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Deformation Behavior of a Slab with Width Reduction in a Hot Mill

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The deformation of a slab with various width reductions has been investigated using a rigid-plastic finite-element analysis. A commercial finite-element code was used to analyze a dog-bone profile, mean thickness, length of slab, and longitudinal width profile after edging and horizontal rolling. The deformation behavior of a slab in a heavy edger mill was also compared with deformation in a sizing press. It was found that the sizing press followed by horizontal rolling is more efficient in width reduction than deformation by a heavy edger mill followed by horizontal rolling. The finite-element analysis results for the deformation of a slab also show reasonable agreement with measurements from an actual mill test, and from physical modeling experiments.

Keywords dog-bone profile, edging, heavy edger mill, hot mill, roughing mill, sizing press, width reduction

1. Introduction

Roughing mills are used to manufacture medium-sized plates from slabs. Horizontal rolls squeeze the slab to produce a plate of a given thickness. The width of the plate is controlled by a vertical set of rolls, which is called an edger mill. It is located in front of the horizontal rolls. In a typical hot-rolling process, the final plate size varies depending upon the size of the initial slab, but it is usually in the range of 28 to 40 mm in thickness by 0.8 to 1.8 m in width. To overcome some limitations of a conventional edger mill, such as large width deviation and limited width reduction with lower efficiency, heavy edger mills with the capacity of 300 mm width changes have been used. However, heavy edger mills also have limitations in width reduction due to the locally concentrated deformation on the edge sides of the slab. Recently, there has been a trend to increase the width reduction capability by installing a sizing press in front of the roughing mill. The purpose of the sizing press is to improve the productivity of the slab-rolling process and to increase production yield (Ref 1-4).

The purpose of the current study was to investigate the deformation imparted by a sizing press and horizontal rolls on a slab by using rigid-plastic finite-element analysis models. The deformation behavior of a slab during vertical rolling with a heavy edger mill was also investigated and compared with the sizing press deformation.

2. Finite-Element Analysis

2.1 Overview of the Sizing Press Process

Figure 1 shows a schematic drawing of the roughing mill layout, including the sizing press. The width reduction by a sizing press is achieved with stepped tooling and a series of deformation strokes. After each deformation stroke, the tooling is retracted and the slab is fed forward. The cycle can be characterized as forward feed of slab → reduction → opening of tooling. A sizing press can be designed so that the width reduction per pass may be up to 350 mm.

Figure 2 shows the geometric relationship between the slab and the tooling during width reduction in a sizing press. The angle of inclination of the tooling has an effect not only on the press capacity and productivity, but also on the dog-bone profile that is produced and on the efficiency of the width reduction.

Figure 3 illustrates the deformed shape of a slab produced by a sizing press and horizontal rolling. The efficiency of the width reduction in a sizing press is expressed as the width change from both sizing and rolling divided by the width change from the sizing alone. There is some width recovery during the rolling step due to the dog-bone profile that is produced during sizing. The increase in slab thickness near the edges, which is caused by the sizing press, results in an increase in width during subsequent horizontal rolling.

It is important to know what percentage of the slab causes the width recovery. The mathematical definition for the efficiency of the width reduction (η) by the sizing press is:

$$\eta = \frac{W_0 - W_1}{W_0 - W_e} = \frac{W_0 - W_1}{\Delta W} \quad \text{(Eq 1)}$$

As the efficiency of width reduction is increased, the capacity of width change in the roughing mill is increased.

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Nomenclature

H_0	initial thickness of slab before pressing (mm)
H_m	mean thickness of slab after pressing (mm)
h	pressing amplitude (mm)
L	initial parallel contact length of tooling (mm)
L_d	maximum contact length of tooling with slab (mm)
L_0	initial length of slab (mm)
L_1	length of slab after sizing reduction (mm)
W_0	width of slab before sizing (mm)
W_e	width of slab after sizing (mm)
W_1	width of slab after horizontal rolling (mm)
ΔW	width reduction of sizing press (mm)
θ	inclination angle of the tooling
η	efficiency of width reduction

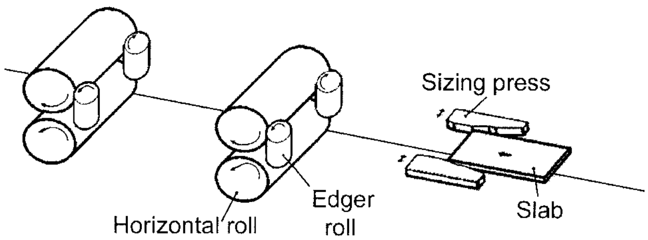

Fig. 1 Roughing mill layout with sizing press

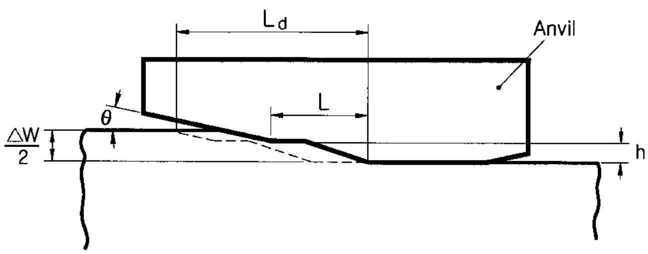

Fig. 2 Geometric relationship between tooling and the slab

2.2 Analysis of Sizing and Rolling Process

There are several pressing methods that can be used in a sizing press, but in this study the deformation behavior of the slab was analyzed for a one-directional pressing method. To simulate the deformation of the slab during both sizing and subsequent rolling, a rigid-plastic (FEM) was performed. In the analysis, the gap of the horizontal roll was made to be the same as the initial slab thickness, so that only the dog-bone profile produced during sizing is rolled. MARC (MSC Software Corporation, Santa Ana, CA), an FEM commercial code, was used to model the deformation of the slab. Table 1 shows the input variables.

For the flow characteristics of a carbon steel slab at high temperatures, the model by Shida (Ref 5) for the stress-strain curve was used. The initial temperature of the slab was assumed to be uniform at 1200 °C. This uniform temperature assumption is reasonable, because sizing is a process that starts immediately after the slab is extracted from the reheat furnace. The slab length used in the FEM simulation was set so that the width reduction imparted by the tooling of the squeeze press might be completed after six to eight deformation strokes.

3. Physical Modeling

To investigate the width variation of the slab during sizing, physical modeling experiments were conducted. A sizing simulator, driven by a pneumatic-based actuator, manufactured on a scale of 1 to 10 the actual sizing press used in these experiments. Table 2 gives the conditions for the physical modeling experiments.

Plasticine, a material showing similar flow characteristics to hot steel, was used in the physical simulations. The width of the slab, which was pressed with the model simulator, was measured at intervals of 5 mm along the longitudinal direction of the slab. The rolling was conducted on a horizontal rolling mill having 100 mm diameter rolls.

4. Mill Tests

Production mill tests were conducted to verify and adjust the results obtained by the FEM simulation. Figure 4 shows the test methods used in the production mill.

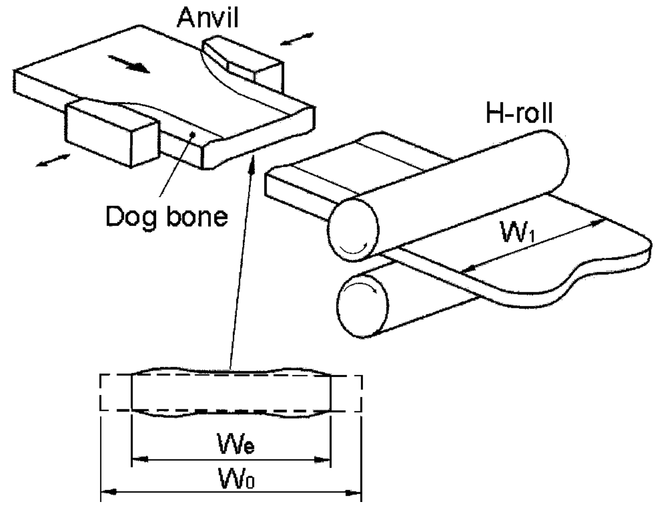

Fig. 3 Configuration of slab deformation by the sizing press

Table 1 Input variables for finite-element analysis

Variable	Input value
Slab thickness, mm	203, 250
Slab width, mm	1000-1800
Width reduction, mm	50-300
Temperature, °C	1200
Friction coefficient, μ	0.3
Tooling speed, mm/s	300
Tooling angle, degrees	12, 18
Forward feed, mm	386
Roll diameter, mm	ϕ 1350
Rolling speed, m/s	2.0
Flow strength, kg_f/mm^2	Shida equation

Two separate tests were performed to differentiate the sizing only (test I) and the sizing-horizontal rolling (test II). After air-cooling the slab, the deformed shape was measured at 10 mm intervals along the width direction. Additionally, the amount of width variation along the length of the slab was measured at intervals of 50 to 100 mm.

5. Results and Discussion

5.1 Dog-Bone Profile

Figure 5 shows the dog-bone profiles on the topside of the slab produced by the sizing press for a 203 mm thick by 1000 mm wide slab. As shown in Fig. 5(a) for the front end, for a width reduction of ≤150 mm the thickness primarily increases in the center region of the slab, resulting in a single center bulge. For width reductions of >150 mm, a double bulge profile is produced with maximum thicknesses observed in both the central region and the edge region of the slab. The plot in Fig. 5(b) shows the dog-bone profiles for the middle section of the slab. In this section, a single bulge is observed in the edge region of the slab. As the width reduction increases, the position of the maximum thickness associated with the bulge moves toward the central region of the slab.

Figure 6 shows a comparison of dog-bone profiles produced by a heavy edger mill and a sizing press. The simulation is for a width reduction of 140 mm on a 900 mm wide slab. The thickness displacement for deformation in the heavy edger mill is larger than that in the sizing press. In the heavy edger mill, the deformation is largely concentrated as displacement in the

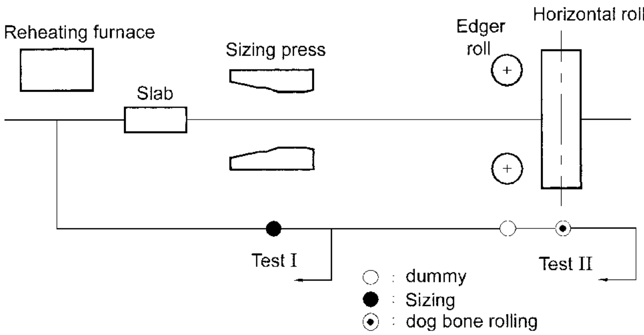

Fig. 4 Methods for production mill tests

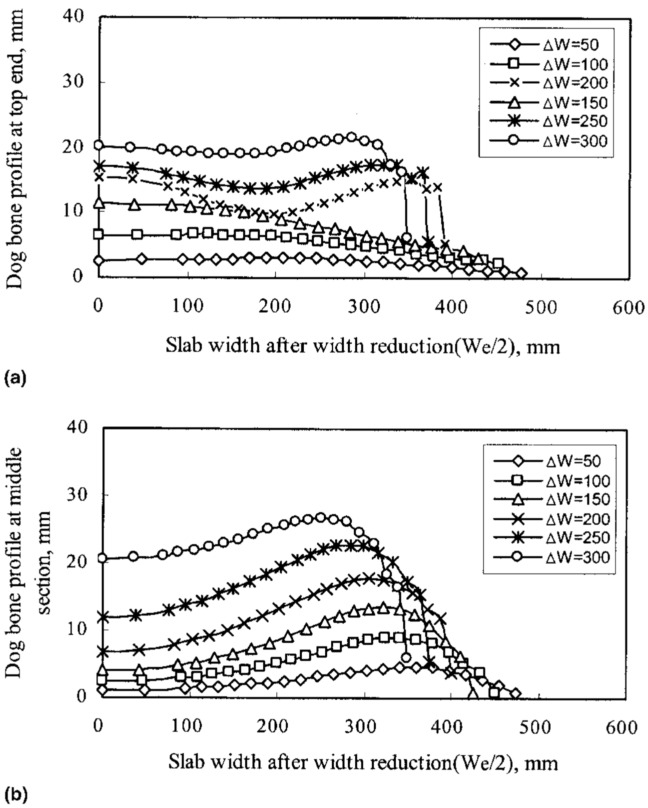

Fig. 5 Dog-bone profile after sizing reduction: (a) top section; and (b) middle section

Table 2 Physical modeling experimental conditions

Variable	Input value
Material	Plasticine ($CaCO_3$ + grease)
Slab thickness, mm	20
Slab width, mm	100 ~ 185
Width reduction, mm	5 ~ 30
Forward feed, mm	38
V-roll diameter, mm	ϕ 100
H-roll diameter, mm	ϕ 100

thickness direction, whereas in the sizing press a significant amount of the deformation occurs in the slab length direction. The deformation imparted by the sizing press is different from vertical rolling. In vertical rolling, the dog-bone distribution in the width direction is subjected to local deformation on the edge of the slab due to the small contact length between the roll and the slab. In contrast, the sizing process has a large contact length, causing the largely compressive deformation to penetrate deeper toward the central region of the slab.

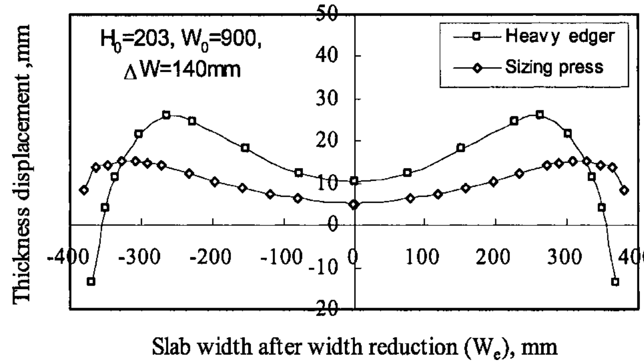

Fig. 6 Comparison of heavy edge rolling with sizing press for the dog-bone profile

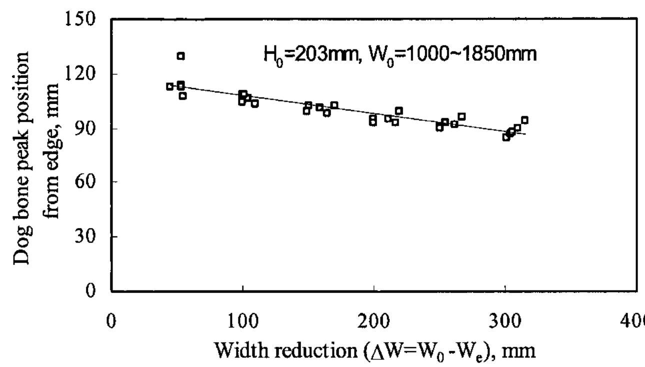

Fig. 7 Relationship between peak position from the edge and width reduction.

Figure 7 shows the position of the maximum thickness displacement as measured from the edge of the slab for various width reductions. As the width reduction is increased, the peak position moves closer to the edge of the slab.

Figure 8 shows a comparison between measured values and the FEM results for a dog-bone profile in the middle section of the slab. The results of the analysis are in agreement with measured data from the actual sizing press.

5.2 Slab Mean Thickness

Figure 9 shows the mean thickness of the middle section (H_m) of the slab for various width reductions made in a sizing press. The increase in mean thickness caused by the sizing is in the range of 5 to 20%, depending on the initial conditions of the slab and the amount of width reduction imparted. The mean thickness of the slab can be obtained by dividing the cross-sectional area after the sizing press by the gap of the sizing press. Because the mean thickness can vary slightly within the slab from front to back, the average of the minimum and maximum values was used in reporting the mean thickness value.

Figure 10 shows a comparison of the measured mean thickness values with the results of FEM analysis obtained for 13 slab reduction tests. The average error between the simulated mean thickness and the measured mean thickness is approximately 2.8 mm. The accuracy of the FEM simulations is satisfactory.

5.3 Slab Length

Figure 11 shows the ratio of the slab length after width reduction (L_1) to the length before reduction (L_0), as a function

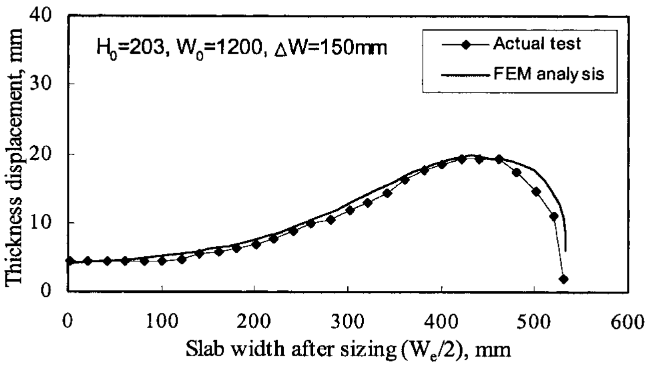

Fig. 8 Comparison of FEM results with actual test values for the dog-bone profile

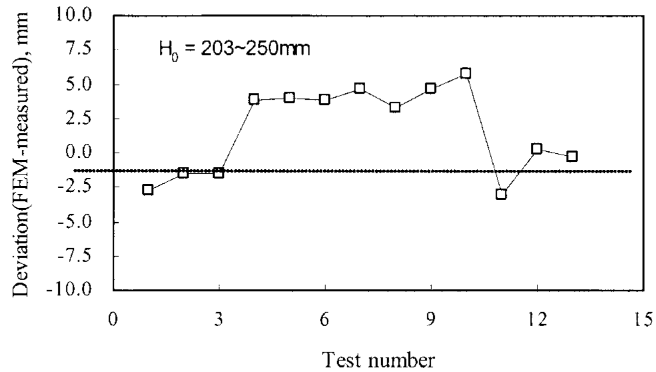

Fig. 10 Prediction accuracy of slab mean thickness after width reduction

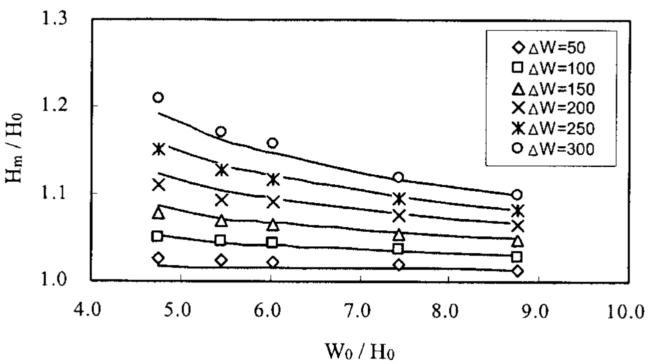

Fig. 9 Relationship between the relative mean height (H_m/H_0) and the relative initial width (W_0/H_0).

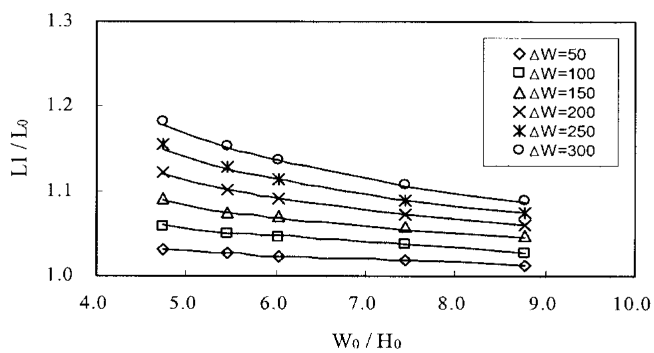

Fig. 11 Relationship between the relative length after width reduction (L_1/L_0) and the relative initial width (W_0/H_0)

of the ratio of original width (W_0) to the thickness (H_0) of the slab.

As the initial width-to-thickness ratio of the slab increases, the elongation in the longitudinal direction of the slab increases, so that the slab length after sizing is longer. The change in slab length resulting from the sizing is an increase in the range of 5 to 20%. The exact amount of the increase depends on the specific width reduction.

Figure 12 shows a comparison of mill test results for slab length after sizing with values determined from FEM simulations. The simulation error is estimated to be satisfactory.

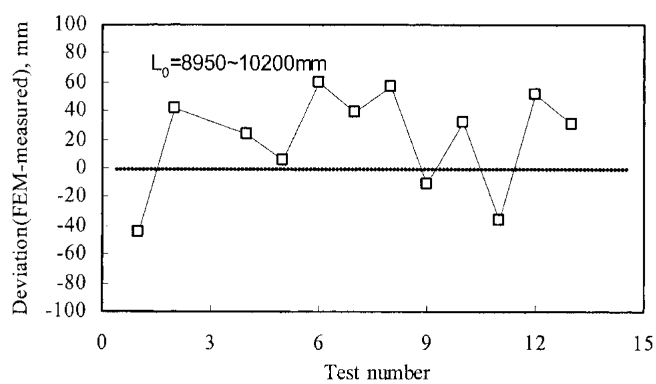

Fig. 12 Prediction accuracy of slab length after width reduction

5.4 Efficiency of Width Reduction

Figure 13 shows the relationship between the width reduction and the amount of width recovery (spread) after horizontal rolling for dog-bone profiles produced by the sizing press.

As the initial slab width is increased, the amount of width spread is also increased. As the slab width increases, the thickness direction of deformation becomes concentrated on the edge of the slab during pressing and can more easily contribute to the spread after rolling.

Figure 14 shows a comparison of the width spread due to vertical rolling (edger mill) with the spread due to sizing (sizing press) in reducing the slab. The width spread during dog-bone rolling for the vertically rolled slab is higher than that for the sizing press, due to the local concentration of deformation at the slab edge during vertical rolling. Hence, the efficiency of width reduction by vertical rolling is less than that of a sizing press. Figure 15 plots the efficiency of the sizing press as given by Eq 1 against various width reductions.

The efficiency of the width reduction in a sizing press is in the range of 80 to 92%, which is higher than the 30 to 70% efficiency of a conventional vertical-horizontal rolling mill (Ref 1).

5.5 Width Variation

An incidental problem with the use of a sizing press is cyclic variation in the width measurement along the length of the slab after sizing. The source of this variation is directly related to the sizing process, which involves a series of sequential deformations. As the sizing press squeezes the slab, the tools are retracted and the slab is fed forward. At this point, the tools squeeze the slab again. A width variation (the difference between the maximum width and the minimum width) can be used to quantify this feature.

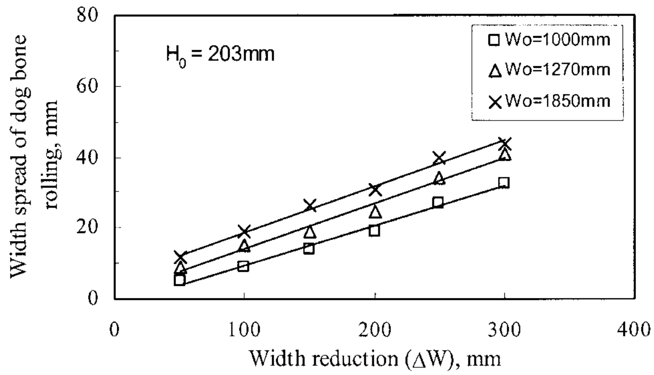

Fig. 13 Variation of width spread during dog-bone rolling with width reduction

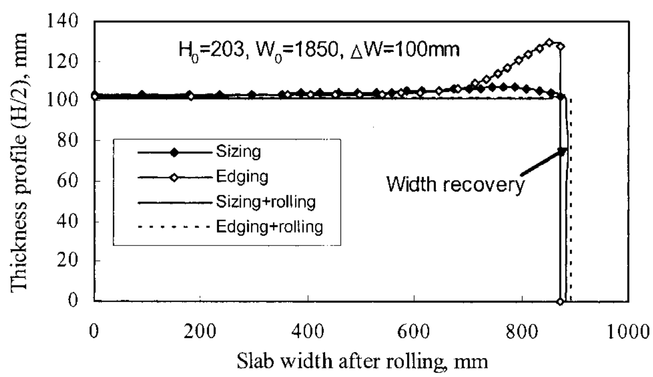

Fig. 14 Comparison of vertical rolling with the sizing press for width spread

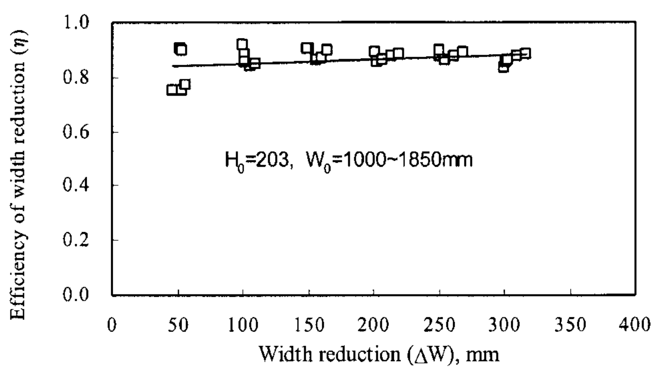

Fig. 15 Relationship between width efficiency and width reduction

To study the width variation, FEM analysis and physical modeling experiments were conducted for the sizing process followed by horizontal rolling. Figure 16 shows the width profiles along the slab length after sizing and after sizing plus rolling, which were obtained by the physical modeling experiments.

The first observation concerns the effect of the inclination angle of the sizing tooling, where, as expected, increases in the angle cause increases in the width variation. After horizontal rolling, the width variation for the sizing press increases slightly due to differences in the dog-bone profile within the tooling angle.

Figure 17 shows the width variation along the slab length after sizing obtained in production mill tests. For width reductions of 250 m and 350 mm, a width variation of 5 to 10 mm occurs. To decrease such width variation, the squeeze press tooling shape and/or the rolling method needs to be improved.

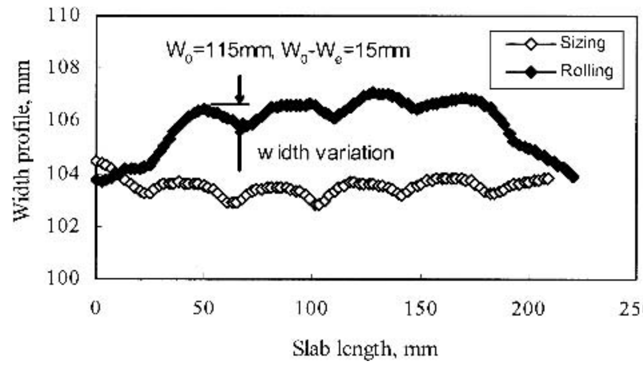

Fig. 16 Experimental measurements of width variation

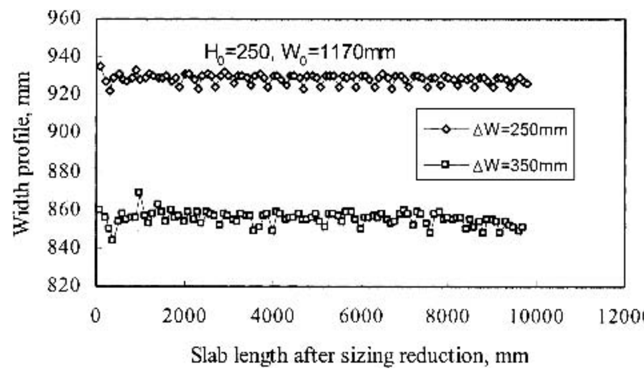

Fig. 17 Actual test results of width variation

6. Conclusions

The deformation behavior of a slab reduced by a sizing press and horizontal rolling was analyzed by the rigid-plastic FEM. The following conclusions were obtained:

- The dog-bone profile created by the sizing press is smaller than the one created by a heavy edger mill. With the sizing press, a significant amount of deformation occurs in the slab length direction.
- Increases in the mean thickness and in slab length by the sizing press are in the range of 5 to 20%. The exact amount depends upon the initial conditions of the slab and the amount of width reduction.
- The efficiency of width reduction by the sizing press is in the range of 80 to 92%.
- The width variation in the slab length direction after sizing and rolling is in the range of 5 to 10 mm.
- The FEM simulation is in good agreement with data from production mill tests and data from physical modeling experiments.

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