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Masatoshi Inoue, Shun-ichi Nishida, Kazuro Omori, Isamu Okamura, Katsushi Fujioka, Niro Katayama

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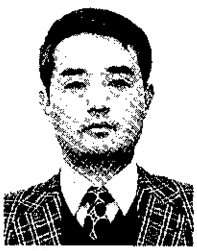
Masatoshi Inoue
Manager,
Plate Rolling Sec.,
Hot Rolling Dept.,
Mizushima Works


Shun-ichi Nishida
Hot Rolling Technology Sec., Hot Rolling Dept., Mizushima Works


Kazuro Omori
Staff Assistant Manager, Development & Design Sec., Equipment Dept., Mizushima Works


Isamu Okamura
Electrical & Instrumentation Technology Sec., Mizushima Works


Katsushi Fujioka
Staff Assistant Manager, Electrical & Instrumentation Technology Sec., Mizushima Works


Niro Katayama
Electrical & Instrumentation Technology Sec., Mizushima Works

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1 Introduction

Important factors in decreased yield in plate rolling are plan view pattern losses due to side crops and end crops and sectional profile losses due to edge overlapping and bulging. Various plan view pattern control methods have been developed to reduce plan view pattern losses[1-5]. In the plate mill at Kawasaki Steel's Mizushima Works, the MAS (Mizushima automatic plan view pattern control system) rolling method was developed and a substantial improvement in yield was achieved[6]. The original version of this new rolling method, however, did not reached a level of sophistication allowing omission of the trimming process. Therefore, the authors developed manufacturing techniques for **trimming-free plates (TFP)**, in which a rectangular plan view pattern is obtained and sectional profile losses are eliminated.

Basic experiments were carried out using lead and hot steel. Based on the results, an edger with various functions such as edging with grooved rolls and hydraulic AWC (automatic width control) was installed in close proximity to the finishing mill for the first time in the world. In addition, the shear line was equipped with a cold milling machine of high cutting accuracy, capable of meeting ever-increasing user requirements for high dimensional accuracy of products.

In the current Mizushima plate mill, a high-accuracy width control system using the edger in the sizing passes, broadside passes, and finishing passes, was installed in order to optimize MAS rolling and edging. At the same time, the manufacture of TFP was realized as a result of the highly accurate cutting by the cold milling machine.

This report presents an outline of TFP production equipment and describes the manufacturing techniques for TFP and the results of the manufacture of this steel plate.

2 Technical Problems for TFP Production

The aim with TFP is to ensure a quality level, in the as-rolled state, equivalent to that of conventional plate after trimming, as shown in **Fig. 1**. To achieve this, it is necessary to obtain not only a rectangular plan view pattern but also a rectangular sectional profile and to conduct width reduction with an edger.

In regard to width reduction characteristics, there had

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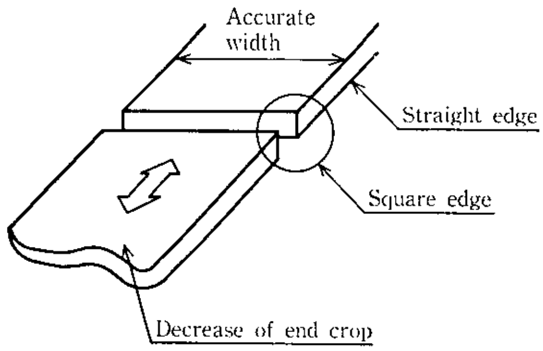


Fig. 1 Requirements for trimming free plates (TFP)

been few reports on wide materials with a width-to-thickness ratio exceeding 100, which is characteristic of plate rolling, or on edge overlapping and bulging[1,7]. To obtain a grasp of the basic characteristics of edging and examine the functions required of an edger, basic experiments were conducted using lead and hot steel, and the following results were obtained[8-10]:

(1) The widespread ratio (widespread/width reduction) of the steady region is 50 to 80%. The smaller the width reduction, the higher the widespread ratio.
(2) The width shortage at the top and bottom ends depends on the width reduction. The width shortage at the top and bottom ends increases with increasing width reduction.
(3) The effect of plate thickness and width on the widespread ratio of the steady region and of the width shortage at the top and bottom ends is not significant under the rolling conditions to be expected in actual rolling.
(4) The amount of edge overlap decreases when the corners of slab edges are chamfered before the broadside passes. It is also possible to reduce the amount of edge overlap to zero by increasing the chamfered area.
(5) A three-point widthwise restraint pattern using upper and lower support rolls is the most effective means of preventing buckling.

3 Outline of TFP Production Equipment

To produce TFP, an edger was installed adjacent to the finishing mill, and a cold milling machine was installed on the shear line. The layout of the edger and milling machine is shown in **Fig. 2**.

3.1 Outline of Edger

At the Mizushima plate mill, an edger was installed adjacent to the finishing mill in 1984 on the basis of the knowledge obtained from basic experiments. The center-to-center distance between the finishing mill and the edger is 3 625 mm. The construction and main specifications of the edger are shown in **Fig. 3** and **Table 1** respectively.

The vertical rolls are each provided with a flat area and a grooved area. These rolls shift vertically when chamfer rolling is performed with the grooved areas.

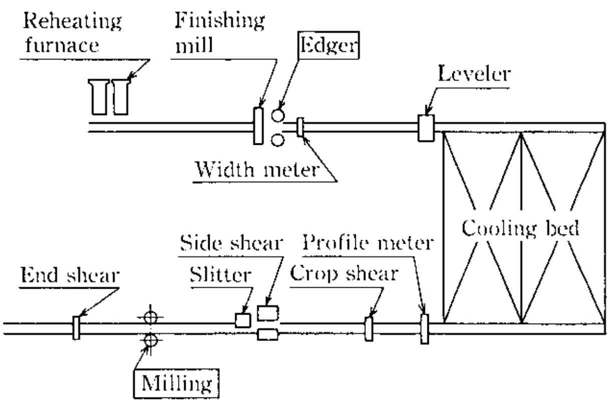


Fig. 2 Layout of the edger and milling

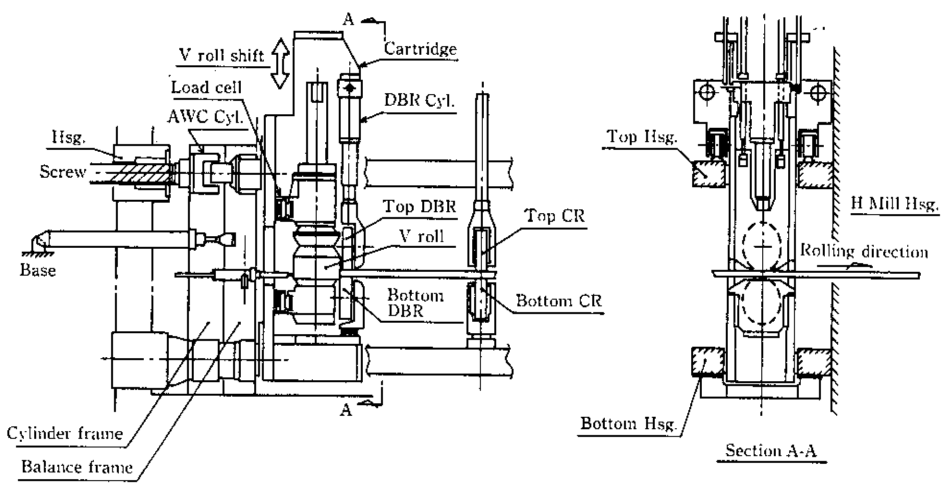


Fig. 3 Schematic view of TFP edger

Table 1 Specifications of the edger

Rolling force (Flat part)	400 ton
Rolling force (Grooved part)	310 ton
Rolling torque	50 t·m
Rolling speed	2.5~7.5 m/s
Roll diameter	ϕ 800/ϕ 700 mm
Angle of groove	120°
Speed of motorized screw-down	60/120 mm/s
Speed of hydraulic AWC	100 mm/s

Support rolls for the prevention of buckling are provided so that the required width reduction can be obtained even with material of high width-to-thickness ratio.

The screwdown device has the function of hydraulic AWC. Powerful direct-moving servo valves are provided, and the device is capable of width reduction control, to cope with longitudinal width deviations of the plate, and width shortage prevention control at the top and bottom ends.

3.2 Outline of Cold Milling Machine

In July 1987, the shear line was equipped with a cold milling machine which produces cut faces of such high accurate that even edge preparation by users can be omitted.

The main specifications of the milling machine are given in **Table 2**. The cutter is of a helical milling type with a 25° tilt in the material feed direction and features high feed speeds, large cut depth, and an extended range of work thicknesses.

In addition to center position control (CPC) and edge position control (EPC), cutting control functions include straight position control (SPC) based on the plan view pattern data for the plate measured at the head of the shear line. The concepts of these milling control methods are shown schematically in **Fig. 4**.

Table 2 Specifications of the milling

Place	Between side shear and end shear
Type	Helical milling
Cutter head	1 000 mmϕ × 2
Feed speed	42 m/min max
Depth of cut	20 mm/each side max
Work thickness	4.5~80 mm
Milling control	Center position control (CPC) Edge position control (EPC) Straight position control (SPC)
Motor power	DC 200 kW × 2

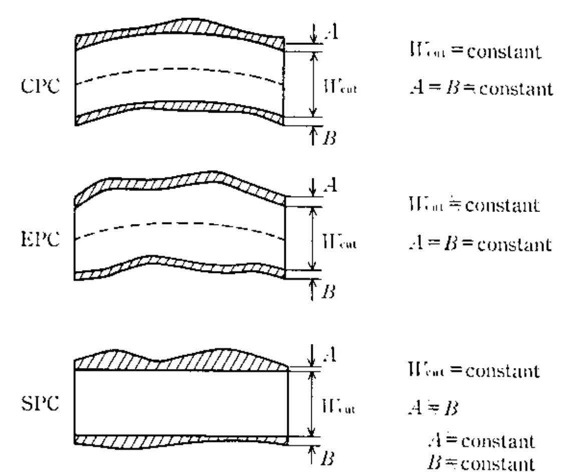


Fig. 4 Method of milling

4 Manufacturing Techniques for TFP

A conceptual diagram of the manufacture of TFP is shown in **Fig. 5**. This manufacturing technology comprises the following techniques:

(1) Edge overlapping is prevented by using the grooved area of the vertical rolls to conduct chamfer rolling as required in the sizing passes.

(2) The width profile after the broadside pass is controlled by MAS rolling in the sizing passes and edging in the broadside passes.

(3) In the finishing passes, width deviations are eliminated to obtain a rectangular plan view pattern by repeating the edging using AWC and horizontal rolling.

(4) Shapes of top and bottom crops are controlled by MAS rolling in the broadside passes and edging in the finishing passes.

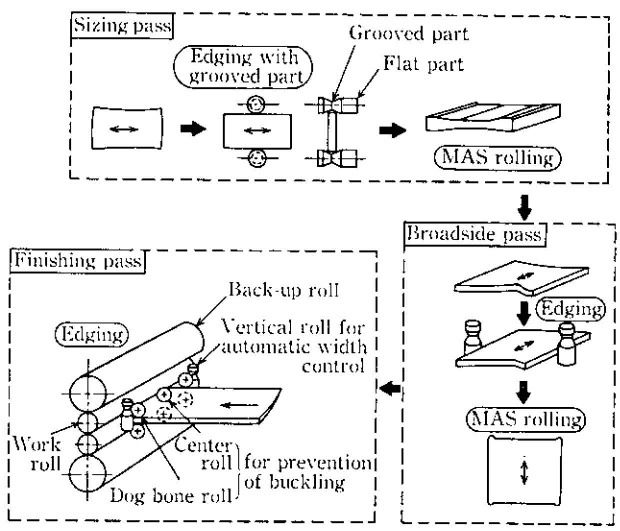


Fig. 5 Rolling schedule of TFP (MAS: Mizushima automatic plan view pattern control system)

These techniques are described in detail in the following.

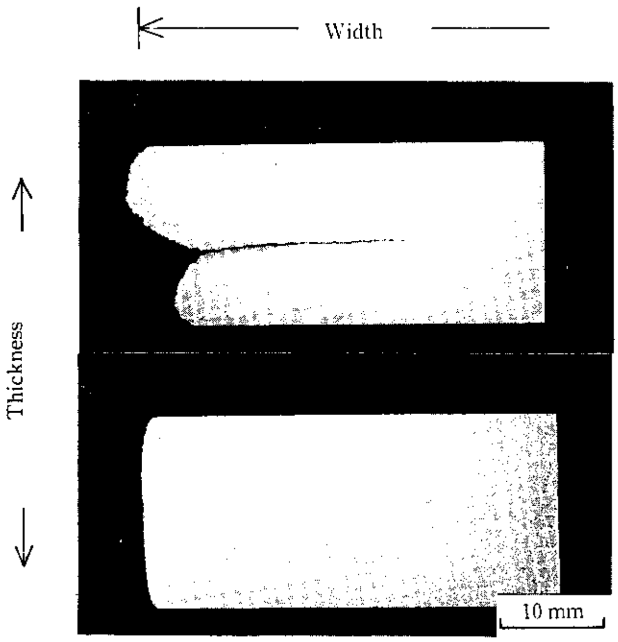
4.1 Technique for Preventing Edge Overlapping

The amount of edge overlap is reduced by edging in the finishing passes[10]. However, edging in the finishing passes is insufficient to prevent edge overlapping when the slab thickness is large, the broadside rolling ratio high, and the reduction ratio during the broadside pass low[10]. Successful rolling under these conditions requires chamfer rolling in the sizing passes using the grooved area of the vertical rolls.

The line pipe material API 5LX-X70 described in **Table 3** is an example from actual results of a case in which edge overlapping was prevented by the application of chamfer rolling. **Photo 1** shows a comparison of a section of plate rolled by the conventional process (without edging) and that of a plate rolled by the TFP process with chamfer rolling. Edge overlaps of 20 to 30 mm, which occur in the conventional process, can be eliminated by the TFP process. In addition, a rectangular sectional profile is obtained due to the edging in the finishing passes.

Table 3 Material with chamfer rolling for prevention of edge overlap

Steel grade	API 5LX-X70
Rolling dimensions (mm)	18.89 × 4 371 × 35 100
Slab dimensions (mm)	310 × 2 400 × 4 300
Broadside rolling ratio	1.82
Longitudinal rolling ratio	8.16



Upper: Conventional process
Lower: TFP process

Photo 1 Comparison of plate section

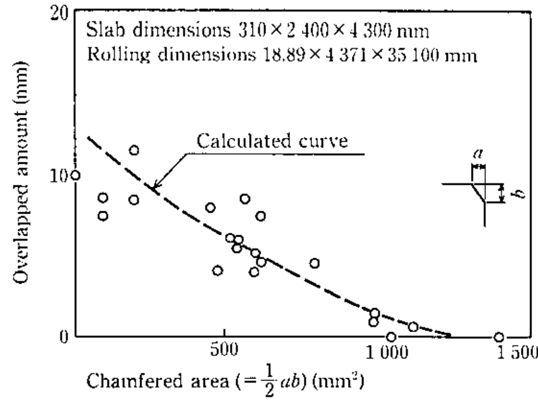


Fig. 6 Effect of chamfer rolling on the amount of overlap

The relationship between the chamfered area and the amount of edge overlap is shown in **Fig. 6**. The amount of edge overlap decreases when the chamfered area increases, and it is possible to reduce the amount of edge overlap to zero by chamfering above a certain value. The broken line in the figure represents values calculated by a model equation in a lead model experiment[10]. These values are in good agreement with phenomena seen in actual rolling.

4.2 Combined Techniques of MAS Rolling and Edging

The effect of differences in width profile after the broadside passes of the plan view pattern and sectional profile after rolling is illustrated in **Fig. 7**. In order to obtain a rectangular sectional profile by edging in the finishing passes and, at the same time, decrease crop losses at the top and bottom ends, it is necessary to maintain sufficient reduction in the width direction along the full length of the plate, with the width profile

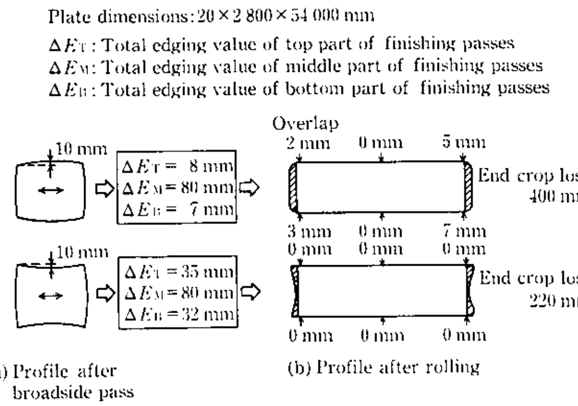


Fig. 7 Influence of profile after broadside pass on the amounts of overlap and end crop after rolling

after the broadside pass of a spool shape (i.e., the width of the top and bottom parts being larger than that of the middle part).

MAS rolling in the sizing passes and edging in the broadside passes are means of controlling the width profile after the broadside passes. To optimize the two, a prediction model for the width profile after the broadside pass is necessary.

4.2.1 Width profile prediction model

The prediction model for the width profile after the broadside passes is composed of a prediction equation for the value of the convex shape (the width difference between the middle and top and bottom parts, T_C) caused by the sizing passes and broadside passes, and that for the modified value of the convex shape (ΔT_{CE}) following edging in the broadside pass.

The prediction equation for the value of the convex shape caused by the sizing passes and broadside passes is given by Eq. (1).

$$T_C = (a_1 S_T^{n1} \cdot H_{DBT}^{n2} \cdot HP^{n3} + a_2)\left(\frac{S_W}{S_T}\right)^{n4} + a_3 \cdots (1)$$

where S_T: Slab thickness
S_W: Slab width
H_{DBT}: Thickness before broadside passes
HP: Broadside rolling ratio
a_i, n_i: Constants

The prediction equation for the modified value of the convex shape due to edging in the broadside passes is given by Eq. (2):

$$\Delta T_{CE} = \sum_j \{b_1 + b_2(f_T + f_B)\} H_j^{m1} \cdot \left(\frac{H_j}{H_{DW}}\right)^{m2} \cdot \Delta E_j \cdots (2)$$

where f_T: Forward slip ratio
f_B: Backward slip ratio
H_{DW}: Thickness after broadside passes
H_j: Thickness before edging
ΔE_j: Edging value
b_i, m_i: Constants

4.2.2 Optimization of combined techniques

Figure 8 shows a comparison of width profiles after the broadside passes for simple MAS rolling in the sizing passes, simple edging in the broadside passes, and combined MAS rolling and edging. With simple MAS rolling in the sizing passes, Fig. 8 (a), the area of maximum width is at a slight distance from the top and bottom ends. When simple edging is conducted, the widths at the top and bottom ends are large, and edging is not effective in width profile control in the regions near the middle (Fig. 8(b)).

Control values in these two cases are optimized as follows:

(1) The width shortage at the top and bottom ends, which occurs in the width profile with simple MAS rolling, is compensated for by edging.

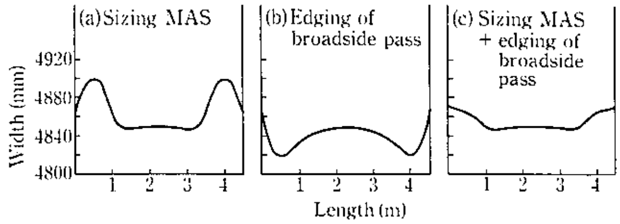


Fig. 8 Width pattern after broadside pass (broadside ratio: 3.0)

(2) When width deviations due to MAS rolling are large, as shown in Fig. 8(a), the control value of MAS rolling is reduced and the edging value is increased correspondingly.

An optimum width profile after the broadside passes, as shown in Fig. 8(c), can be obtained under any rolling condition by these adjustments.

The top and bottom end crop profile is controlled by an optimum combination of MAS rolling in the broadside passes and edging in the finishing passes.

4.3 Feedforward AWC Technique

The following points should be taken into consideration when AWC is applied to edging control in plate rolling:

(1) Width deviations occur due to non-homogeneous plastic deformation in the sizing passes and broadside passes, and because of MAS rolling and edging in the broadside pass. These width deviations are much larger than those caused by skid marks.
(2) The widespread ratio due to horizontal rolling after edging is low in the non-steady regions at the top and bottom ends, as shown in **Fig. 9**. The proportion of these non-steady regions in the full length of the material is high.

The application of roll-force type overcompensation AWC is ineffective in view of these facts, and therefore an FF(feedforward)-AWC system was adopted in which measured values of width profile before edging are used.

The FF-AWC system comprises a width-data collection system, a process computer, a controller for AWC, and a hydraulic system. Hydraulic pushdown is controlled by the AWC controller on the basis of AWC control values at points selected by the process computer.

Characteristic point data calculated by applying the spline function based on measured width data and widespread ratios at each selected point are used for determining AWC control values. Here the spline function $f(x)$ is a divided n-dimensional polynomial that satisfies the following equations at each node x_i:

$$f_i^{(j)}(x_i) = f_{i+1}^{(j)}(x_i), \quad j = 0 \sim n \cdots\cdots\cdots (3)$$

$$f(x) = f_i(x), \quad (x_{i-1} < x \leq x_i) \cdots\cdots\cdots (4)$$

This function is effective in the approximation of data

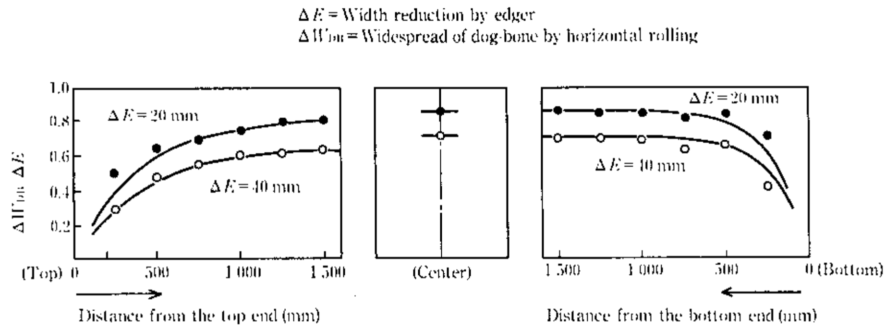


Fig. 9 Widespread ratio by horizontal rolling

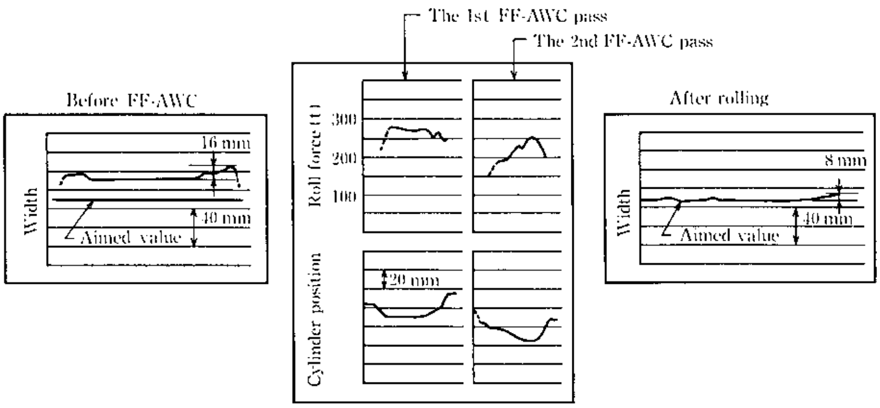


Fig. 10 Results of FF-AWC

on points of inflection, such as those seen in a width profile. The widespread ratio is given by the function form of the following equations on the basis of experimental data:

$$r(x) = \begin{cases} r_M(1 - e^{-x/x_T}) & (0 \leqq x \leqq l/2) \cdot\cdot(5) \\ r_M(1 - e^{-(l-x)/x_B}) & (l/2 < x \leqq l) \cdot\cdot(6) \end{cases}$$

where $r(x)$: Widespread ratio
r_M: Widespread ratio in steady region
l: Plate length
x_T, x_B: Constants

The width profile before FF-AWC, rolling forces and cylinder positions during FF-AWC, and the width profile after rolling are shown in **Fig. 10**. By applying FF-AWC, it is possible to control the width profile after rolling to the target width values along the full length of the plate.

5 Results of TFP Manufacture

Middle-width accuracy and width deviations in a typical case are shown in **Fig. 11**. The middle-width accu-

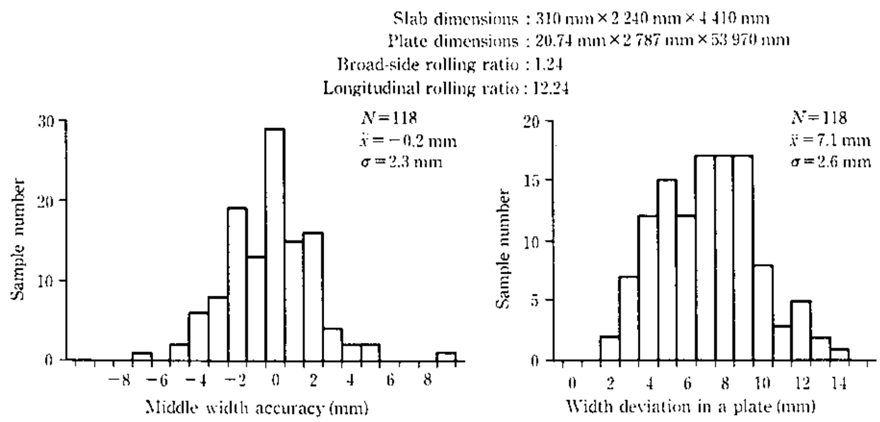


Fig. 11 An example of width accuracy and width deviation by TFP process

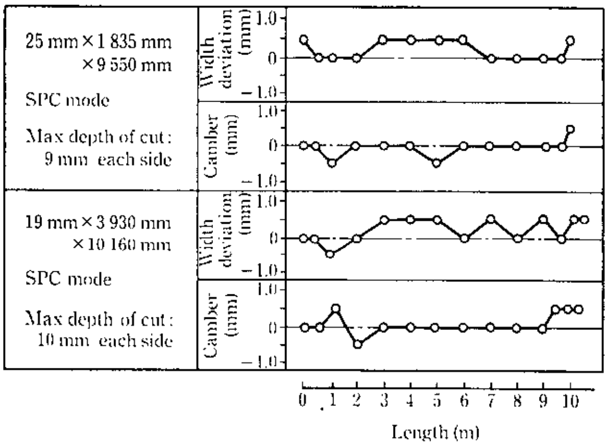


Fig. 12 Cutting accuracy of SPC mode by milling

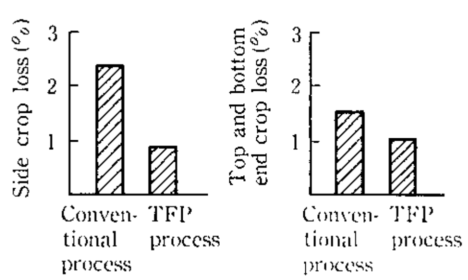


Fig. 13 Crop loss saving by TFP process

racy is very high with $\bar{x} = -0.2$ mm and $\sigma = 2.3$ mm. In spite of the long rolling length of 54 m, the width deviation was also very good with $\bar{x} = 7.1$ mm and $\sigma = 2.6$ mm. These high accuracies are such that edge preparation can be conducted with a milling machine in the as-rolled state.

Cutting accuracies of the SPC (straight position control) mode by a milling machine are shown in **Fig. 12.** High accuracies of width ± 0.5 mm, impossible with conventional side shear trimming, were obtained for both width deviation and straightness in the longitudinal direction. Orders for plates cut with a milling machine to such high accuracy precision cutting specifications are now being received.

In addition, reductions in width loss have become possible due to the better width accuracy achieved in the TFP process and the introduction of a milling machine, contributing greatly to yield improvement. As shown in **Fig. 13**, a 2% improvement in yield was achieved by reducing width losses and top and bottom end crop losses. The present ordered yield is in the range of 96%.

6 Conclusions

At the plate mill at Mizushima Works, an edger was installed adjacent to the finishing mill, and a milling machine was installed in the shear line, establishing TFP manufacturing techniques in this mill. This report has described in outline the edger and milling machine, various techniques developed to produce TFP, and the results of commercial production.

(1) The edger installed adjacent to the finishing mill (distance: 3 625 mm) has a vertical shifting mechanism employing vertical rolls with grooved areas, support rolls for the prevention of buckling, and a hydraulic AWC function.
(2) The milling machine is of the helical milling type. In addition to center position control (CPC) and edge position control (EPC), cutting control functions also include straight position control (SPC), thus realizing high-accuracy cutting.
(3) The TFP manufacturing technology comprises a technique for preventing edge overlapping, an optimal combination of the MAS rolling method and the edging method, and an FF-AWC edging control technique.
(4) The improvements in rolling width accuracy realized with the TFP process and milling machine are contributing greatly to increased yield while helping to meet ever-increasing user requirements for better dimensional accuracy in steel plate products.

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