Abridged version

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Deformation of Slab under Heavy Reduction of Width by Sizing Press

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Deformation of Slab under Heavy Reduction of Width by Sizing Press*



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1 Introduction

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The hot rolling mill at Mizushima Works is equipped with the world's first successive press-type sizing device. This equipment, called the sizing press, was developed to simplify the varied widths of CC slabs required for supply to the hot-rolling mill and to ensure synchronized operation between the continuous casting and hotrolling processes. The sizing press has been operating smoothly since its start-up in 1987.^{1,2)}

Width reduction by vertical rolls has generally been adopted to reduce the slab width. In this method, the width return during rough rolling is great and there are

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problems such as inadequate width at the leading and tail ends and increased crop losses.³⁾ In developing the sizing press method, examinations were made into the optimum anvil shape and load during pressing using the rigid-plastic finite element method. This study included a comparison of slab deformation with the conventional vertical roll method. The results made the advantages of the sizing press method clear.⁴⁾

The authors conducted 1/10-scale model experiments and experiments on an actual mill. This report mainly describes the results of the investigation into slab deformation behavior. For the steady portion of the slab, a model equation was developed for predicting the amount of width return in rough rolling after pressing. For the nonsteady portions, slab deformation was categorized using an upper bound technique analysis and model experiments were conducted to determine a method of minimizing crop losses.

2 Method of Press Forming

The cross section of the slab is schematically shown in **Fig.** 1(a). The plan views of the leading and tail ends of the slab upon preforming by a press are shown in

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Tongue Fish tail A B A B B σ_{CE} Crop area σ_{CE} B (c) Definition of parameter of crop figure

Fig. 1 Definition of parameters

Fig. 1(b). The definition of crops is shown in Fig. 1(c). Incidentally, various symbols which will be used in this report are defined as follows:

- W_0 : Slab width before pressing (mm)
- W_1 : Slab width just after pressing (mm)
- $H_{\rm C}$: Thickness at the slab width midpoint immediately after pressing (mm)
- $H_{\rm E}$: Thickness at the edges of stab width immediately after pressing (mm)
- S: Cross sectional area of the slab immediately after pressing (mm^2)
- H_2 : Slab thickness when horizontal rolling is conducted after pressing (mm)
- δ_{CE} : Distance between the steady-width portion and the middle of crop end (mm)
- H_0 : Slab thickness before pressing (mm)
- ΔW : $W_0 W_1$ (mm)
- H_{max} : Maximum thickness of the dog-bone of slab immediately after pressing
 - W_P: Dog-bone peak interval immediately after pressing (mm)
 - W_2 : Slab width when horizontal rolling is conducted after pressing (mm)
- ΔW_2 : $W_2 W_1$ (mm)
- l_{a} , t_{a} : Length of the sides of leading and tail slab ends, respectively, in contact with the parallel portion of the anvil

The plan view of the sizing press is shown in Fig. 2. After a speed reduction, the rotary motion imparted by the main motor is converted into a reciprocating motion of the inner blocks, which are directly connect-



Fig. 2 Outline of sizing press

ed to the anvils; this reciprocating motion is of a constant frequency. While the anvils are opening, the slab is transferred and stopped by the pinch rolls, and the slab width is reduced to a specified anvil gap W_1 . The slab width is reduced successively by repeating this operation over the slab length. The leading and tail ends of the slab are preformed to minimize crop losses, avoid width shortages at the leading and tail ends and prevent buckling.5,6) In this preforming, the slab width is reduced by a specific amount by setting the contact lengths l_a and t_a between the sides of leading and tail ends of the slab and the parallel portion of the anvil to specified values. After the leading end of the slab is preformed, the slab is pressed in the direction of the tail end in successive steps to a specified position. The slab is then transferred forward for the purpose of preforming tail end. After tail end is preformed, the slab is transferred back to the previous position and is pressed to the tail end. In another method, the slab is pressed in one direction from the leading to the tail end. In this case, preforming of the tail end is not conducted. The selection of method is determined on the basis of pressing conditions and slab sizes.

As shown in Fig. 2, the anvils are of a trapezoidal shape, with fixed angles at the entry and exit portions and has a parallel portion between these angled surfaces.

3 Deformation of Steady Portion of Slab

This section describes the deformation of the steady portion of the slab. In the model experiments, a 1/10scale press and roughing mill were used and hot slabs were pressed and roughed. **Tables 1** and **2** give the experimental conditions as converted into actual dimensions. An electric furnace internally sealed with argon gas was used to the sample heat slabs. The pressing

Table 1 Experimental conditions (1/10 model)

Specification	Amplitude		80 mm
	Anvil frequency		0.5 Hz
	Entrance angle of anvil		13 degree
	Exit angle of anvil		15 degree
	Parallel length of anvil		510 mm
Condition	Material		SS41
	Heating temperature		1 150°C
	Slab thickness	(H_0)	220 mm
	Slab width	(W_0)	1 000~1 900 mm
	Quantity of width reduction	(ΔW)	100~300 mm
	Pre-press length at leading end	(l_{\star})	0~400 mm
	Pre-press length at tail end	(t_s)	0, 300 mm
	Pre-press reduction at tail end	$(\Delta W_{\rm F})$	0∼300 mm
	1		1

Table 2 Pass schedule of roughing mill*¹ (1/10 model)

Pass	R1	R2	R3	R4	R5	R6
Thickness (mm)	220	160	120	90	60	40

*1 Diameter of horizontal roll: 1 460 mm¢

Diameter of edger roll: 1 200 mmø

conditions with actual equipment will be explained hereafter as required.

3.1 Cross Sectional Shape of Slab after Pressing

Accurate prediction of the cross sectional shape of the slab after pressing is very important for ensuring a proper pass line during pressing and for estimating slab thickness limitations on entry into the rolls during the subsequent rough rolling and the amount of width return in rough rolling.

Measured results are shown in Fig. 3. The cross section of the slab was measured at the leading and tail ends and at the lengthwise midpoint with a contact linear encoder. The leading end of the slab shows a single-bulge deformation, in which the thickness at midwidth is large, while the steady portion and tail end show a double-bulge deformation. The shape of the tail end is changed by the preforming, as will be described later. As can be seen in Fig. 3, the thickness peaks are highest in the steady portion and seriously affect the next process when the slab comes into rough rolling. The curves in the figure were obtained by approximating observed values by even degrees of the transverse coordinates X with the middle of the width serving as the axis of symmetry, as given by the following equation, and the coefficients $\alpha_1 \sim \alpha_4$ were found by multiple regression.

$$H = \alpha_1 X^6 + \alpha_2 X^4 + \alpha_3 X^2 + \alpha_4 \quad \cdots \quad \cdots \quad (1)$$

As shown in Fig. 3, Eq. (1) expresses observed values



Fig. 3 Thickness distributions of cross section of slabs after press and regression curves ($H_0 = 220 \text{ mm}, \Delta W = 300 \text{ mm}$)

with high accuracy. This equation makes it possible to smooth abnormal observed values (scale exfoliation from the material surface) and correct for asymmetrical cross profiles in the width direction.

The maximum dog-bone thickness H_{max} , peak interval W_{P} , edge thickness H_{E} , and center thickness H_{C} found with Eq. (1) were used in developing the equation for predicting the width return described in the following section.

3.2 Predictive Equation for Width Return

After width reduction by pressing, the slab is horizontally rolled to thickness of H_2 by rough rolling, as shown in Fig. 1. H_2 is generally equal to the slab thickness before pressing H_0 . However, cases where H_2 is not equal to H_0 were also considered. A model equation for predicting W_2 with high accuracy is developed using H_0 , W_0 , ΔW and H_2 as known values.

The procedure for developing the predictive equation for width return is shown in **Fig. 4**. The cross section of the slab after pressing obtained in Eq. (1) is approximated by a polygon as shown in Fig. 4 and the cross sectional area S is found. If it is assumed that no metal flow occurs in the longitudinal direction, the amount of width return after rough rolling ΔW_2 is found by the following equation:

S can be found by integrating Eq. (1) in the width direction. However, S is calculated geometrically by the following equation when the cross profile is approximat-

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Fig. 4 Configuration of prediction equation of width spread



Fig. 5 Prediction of slab sectional area by poligonal approximation



Fig. 6 Relationship between actual width spread and calculated value by Eq. (2)



Fig. 7 Relationship between actual width spread and calculated value by Eq. (4)

ed by a polygon:

$$S = \frac{1}{4} \{ W_1 (2H_E + 4H_{max} - 2H_C) - W_P (H_E + 3H_{max} - 4H_C) \} \dots (3)$$

Results of a comparison of the integral values of Eq. (1) and S found by Eq. (3) are shown in Fig. 5. Agreement between the two types of values is very good irrespective of slab size and pressing condition. This means that S can be found if $H_{\rm E}$, $H_{\rm max}$, $H_{\rm C}$ and $W_{\rm P}$ are expressed by pressing conditions. $H_{\rm max}$ not only is used for finding S, but also gives important information on practical operation.

Figure 4 shows ΔW_2 representing the amount of width return obtained by the rough rolling of machined slabs in which H_{max} and W_P/W_1 are systematically varied. When H_{max} is constant, ΔW_2 decreases with decreasing W_P/W_1 . It is apparent that ΔW_2 is negative when $W_P/W_1 = 0$ (single-bulge deformation). Because W_P/W_1 greatly affects the longitudinal and transverse distribution of metal flow during horizontal rolling, Eq. (4) was obtained by correcting Eq. (2):

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where a_0 is a proportionality constant.

The relationship between ΔW_2 as observed and ΔW_2 as calculated by Eqs. (2) and (4) using S found by Eq. (3) is shown in **Fig. 6** and 7, respectively. In Eq. (4), a_0 was taken as 1. Although good correlation is observed in both cases, irrespective of pressing condition and slab size, the correlation with Eq. (4) corrected by W_P/W_1 is stronger. Eq. (4) is based on $H_2 = H_0$; cases where $H_2 \neq H_0$ are described below.

(1)
$$H_2 < H_0$$

In this case, the slab is rolled to a thickness smaller than the thickness before pressing H_0 by the first horizontal rolling pass on the roughing mill. A draft of $H_0 - H_2$ is added after the slab thickness is reduced to H_0 in the roll gap. Therefore, the amount of width spread due to the draft of $H_0 - H_2$ is denoted by ΔW_d and added to Eq. (4). To express ΔW_d , the following equation based on J. G. Beese's equation⁷, which provides relatively high accuracy, was used:

where a_1 to a_3 are constants and R is the radius of the roughing mill work-rolls.

(2) $H_2 > H_0$

The dog-bone is not completely flattened in this case. Rolling may be conducted under these conditions due to the limited rolling force of the rolling mill. In this case, ΔW_2 calculated by Eq. (4) is interpolated as shown in the following equation so that $\Delta W_2 = 0$ when $H_2 = H_{\text{max}}$ (rough rolling is not conducted) and $\Delta W_2 = \Delta W_{2, \text{Eq. (4)}}$ when $H_2 = H_0$.

$$\Delta W_2 = \Delta W_{2, Eq. (4)} \cdot \frac{H_{\max} - H_2}{H_{\max} - H_0} \cdots \cdots \cdots \cdots \cdots (6)$$

The above comprises the basic content of the predictive equation for width return.

As mentioned above, if the parameters of the cross section of the slab after pressing $H_{\rm E}$, $H_{\rm max}$, $H_{\rm C}$ and $W_{\rm P}$ can be expressed by pressing conditions, the amount of width return ΔW_2 can be predicted by substituting these parameters in the basic equations.

Effects of the amount of width reduction ΔW on these parameters were investigated in model experiments. The results are shown in **Fig. 8**. From Fig. 8, the following relationship is approximately derived:

$$H_{\rm E} \doteq H_0 \left(b_1 \cdot \frac{\Delta W}{W_0} + 1 \right)$$

$$H_{\rm max} \doteq H_0 \left(b_2 \cdot \frac{\Delta W}{W_0} + 1 \right)$$

$$H_{\rm C} \doteq H_0 \left(b_3 \cdot \frac{\Delta W}{W_0} + 1 \right)$$

$$W_{\rm P} \doteq W_0 \left(b_4 \cdot \frac{\Delta W}{H_0} + b_5 \right)$$
(7)

where b_1 to b_5 are constants. ΔW_2 is found by combining Eqs. (7), (3) and (4).

When independent variables having slight effect are removed by multiple regression by changing the population variously and Eq. (5) is taken into consideration, the amount of width return ΔW_2 due to rough rolling after pressing is expressed by the following equation:

$$\begin{aligned}
dW_2 &= C_1 \Delta W^{n_1} + C_2 \cdot \frac{\Delta W^{n_2} W_1}{H_0} + C_3 \cdot \frac{\Delta W^{n_3}}{H_0^2 W_1} \\
&+ C_4 \cdot \frac{\Delta W^{n_4}}{H_0^2} + C_5 \cdot \frac{\Delta W^{n_5}}{H_0 W_1} + C_6 \cdot \frac{\Delta W^{n_6}}{H_0} \\
&+ C_7 W_0 \cdot \left\{ \left(\frac{H_0}{H_2} \right)^{\beta} - 1 \right\} \dots \dots \dots (8)
\end{aligned}$$



Fig. 8 Effect of width reduction on parameters which constitute a porigon of slab cross section

where C_1 to C_7 are constants and n_1 to n_6 are positive integers.

Equation (8) is applied to the case of $H_2 \leq H_0$. In the case of $H_2 > H_0$, ΔW_2 , with the seventh term on the right side of Eq. (8) taken as zero, is used in place of $\Delta W_{2, Eq.(4)}$ in Eq. (6).

 ΔW_2 is divided by ΔW and the efficiency of width reduction η is defined by the following equation:

$$\eta = 1 - \frac{\Delta W_2}{\Delta W} \dots (9)$$

The smaller ΔW_2 , the higher η , i.e., the more efficiently width reduction will be conducted.

Width reduction was conducted by pressing on an actual mill under the conditions given in **Table 3** and rough rolling was then conducted. Figure 9 gives a comparison between observed η after one rough rolling pass and η calculated by Eq. (9). The slab width after

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Table 3 Conditions	of	actual	press	test
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Specification	Amplitude		100 mm	
	Anvil frequency		0.7 Hz	
	Entrance angle of a	nvil	13 degree	
	Exit angle of anvil		19 degree	
	Parallel length of anvil		450 mm	
Condition	Material		Ultra low carbon~high strength steel	
	Slab thickness	(H_0)	200~240 mm	
	Slab width	(W_0)	930~1 990 mm	
	Width reduction	(ΔW)	34~360 mm	
	R1 roll gap	(H_2)	173~239 mm	
	1		1	



Fig. 9 Comparison of efficiency of width reduction, η , between actual results and calculated results (420 slabs)

rough rolling was measured using a laser width meter installed behind the first roughing stand. (This data is not the data used for determining the coefficients of Eq. (8).) Both observed and calculated values show high η -values, and there is relatively good agreement between the two. Low η -values were obtained at $H_2 < H_0$, i.e., when the slab was reduced by rough rolling to a thickness below the initial slab thickness. This is due to an increase in the amount of width spread described by the seventh term on the right side of Eq. (8). The above-mentioned equations are used in the process computer for sizing press setup at the actual mill.

4 Deformation of Nonsteady Portions of Slab

Parameters for the preforming of the leading and tail ends of the slab are the reduction and contact length in preforming. The former is closely related to the width accuracy of the leading and tail ends⁶⁾, and the latter has a great effect on the plane shape of these ends.

This section describes the results of a deformation analysis of the leading and tail ends of the slab by the upper bound technique, changes in the crop shape observed in model experiments, and results of an examination of a method of minimizing crop losses.

4.1 Analysis by Upper Bound Technique

To clarify the effect of pressing conditions on the nonsteady portions of the slab, an analysis by the upper bound technique was conducted for supposed planestrain forging using anvils with flat surfaces.

If the slab is divided into polygonal rigid elements and the plastic deformation of the whole is supposed to occur only as a result of the relative slip between the elements, plastic work E is given by the following equation.⁸⁾

where K is the shear yield stress of the slab, F is the working load, V is the anvil velocity, ΔV is the tangential velocity discontinuity between the elements, and l is the length of the line of velocity discontinuity.

In this analysis, the five deformation modes shown in Fig. 10 were considered on the basis of the parameters of slab width W_0 , anvil length L, and distance between anvil edge and slab edge d (a negative value shows a case where one edge of the anvil is projecting from the slab edge). Hodographs of the respective modes are also shown in the figure. Mode 1 represents a simplified model of a slip-line field for compression between parallel punch surfaces⁹; deformation does not occur at the slab edges. In modes 2 and 4, the corners of the slab move outward (to the right in the figure), forming a fishtail shape. Conversely, a tongue shape is formed in



Fig. 10 Classification of slab deformation by upper bound technique

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modes 3 and 5.

In mode 1, l and ΔV between the elements (1) and (2) and (between (1) and (3) are given as follows:

Substituting Eqs. (11) and (12) into Eq. (10), the following is obtained:

If K and V are constant, the minimization of E is equivalent to that of the working load F/K given by the following equation:

Similarly, the working loads of modes 2 to 5 are expressed as follows:

$$\left(\frac{F}{K}\right)_{\text{modes 2,3}} = \frac{(W_0/2 - p)^2 + (L/2)^2}{W_0/2 - p} \left\{1 + \frac{|\cos(\xi + \delta)|}{\cos(\xi - \delta)} + \frac{\sin(2\delta)}{\cos(\xi - \delta)}\sqrt{\frac{(p - q)^2 + (L/2 + d)^2}{(W_0/2 - p)^2 + (L/2)^2}}\right\} \cdots (15)$$

where $\delta = \cos^{-1} \{ (W_0/2 - p)/\sqrt{(W_0/2 - p)^2 + (L/2)^2} \}$ $\xi = \tan^{-1} \{ (p - q)/(L/2 + d) \}$

Here, p and q are parameters for minimizing the working load in each mode. The working load was minimized by the direct search method in Eq. (15) and by the partial differential of q in Eq. (16).

Minimum values of F/K in each deformation mode were determined by systematically changing the anvil position d, anvil length L, and slab width W_0 . The deformation mode with the lowest value of F/K (a mode that occurs under the given geometrical conditions) was then selected. The result is shown in Fig. 11. If d < 0, mode 4 (fishtail) occurs when L is small, while mode 5 (tongue) occurs when L is large. If d > 0, deformation changes with increasing L from mode 2 (fishtail) to mode 3 (tongue) and then to mode 1 (no deformation of the ends).

4.2 Effect of Preforming Conditions on Sheet Bar

From the preceding discussion, it is apparent that the shapes of the leading and tail ends of slab after pressing can be predicted. After pressing, the slab undergoes several passes of horizontal rolling and width reduction by edging in the rough rolling process; the crops at the leading and tail ends are then cut off before the material



Fig, 11 Relationship between deformation modes and geometrical conditions



Fig. 12 Relationship between mean crop length of sheet bar and parameter δ_{CE} (Actual press)

enters the finishing mill. The length of the crops, which must be cut off as scrap, greatly affects product yield, therefore the minimization of crop length is a key point.

The relationship between the crop shape and mean crop length of sheet bar after rough rolling on an actual mill is shown in Fig. 12. The plotted data was obtained by image processing data with a CCD camera at the entry side of the crop shear ahead of the finishing mill. The abscissa is the value of $\delta_{\rm CE}$, which represents the distance from the imaginative boundary line A-B (between the steady-width portion and the crop portion) to the end of crop width center, as shown in Fig. 1. The positive figures indicate a fishtail, and the negative a tongue. The ordinate is the mean crop length obtained by dividing the crop area by the crop width. Although the data includes conditions under which width reduction was conducted by vertical rolls (vertical scale breaker) in addition to that performed with the press, it is apparent that a V shape with a minimum crop length is shown at $\delta_{CE} = 0$ regardless of other conditions. In

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Fig. 13 Effect of pre-press condition at slab leading end on parameter δ_{CE} (1/10 model)

other words, crop losses are minimized by ensuring that $\delta_{CE} = 0$.

Next, the 1/10-scale model experiments are described. Preforming and pressing were carried out under the conditions given in Table 1, and rough rolling was then conducted under the conditions shown in Table 2. Width reduction during rough rolling was performed using vertical rolls (edger). The vertical roll gap was so set as to obtain the slab width after pressing, W_1 .

Figure 13 shows the effect of the contact length of the anvil at the leading slab end I_a on the shape of the leading end of sheet bar δ_{CE} after six rough rolling passes. The same reduction in preforming was applied as with the steady portion. This $\delta_{\rm CE}$ decreases with increasing I_a ; that is, the longer I_a , the more readily the leading end will deform into the tongue shape. This tendency does not depend on the slab width W_0 or amount of width reduction ΔW . However, the smaller W_0 , the more readily a tongue will form. Further, the larger ΔW , the greater the sensitivity to I_a encouraging the formation of a tongue. This finding agrees with the analytical result that the deformation mode changes from fishtail to tongue when the ratio of anvil length to slab width L/W_0 shown in Fig. 11 increases, and suggests that the plane shape after pressing is apt to remain after rough rolling.

For the tail end, pressing is conducted again from the leading end after preforming. Besides the contact length t_a , therefore, the reduction in preforming ΔW_P can be changed when it is within the amount of width reduc-

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Fig. 14 Effect of pre-press condition at slab tail end on parameter δ_{CE} (1/10 model)

tion ΔW of the steady portion.

The effect of ΔW_P on δ_{CE} at the tail end of the sheet bar is shown in Fig. 14. As with the leading end, the smaller the slab width W_0 and the longer the contact length of anvil at the tail end, t_a , the less δ_{CE} will be. However, the value of $|\delta_{CE}|$ is larger at the tail end than at the leading end; this suggests that crop losses will be large.

To minimize crop losses, $|\delta_{CE}|$ is reduced. For this purpose, it is necessary to express δ_{CE} in terms of preforming and pressing conditions. The deformation in modes 4 and 5 shown in Fig. 10 occurs mainly during preforming and, therefore, a change from the mode 5 to the mode 4, δ_{CE} in Fig. 11 results in an increase in δ_{CE} . Consequently, if L is constant, δ_{CE} increases when d/W_0 is reduced, i.e., when l_a and t_a are small and W_0 is large. These are important parameters for rendering δ_{CE} in a quantitative expression. The experimental results shown in Figs. 13 and 14 reveal that the effect of l_a on δ_{CE} changes due to ΔW_P at the leading end, and that δ_{CE} changes due to ΔW_P at the tail end. Based on these points, δ_{CE} was expressed as follows:



Fig. 15 Comparison of δ_{CE} between experimental and calculated results



Fig. 16 Trend of crop loss

where d_1 to d_9 are constants. Figure 15 shows the relationship between δ_{CE} as observed and δ_{CE} as calculated by the two equations, with d_1 to d_9 determined by multiple regression. A relatively strong correlation exists between the calculated and observed values for both the leading end and the tail end, and it is apparent that the crop length can be predicted. Optimum preforming conditions suited to pressing conditions and slab sizes are found by minimizing $|\delta_{CE}|$ in Eqs. (17) and (18).

The transition of crop losses in an actual mill is shown in Fig. 16. Although the amount of width reduction is naturally larger than in the conventional method using vertical rolls, crop losses are reduced through controlling $|\delta_{CE}|$ to minimum.

5 Conclusions

Experimental and theoretical examinations were conducted into the slab deformation peculiar to a press, in particular the sizing press for slab width reduction which is the key equipment in the synchronized operation of the continuous casting and hot rolling processes at Mizushima Works. The following conclusions were obtained:

- (1) The cross section of the slab after pressing shows a dog-bone shape with a large peak in the steady portion, while it virtually shows a single-bulge shape in the nonsteady portion of the leading end.
- (2) The concept of a model for predicting the amount of width return in the rough rolling after pressing was described and a model equation was shown. The equation has been put into practical use.
- (3) The effect of the positional relationship between the anvils and slab on the plane shape of the slab after pressing was clarified by the upper bound technique.
- (4) To minimize crop losses, the effect of preforming conditions on the crop shape of sheet bar was clarified, and a method of minimizing crop losses was established.

Following the implementation of the results of this study, strip width deviations have decreased¹⁾ and crop losses have been reduced.

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