of width and thickness
2	Bite and back rolling in direction of thickness	Formation of recesses at leading and tail ends of ingot, followed by effective metal flow to recesses
3	Bite and back rolling in direction of width	Formation of recess at tail end of ingot, followed by effective metal flow to recess
4	Bite and back rolling in direction of thickness	Formation of recesses at leading and tail ends Absorption of dog bone formed at stage 3
5	Corrcetion of form	Final light reduction by effective metal flow to remaining recess

Ingot : 21 t capped steel

Fig. 9 Examples of rolling schedule to study changes in crop shapes and width accuracy by actual mill



Full-width reduction:286 mm

Photo. 3 Comparison of rolling methods on crop shapes

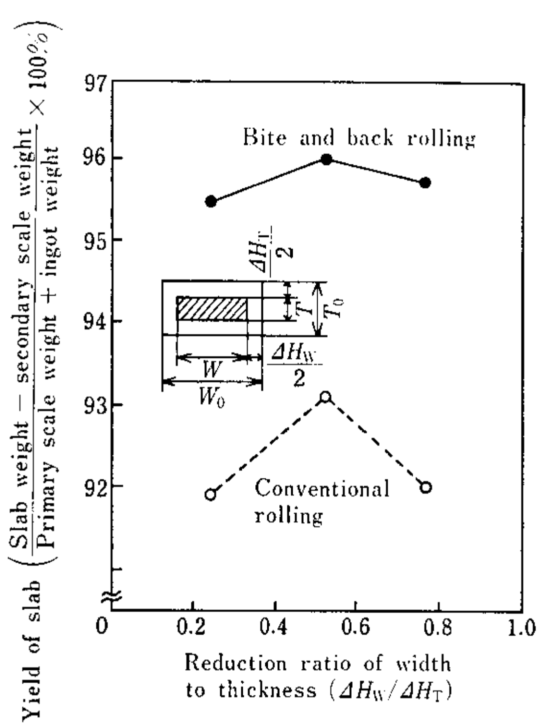


Fig. 10 Relation between rolling methods and yield of slab (21 t capped steel ingot)

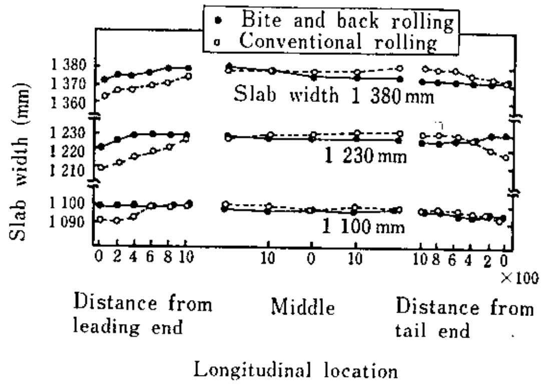
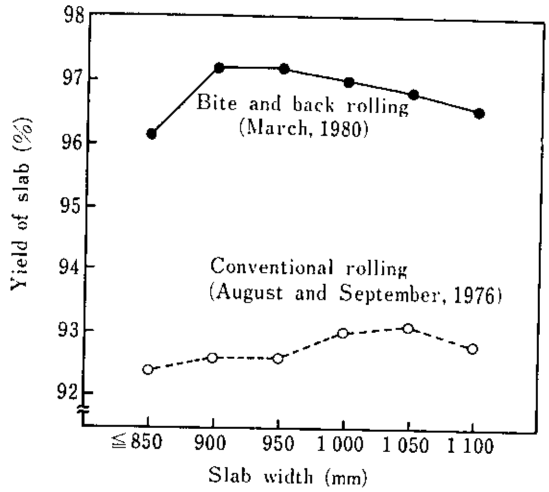


Fig. 11 Comparison of longitudinal distributions of slab width in bite and back rolling and conventional rolling



(Ingot size : Upper part 1 222 × 810
Lower part 1 258 × 910)

Fig. 12 Actual yield of 18 t capped steel ingots

thickness, as shown in **Fig. 10.** Also the width accuracy of the slab by "Bite and Back" rolling shows an improvement over the conventional rolling in any slab width sides shown in **Fig. 11.** As for longitudinal distribution of slab widths, the leading edge narrows in both the rolling methods, but the conventional rolling method gives a more conspicuous taper. At the tail end, conventional rolling gives a tapered end in the same way as at the leading end, but "Bite and Back" rolling gives no width sag.

As mentioned above, the advantage of "Bite and Back" rolling that slab rectangularity is greatly improved to make large contribution to the improvement of slab yield has been proved by model and actual mill experiments.

4 Outcome

Immediately upon developing, the "Bite and Back" rolling techniques were incorporated into the standard manufacturing process at No. 2 Slabbing Mill of Chiba Works of Kawasaki Steel. **Fig. 12** shows an example of slab yield record by width in respect of 18 t capped steel ingot, together with a comparison with the conventional rolling method. Slab yield obtained by "Bite and Back" rolling showed about 4% improvement over conventional rolling. As a result, the world record of 95.9% of slab yield for capped steel was achieved by Kawasaki Steel in March, 1980. The decrease in rolling efficiency by performing "Bite and Back" rolling is only about 10%, and even discounting increases in unit consumption of electric power, water and the like, a great reduction in cost has been achieved by "Bite and Back" rolling. The same results are also being obtained at Mizushima Works of Kawasaki Steel.

5 Conclusion

With the aim of minimizing crop losses that occur in slabbing operation and improving slab yield, examinations were made on basic deformation behavior of crops by means of model experiments using steel. On the basis of these experimental results, a new slab rolling method ("Bite and Back" rolling) was developed to greatly reduce crop losses without an undue decrease in productivity and with existing facilities; and slab rectangularity after rolling and a decrease in overlap length were successfully achieved, thereby greatly improving slab yield. These techniques can be applied not only to slabbing but also to other fields and are expected to grow more popular in the coming years.

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