NIPPON STEEL TECHNICAL REPORT No. 75 NOVEMBER 1997

UDC621.771.23

High Reduction Rolling Technology on Pair Cross Mill

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Abstract:

The plate mill of Nippon Steel's Kimitsu Works in 1991 introduced the world's first pair cross (PC) mill used as plate finishing mill. The application of heavy-reduction rolling to plates is an extremely important issue from the viewpoint of improving steel properties and productivity. The development of heavy-reduction (high-accuracy and high-efficiency) rolling technology based on the introduction of the pair cross mill made it possible to improve greatly not only plate shape and crown but also mechanical properties and productivity. Described here are the progress of thermo-mechanical control technology and the development of heavy-reduction metallurgy, two essential factors responsible for the development of the heavy-reduction rolling technology. The details of adoption of the pair cross mill as the best solution to rolling technology problems is described, an overview of the rolling mill and its control system is given, and the theoretical model used to control the crown and shape of plates is discussed. Further, the new method of deciding a rolling pass schedule to which the theoretical model is adopted is presented. The results of practical application of the pair cross mill to plate rolling are introduced.

1. Introduction

In recent years, plate rolling technology has made great progress in plate thickness and width control. More specifically, an attached γ-ray thickness gage and an attached edger can be cited as examples of the control methods, respectively.[1-2] In the plate shape and crown control field, work roll bending and work roll shifting mills appeared[3-5], but further improvements in rolling efficiency, decreases in the releveling ratio, and increases in yield were demanded. The lack of shape control capability in general plate rolling made it difficult to achieve sufficient crown accuracy and flatness. In particular, the light-load shape forming passes on late finishing passes severely detracted from the rolling efficiency.

Regarding mechanical properties, the development of controlled cooling technology in the late 1970s enabled great advances in the thermo-mechanical control process (TMCP) for plate rolling. Nippon Steel clarified the possibility of accomplishing still higher

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strength and toughness by the ultimate use of the TMCP technology by utilizing heavy-reduction rolling metallurgy. The above-mentioned constraint of shape control, however, made it difficult to apply heavy-reduction rolling on a practical use.

This article reports the development results of heavy-reduction rolling technology with a plate pair cross mill that made it possible to solve these plate shape and crown control problems, to achieve the rolling of plates with high accuracy and efficiency, and to provide higher strength and toughness, based on heavy-reduction metallurgy.[6-7]

2. Background for Development of Heavy-Reduction Rolling Technology

2.1 Development of thermo-mechanical control technology and limitation of controlled rolling

The basic properties required of plates are strength, low-temperature toughness, and weldability. While weldability is practically governed by the chemical composition of the plate steel, strength and low-temperature toughness depend on the microstructure (grain size and volume fraction of such second phases as pearlite and bainite) as well as the chemical composition. Generally, strength and low-temperature toughness both improve with decreasing grain size, and strength increases with increasing the volume fraction of low-temperature transformed second phases. To obtain good strength and low-temperature toughness, it is important that an optimum microstructure should be formed by the best combination of reheating, rolling, and accelerated cooling at the plate mill.

In the 1960s, it was recognized that hot rolling was important in controlling microstructures and mechanical properties. The utilization of microalloying elements such as niobium and vanadium and the effect of rolling temperature on the microstructure and mechanical properties of plates were actively studied. The idea of controlled rolling (CR) that hot rolling should be performed to refine the microstructure of the plate steel and to increase its strength and toughness accordingly was practically established.

The water-cooling thermo-mechanical control process (TMCP) that regulates the cooling rate after controlled rolling was developed in the late 1970s and has advanced as mainstream thermo-mechanical control technology to date. The metallurgical feature of the TMPC is that a fine-grained and high-strength microstructure is formed by cooling at a given rate to the desired temperature the γ (austenite) structure, which contains many lattice defects introduced by controlled rolling. The grain size of the plate steel decreases with increasing amount of strains (lattice defects) introduced by controlled rolling and further with accelerated cooling after rolling. For these tendencies, strength and low-temperature toughness both strongly depend on the conditions of controlled rolling and accelerated cooling.

Fig. 1 schematically shows the temperature history and the change in the γ structure in controlled rolling. The rolling temperature region can be divided into three parts in decreasing order of temperature: (1) γ recrystallization temperature region; (2) γ non-recrystallization temperature region; and (3) γ/a two-phase temperature region. In the region (1), the γ gradually decreases in grain size by repeated recrystallization after each rolling pass. In the region (2), the γ is elongated without being recrystallized, so that the grain-boundary area per unit volume increases. This means an increase in the number of α (ferrite) nucleation sites after rolling, and it results in the refinement of α grains. When the cumulative amount of reduction is increased in this temperature region, worked structures such as deformation bands are formed within elongated γ grains and act as α nucleation sites. In the region (3), the strength is increased by the work hardening of α in addition to the effect shown for the region (2). If the amount of reduction taken in this temperature region is too large, anisotropy of mechanical properties may occur with attendant deterioration of toughness.

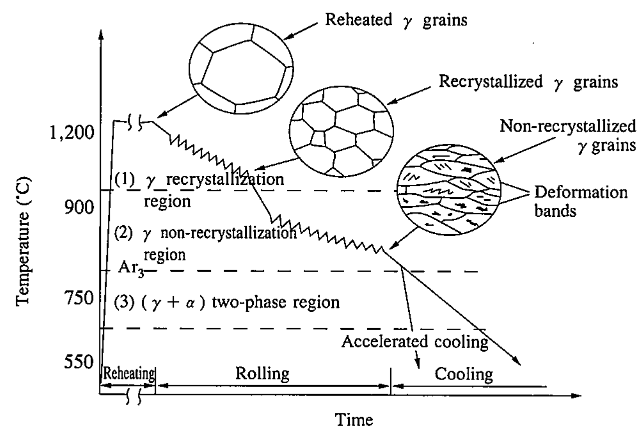


Fig. 1 Schematic illustration of temperature history and change in microstructure in controlled rolling

Of the three rolling temperature regions, the second one has the largest impact on grain refinement. **Fig. 2** shows the effect of the cumulative amount of reduction in the γ non-recrystallization temperature region on the α grain size of the 0.1C-0.3Si-1.4Mn steel. In conventional controlled rolling, the α grain size was refined by increasing the cumulative reduction ratio (cumulative reduction thickness/controlled rolling start thickness) in the temperature region (2). When the plate thickness is relatively large, however, it is difficult to enjoy this benefit because the cumulative amount of reduction that can be taken on the plate is small. As can be seen from **Fig. 2**, the α grain refinement tended to level off when the cumulative reduction ratio reached about 60%, and there was a limit to the degree to which the mechanical properties could be

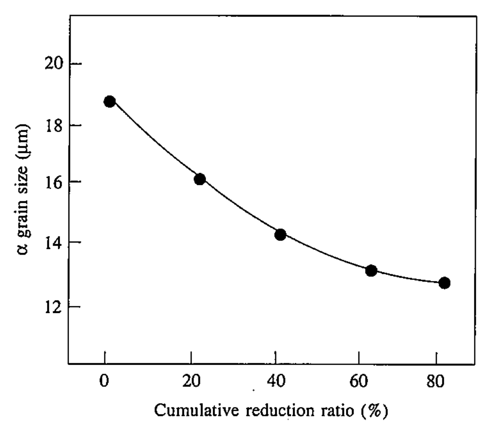


Fig. 2 Effect of cumulative reduction ratio in γ non-recrystallization temperature region on α grain size (0.1C-0.3Si-1.4Mn)

improved by controlled rolling. This situation called for the development of rolling technology capable of refining the α grain size with a limited amount of cumulative reduction.

2.2 Development of heavy-reduction rolling metallurgy

Heavy-reduction rolling metallurgy was developed as a rolling process for refining the α grain size further with the same cumulative reduction amount. **Fig. 3** shows the results of hot charge rolling experiments[8]. The 0.05C-1.55Mn-0.045Nb-Ti-B steel was melted in a vacuum melting furnace, cast into a 150-kg ingot, allowed to cool to 900°C, charged into a 1,200°C furnace, held for 1 hour, rolled to a cumulative reduction of 60% in the γ recrystallization temperature region, and changed in the cumulative reduction ratio and the reduction ratio per pass (reduction thickness/entry plate thickness) in the γ non-recrystallization temperature region. As reported previously, yield strength (YS) and toughness are somewhat improved by increasing the cumulative reduction ratio in the γ non-recrystallization temperature region from 75% to 87%. It should be noted that the toughness can be materially improved by increasing the reduction ratio per pass from 10% to 20% while keeping the cumulative reduction ratio constant at 87%. The slight loss of yield strength in this case may be attributed to the progress of niobium precipitation in the γ region, resulting in the decrease in the amount of precipitation strengthening. The large toughness gain can be explained by the α grain refinement.

The effect of increasing the reduction ratio per pass in refining the α grain size was verified in not only hot charge rolling but also in conventional reheat rolling[9].

To clarify the reason why increasing the reduction ratio per pass refines the α structure and enhances the strength and toughness of plates, basic experiments were conducted using a hot compression device. **Fig. 4** shows the γ structure of the 0.05C-0.3Si-1.6Mn-Nb-B steel immediately after working at the γ non-recrystallization temperature region, when the reduction ratio per pass at 850°C was changed to 10% and 30% while the cumulative reduction ratio at 850°C was kept constant at 50% it reveals boron segregated at prior γ grain boundaries. Since 850°C falls in the γ non-recrystallization temperature region of the steel, it is evident that the γ grains are elongated and that the deformation bands are formed within the γ grains. As already described, the γ grain boundaries and the deformation bands are both preferred α nucleation sites. It is clear that these nucleation sites can be increased by raising the reduction ratio per pass from 10% to 30%.

Fig. 5 shows the density of α nucleation sites measured as the sum of the number of grain boundaries and deformation bands present per unit length in the thickness direction in **Fig. 4**.

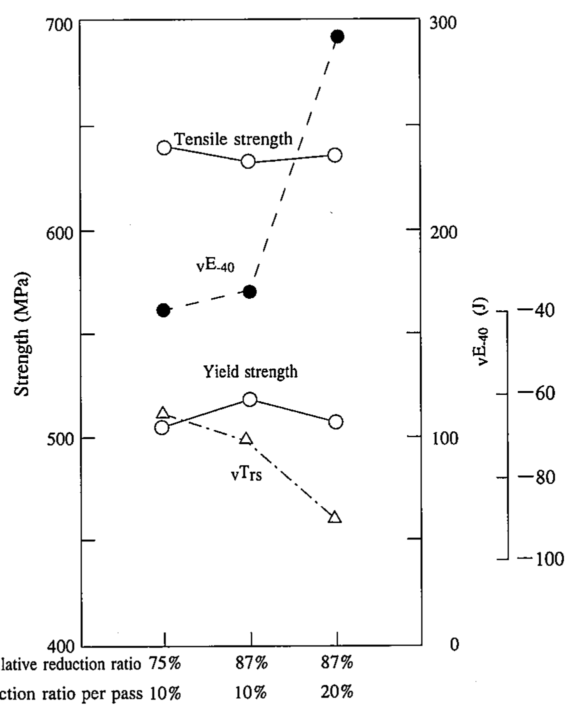


Fig. 3 Effects of rolling conditions in γ non-recrystallization temperature region on mechanical properties

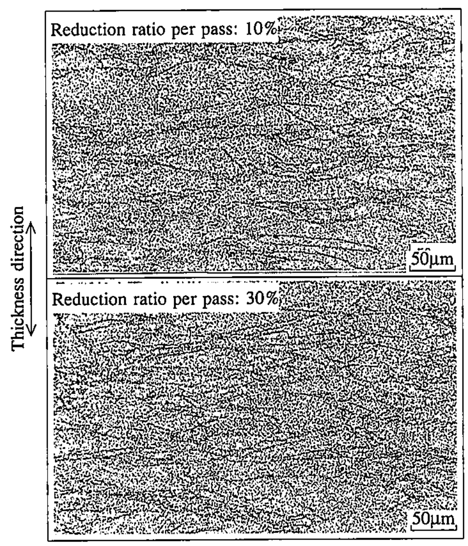


Fig. 4 Effect of reduction ratio per pass in γ non-recrystallization temperature region on worked γ structure

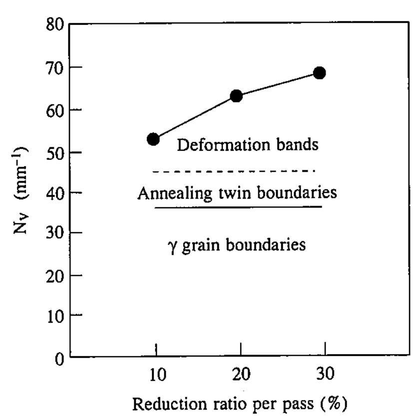


Fig. 5 Effect of reduction ratio per pass on N_V (α nucleation site density) when steel is rolled at 850°C in multiple passes to cumulative reduction ratio of 50%

According to the measured data, the α nucleation sites clearly increase with increasing the reduction ratio per pass. The post-working γ grain boundary area in the γ non-recrystallization temperature region can be generally calculated geometrically by using the pre-working γ grain size. When the pre-working γ grain size is equal, the post-working γ grain boundary area is not affected by the reduction ratio per pass. Therefore, the increase in the number of α nucleation sites in **Fig. 5** can be attributed to the increase in the number of deformation bands within γ grains. The γ structures shown in **Fig. 4** were transformed at a rate of 1°C/s, and the resultant α grain size was measured. The results are given in **Fig. 6**. This figure confirms the α grain refinement of transformed α by the increase in the reduction ratio per pass.

The above results verified that even when the cumulative reduction ratio is constant, raising the reduction ratio per pass can increase the number of α nucleation sites in the γ structure and can decrease the size of α grains after transformation. This heavy-reduction rolling metallurgy can be utilized to improve strength and toughness of plates as shown in **Fig. 3**.

2.3 Rolling technology problems

(1) Decrease in plate thickness deviation (plate crown) in width direction

The plate thickness generally decreases toward the plate edges. This thickness deviation is called plate crown or simply crown. If the plate crown is large enough, the plate thickness deviation may increase to such a degree that the plate is unfit for use in an application involving a strict thickness accuracy requirement. The increase in thickness deviation (difference in thickness through the plate) leads to increased thickness margins being considered during material design or to the loss of yield. The decrease in the plate crown has been an extremely important issue when meeting the increasing stringency of thickness accuracy requirements in recent years and reducing plate production costs by improving yield.

(2) Elimination of light-reduction shape forming passes

When heavy reductions are taken for the purposes of enhancing rolling efficiency and improving mechanical properties, the resultant increase in the rolling force increases the deflection of work rolls. Since the plate crown (thickness difference in the width direction) consequently increases, the difference in the elongation ratio in the width direction increases (the center of the plate in the width direction elongates more than the edges of the plate), and the plate shape (flatness) worsens especially in the thin-gage region.

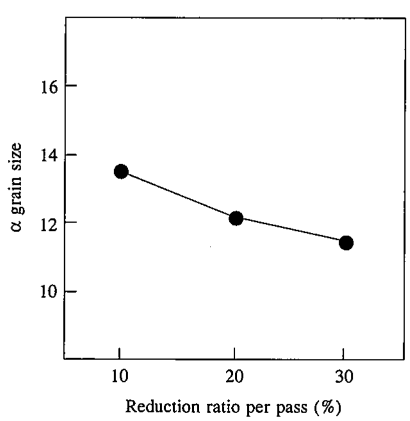


Fig. 6 Effect of reduction ratio per pass in γ non-recrystallization temperature region on α grain size

To avoid this problem and obtain the desired plate shape, in the early stage of rolling (early passes or thick-gage region) where the plate shape is not affected by the difference in the elongation ratio in the width direction, the conventional rolling process rolled the plate in a minimum of passes with a heavy reduction ("full-load pass") within the mill equipment limitations, such as the rolling force and rolling torque, then, in the latter stage of the rolling process (intermediate to final passes in the thin-gage region), the plate had to be rolled with a restrained reduction ratio ("forming pass")[10]. As a result, the increase in the required number of rolling passes unavoidably lowered the productivity of the plate mill. Plate reversing mill has greater freedom as to the number of passes than the continuous hot strip mill in which the number of passes depends on the number of stands. To improve productivity by taking advantage of this freedom and to get the metallurgical benefits of heavy-reduction rolling described in the previous section, it has been a long-standing challenge to eliminate light-reduction shape forming passes in the latter stage of the rolling process or to achieve full-load rolling with heavy reductions in all passes.

3. Development of Heavy-Reduction Rolling Technology with Plate Pair Cross Mill

3.1 Study of optimum plate rolling system

The above-mentioned elimination of light-reduction shape forming passes calls for a powerful crown and shape control capability that does not depend on the reduction thickness, rolling width, and rolling force. The following rolling systems considered feasible by the modification of existing plate mills were studied for introduction at the finishing mill of the plate mill at Nippon Steel Kimitsu Works.

(1) Work roll bending (WRB)

A bending force is applied to the neck of a work roll to compensate for the deflection of the work roll under the rolling load. The cost of this modification is the lowest. Since the bending force is severely restricted by the strength of the work roll neck and bearing, however, it is generally difficult to obtain a high control capability. The work roll bending method is often used in combination with other means. In the case of a plate mill with work rolls of long body length, the work roll bending effect applies only to the end of the roll body, and the control capability with respect to narrow plates is markedly reduced.

(2) Work roll shift (WRS)

The top and bottom work rolls are mutually shifted in the axial direction while maintaining their point symmetry with respect to the center of the mill. This work roll shift is designed to change the contact region between the work roll and the backup roll (BUR), thereby controlling the deflection of the work roll. The significant control of work roll deflection calls for a long shift stroke. The adoption of such a long shift stroke incurs a huge modification cost and requires the solution of various problems, such as the increase in the Hertzian stress developed between the work roll and backup roll, the decrease in mill spring, and the deterioration of plate threadability.

An available method to avoid these problems is the curved roll shift (CRS) mill that can accomplish large crown control with a short shift stroke by imparting a three-dimensional curve-based asymmetrical profile to the work roll. To obtain a large crown and shape control capability with a short shift stroke for the entire plate width range concerned, it is necessary to provide each work roll with a large diameter difference in the body length direction. In this case, the Hertzian stress between the rolls also becomes a problem, depending on the roll curve. When the CRS mill is adopted, therefore, the rolling width range over which the crown control is possible is severely limited in the realistic range of roll curves capable of controlling the Hertzian stress between the rolls to acceptable levels.

(3) Pair cross (PC)

The top and bottom work rolls and backup rolls are crossed as pairs in the rolling direction to change the rolling load distribution between the top and bottom work rolls in the width direction and to control their equivalent crown. The equivalent crown is proportional to the square of the plate width b. An extremely high crown control capability can be easily obtained with respect to wide plates up to 4,500 mm in width, and many and varied plate sizes (thicknesses and widths) can be accommodated. In the case of a pair cross mill, the equivalent crown control can be calculated regardless of the roll profile change during rolling, and the crown and shape can be constantly controlled with high accuracy.

Based on the above ideas, three systems, (1) WRS + WRB, (2) CRS-type WRS, and (3) pair cross, were comparatively studied. The pair cross mill was adopted as a result of this comparative study (**Fig. 7** and **Table 1**).

3.2 Overview of Kimitsu plate pair cross mill

3.2.1 Characteristics of pair cross mill

The Kimitsu plate mill went into practical use in February 1968. As main finishing mill modifications, a hydraulic automatic gage control (AGC) system was installed in 1978, the housings were replaced in 1981, the mill motor capacity was increased in 1983, and the conversion to the pair cross mill as reported here was made in 1991. The finishing pair cross mill is schematically illustrated in **Fig. 8**, and its main equipment specifications are listed in **Table 2**. The following two characteristics can be cited for pair cross mill application to plate rolling:

1) Wide shape and crown control capability

At the pair cross mill, the amount of crown control by the roll cross is proportional to the square of the plate width b as already described and expressed by the equation shown in **Fig. 9**[11]. The crown control range becomes extremely large for very wide materials (up to 4,000 mm in width), such as plates.

2) High-efficiency rolling

The pair cross mill can appropriately control the plate crown and shape independently of the rolling load and according to the rolling width by setting an adequate cross angle for each pass. This enables full-load rolling with heavy reductions in all passes by eliminating conventional shape forming passes[10] (light-reduction passes with the rolling load limited to form the desired crown and shape) in the latter rolling passes. In particular, the pair cross design can reduce the required number of plate rolling passes at a reversing mill and can sharply improve the rolling efficiency.

3.2.2 Overall configuration of control system

In the control system of the pair cross mill, the slab temperature, rolling load[12], plate thickness[13], plate crown, crown ratio change, and rolling shape (wave steepness)[14] are predicted by the

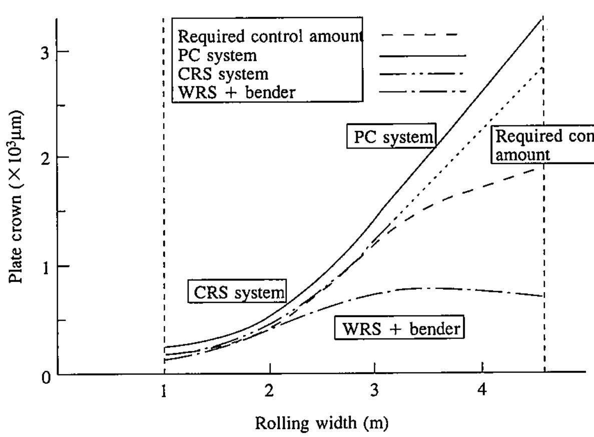


Fig. 7 Crown control capability comparison of plate rolling systems

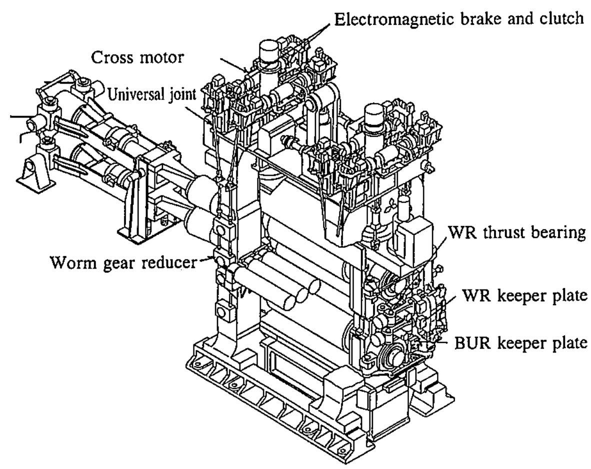


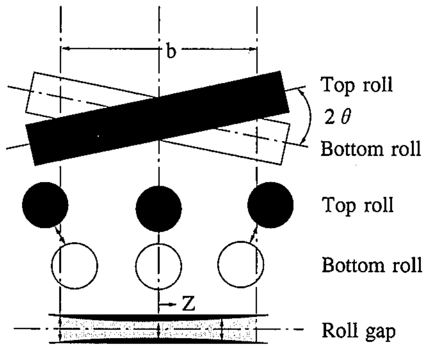
Fig. 8 General view of Kimitsu plate pair cross rolling mill

Table 1 Crown control systems studied for adoption at Kimitsu plate finishing mill

Type / Evaluation item	WRB Work roll bender	CRS Curved roll shift	PC Pair cross
Crown control capability	×	○	○
Rollable width	○	×	○
Hertzian stress between rolls	△	△	○
Overall evaluation	Not adopted	Not adopted	Adopted

Table 2 Main equipment specifications of plate pair cross finishing mill

Mill type	Four-high reversible pair cross mill
Rolling load	Normal maximum: 7,000 tonf
Rolls	Work rolls: 1,000 mm diameter×4,724 mm effective barrel length Backup rolls: 2,000 mm diameter×4,597 mm effective barrel length
Mill drive power	Capacity: 6,500 kW×2 motors Rated torque: 127 t·m×2 motors
Cross drive system	Motor-driven screw system, top/bottom, work side/drive side For top: DC 22/44 kW For bottom: DC 37/74 kW
Cross angle	Setup angle range: 0°-1.0°/roll Setup accuracy: 0.003° Setup speed: 0.092°/s



Amount of profile control in roll gap

$$K_{CROSS} = \frac{2}{D} Z^2 \cdot \tan^2 \theta$$

K_{CROSS} = equivalent roll crown resulted by roll cross
D = roll diameter
Z = distance from center of roll effective barrel length
θ = cross angle

(1) K_{CROSS} parabolically increases in axial direction of rolls.
(2) K_{CROSS} increases in direct proportion to square of cross angle and plate width.

Fig. 9 Effect of crown control by roll cross[11]

elementary models installed in the process computer. The reduction amount, cross angle, and WRB pressure for each pass are set so that each parameter assumes an optimum value. After actual rolling, the rolling temperature, rolling load, plate thickness, and plate crown data are modified to put the model-predicted values close to the actual values and to achieve rolling with highly accurate shape control[15].

The overall functional configuration of the pair cross mill control system is shown in **Fig. 10**. The process computer has the following four main functions:

1) Pass schedule calculation: The overall pass schedule, such as the delivery plate thickness, plate crown, cross angle and rolling temperature, etc. for each pass, is determined before rolling.

2) Roll profile estimating calculation: The roll wear and thermal profiles that change with time are estimated by calculation.

3) Adaptive control calculation: Actual values, such as the plate rolling load and temperature, are collected, predicted values are modified, and setup calculation for the next pass is performed with the progress of rolling.

4) Plate thickness learning calculation: When the actual delivery plate thickness of a pass is measured by a gamma-ray thickness gage, calculation is performed to modify the predicted plate thickness and crown. The results of the calculation are reflected in the subsequent passes.

Furthermore, within-plate thickness control and shape control can be dynamically performed by absolute-value AGC (aim-thickness AGC) with finishing mill DDC (direct digital control) and by WRB control.

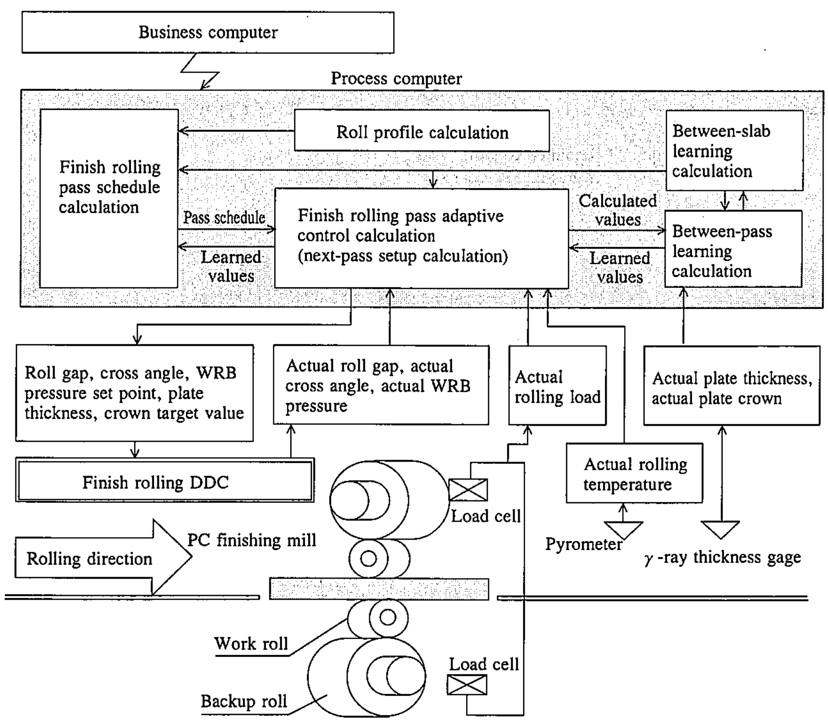


Fig. 10 Overall functional configuration of finish rolling control system

3.3 Development of heavy-reduction plate rolling technology

3.3.1 Theoretical shape and crown analysis model

The most salient feature of the pair cross mill is that the desirable plate shape can be obtained by controlling the plate crown independent of rolling force, it is necessary to estimate with high accuracy the crown and shape of the plate being rolled. The theoretical elemental models related to crown and basic to shape control in the new control system are described below.

1) Equations for calculating delivery plate crown

The plate crown at the delivery side of a rolling mill is determined by the deformation characteristics of both the mill and the slab. A huge amount of numerical calculation is generally required to calculate the delivery plate crown by considering all related factors. This type of research was made early[16,17], and methods for off-line calculation of delivery plate crown have been established to some degree[18,19]. These numerical analysis methods, however, cannot be directly applied to the actual setup and control of plate mills in view of the computing time and computer capacity required.

The Kimitsu plate pair cross mill adopted a simplified model[15], mainly composed of a model for calculating the equivalent plate crown (hereinafter referred to as the mechanical plate crown C_M) that can be accomplished on the condition that the rolling load should be uniformly distributed in the width direction.

Generally, the rolling load is not uniformly distributed in the width direction. The simplified model accounts for the nonuniform rolling load distribution by the mismatch between the mechanical plate crown C_M and the entry plate crown CI_{IN}^{FLAT} and determines the delivery plate crown C_{OUT} by the following equation:

$$C_{OUT} = (1-\eta)C_M + \eta(1-\gamma)C_{IN}^{FLAT} \qquad \cdots\cdots(1)$$

where γ is the reduction ratio (reduction thickness/entry plate thickness), and η is a parameter called the crown ratio inheritance coefficient and calculated as a function of the plate thickness, plate width and roll diameter, among other things. C_{IN}^{FLAT} is the entry plate crown converted into a flat shape through the entry plate thickness H_{IN} by considering the entry plate shape (elongation ratio difference) $\Delta\varepsilon_{IN}$ and is defined by the following equation:

$$C_{IN}^{FLAT} = C_{IN} - H_{IN}\Delta\varepsilon_{IN} \qquad \cdots\cdots(2)$$

where C_{IN} is the entry plate crown.

The mechanical plate crown is calculated next. Even if the rolling load is assumed to be uniformly distributed in the width direction, the calculation of roll deformation at a four-high mill is a statically indeterminate problem, and the roll deformation is generally calculated by numerical analysis techniques like an FEM (finite elements method). The Kimitsu plate pair cross mill adopted a simplified on-line model that obtains the deflection of the work rolls in the actual rolling condition by superposing the simple work roll deflection with a uniform load distribution between the work and backup rolls, and the work roll deflection changes with load distribution changes.

The following simplified equation to represent the mechanical plate crown C_M is derived by a method that assumes the imaginary mechanical condition (simple deflection condition), in which the load distribution between the work and backup rolls is assumed to be expressed only by linear and lower-order components of the width direction coordinates satisfying the conditions of equilibrium with the external forces (rolling load and work roll bending load), supposes a quadratic equation for the load distribution change superimposed in the actual rolling condition to resolve the conflict between the simple deflection condition, and calculates the resultant change in the work roll deflection through a coefficient that describes the effect of the gap distribution between the work and backup rolls on the work roll deflection:

$$\frac{C_M}{2} = C_W - C_{RW'} - \alpha_W(C_W + C_{RW'} - C_B + C_{RB'}) + C_F \qquad \cdots\cdots(3)$$

where C_W and C_B are the axial deformation of the work and backup rolls in the simple deflection condition, respectively; $C_{RW'}$ and $C_{RB'}$ are the initial radius difference (including wear and thermal profiles) between the plate center and crown definition point of the work and backup rolls, respectively; C_F is crown due to work roll flattening; and α_W[20] is a compensation term for the roll gap in the simple deflection condition.

The axial deformation C_W of the work roll and the axial deformation C_B of the backup roll in the simple deflection condition are directly affected by the rolling load P and the work roll bending load F, so that they can be expressed by the following linear equations of P and F:

$$C_W = P_{CW}\cdot P + F_{CW}\cdot F \qquad \cdots\cdots(4)$$

$$C_B = P_{CB}\cdot P + F_{CB}\cdot F \qquad \cdots\cdots(5)$$

The contribution term C_F of work roll flattening to the uniform load crown is given by the following simplified equation that allows for the flattening difference between the plate center and the crown definition point:

$$C_F = P_{CP}\cdot P \qquad \cdots\cdots(6)$$

P_{CW}, F_{CW}, P_{CB}, F_{CB}, and P_{CF} are the influence coefficients that depend on the physical properties of the rolls and the mill conditions.

Substituting Eqs. (4) to (6) into Eq. (3) and rearranging with respect to P and F yield the following equation:

$$C_M = \{2(1-\alpha_W)P_{CW} + 2\alpha_W P_{CB} + 2P_{CF}\}P + 2(1-\alpha_W)F_{CW} + 2\alpha_W F_{CW}\}F - 2(1+\alpha_W)C_{RW'} - 2\alpha_W C_{RB'} \qquad \cdots(7)$$

The coefficient P_M applied to the rolling load in the first term of Eq. (7), the coefficient F_M applied to the work roll bending load in the second term of Eq. (7), and the coefficient E_M applied to the third and subsequent terms of Eq. (7) are given by the following equation:

$$C_M = P_M\cdot P + F_M\cdot F + E_M \qquad \cdots\cdots(8)$$

Estimating calculation can be performed by this linear equation of P and F.

The following model equation is derived by adding the geometrical crown K_{CROSS}[1)] formed by the cross angle, the compensation terms K_1-K_9, and the learning term C_{OFFSET}.

$$C_M = \{P_M(K_1 b + K_2) + K_3\}\cdot P + \{F_M(K_4 b + K_5) + K_6\}\cdot F - 2K_7(1-\alpha_W)C_{RW'} - 2K_8\alpha_W C_{RB'} + K_9 + C_{OFFSET} + 2K_{CROSS} \qquad \cdots(9)$$

2) Plate shape model

The plate shape is represented by the elongation ratio difference $\Delta\varepsilon$ or wave steepness (wave height/wave pitch) λ. Assuming that the wave shape is a sine curve, Eq. (10)[21] holds between $\Delta\varepsilon$ and λ as shown in **Fig. 11**.

$$\Delta\varepsilon = \left[\frac{\pi}{2}\right]^2 \lambda^2 \qquad \cdots\cdots(10)$$

The delivery plate shape $\Delta\varepsilon_{OUT}$ is calculated by Eq. (11) from the crown ratio change by using the shape change coefficient ξ[14,22].

$$\Delta\varepsilon_{OUT} = \xi\left[\frac{C_{OUT}}{H_{OUT}} - \frac{C_{IN}^{FLAT}}{H_{IN}} - \delta\right] \qquad \cdots\cdots(11)$$

where H_{OUT} is the delivery plate thickness, and δ is used as a compensation term for the crown ratio change by considering the effect of the spread of the slab in the width direction.

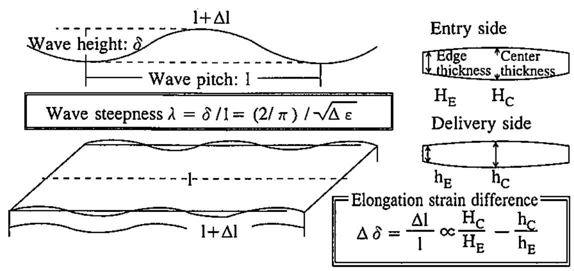


Fig. 11 Plate crown and flatness (wave steepness)

The pair cross mill aims at accomplishing a flat shape in all passes in principle or realizing what is called the constant-crown ratio rolling method[23]. For this reason, the value of C_M required to obtain the desired shape by using Eqs. (1) and (11) is determined when calculating the pass schedule. Rearranging Eqs. (1) and (11) to make both $\Delta\varepsilon_{IN}$ and $\Delta\varepsilon_{OUT}$ zero, the following equation is obtained:

$$C_M = \frac{1}{1-\eta}\left\{C_{OUT} - \eta H_{OUT}\left(\frac{C_{IN}}{C_{OUT}}\right)\right\} = C_{OUT} - \frac{\eta}{1-\mu} H_{OUT}\delta \quad \cdots\cdots(12)$$

When η and δ are given, C_M can be calculated from the target delivery plate thickness H_{OUT} and crown C_{OUT}.

3.3.2 Pass schedule calculation

The most important difference on draft scheduling (determining the reduction distribution per pass) is that the restriction on the number of rolling passes in plate rolling is much looser than that in hot strip rolling. It is necessary to determine a reduction schedule with an optimized number of rolling passes to meet the desired rolling shape (flatness) under the condition that the rolling load and torque should not exceed the maximum permissible capacity of the mill[24,25].

To strictly realize constant-crown ratio rolling with a good plate shape, the rolling operation must be carried out while optimizing the plate crown. If crown control is performed only according to the rolling load as is done at conventional plate mills, the optimum pass schedule greatly varies with such factors as the roll profile and the slab temperature. Selection of optimum percent reduction in the last half of the schedule is severely restricted as a result.

The pair cross mill reported here can effect crown control independently of the plate thickness, plate width and rolling load, entirely different from the conventional crown control method that is dependent on the rolling load. To make the most of this advantage of the pair cross mill, completely new logic was developed for determining the cross angle schedule together with the reduction distribution and for creating a pass schedule that would satisfy "rolling with a minimum number of passes (heavy reductions) and a constant crown ratio".

The new pass schedule calculation method is characteristic in that it takes heavy reductions under full load in all passes by considering the desired shape, unlike the conventional rolling with heavy reductions under full load in the early passes and forming the plate shape with light reductions in the later passes[25]. Using the shape change coefficient ξ, a continuous reduction distribution is realized by consistent logic that assumes that the shape change is insensitive to the crown ratio change in the thick-gage region and sensitive to the crown ratio change in the thin-gage region. **Fig. 12** schematically illustrates the concept of reducing the number of passes by the pair cross design. The restriction of the rolling load in the later passes, an indispensable requirement to ensure the desired shape in the past, is eliminated to increase the amount of reduction and to decrease the number of passes.

The new pass schedule calculation method simultaneously determines the reduction amount and cross angle of each pass by sequentially calculating from the final aim plate thickness and the aim plate crown toward the early passes. The method of determining the reduction amount and cross angle for each pass is schematically illustrated in **Fig. 13**. If the delivery plate thickness and crown are known, the target entry crown ratio for a pass is necessarily determined according to constant-crown ratio rolling as expressed by Eq. (11). The mechanical plate crown required for the pass is then calculated by Eq. (12). There is the range over which the plate shape is not disturbed by the change in the crown ratio. The range over which the mechanical plate crown permissible in terms of the plate shape is restricted can be estimated. The

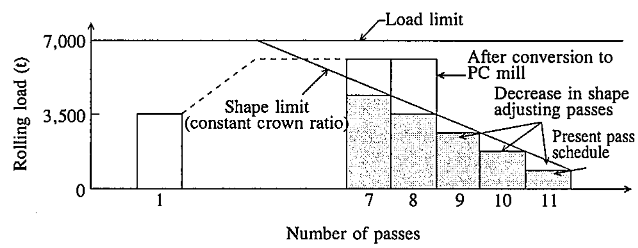


Fig. 12 Schematic illustration of concept of decreasing number of passes by pair cross mill

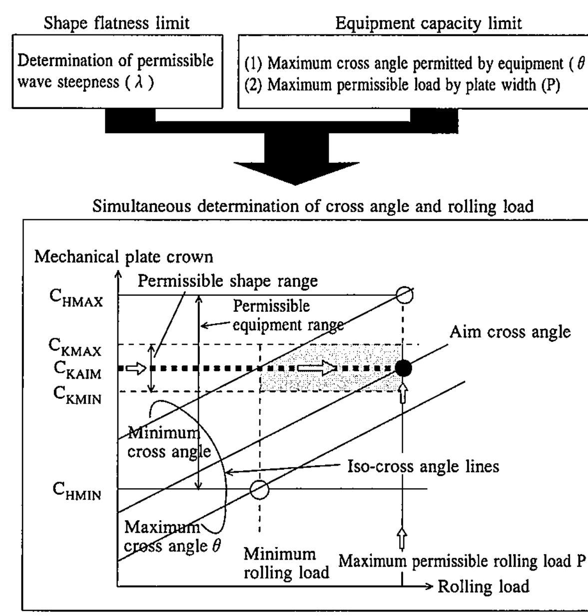


Fig. 13 Method of simultaneously determining reduction amount and cross angle for each pass

maximum, minimum, and aim mechanical crown are denoted by C_{KMAX}, C_{KMIN}, and C_{KAIM}, respectively.

The range of the mechanical plate crown that can be achieved in terms of mill equipment limits with rolling load and cross angle is calculated by Eq. (12). The maximum and minimum values of this mechanical plate crown are denoted by C_{HMAX} and C_{HMIN}, respectively. The range of the mechanical plate crown that meets both of the above-mentioned shape and equipment limits can be determined, and the operationally optimum rolling load and cross angle within this range can be freely sought. The optimum solution in plate rolling is heavy-reduction rolling with the desired shape. Since the crown control range by the cross angle is extremely large at this pair cross mill, it is possible to determine the value which provide the aim flat shape (C_{KAIM}) with the maximum rolling load in almost all cases. In this way, the reduction thickness and cross angle schedules for all passes can be determined by calculating the reduction thickness (rolling load) and cross angle per pass repeatedly from the later passes.

3.3.3 Roll profile estimating calculation

The roll profile is governed by thermal crown[26] and wear crown. It is especially important to determine the thermal crown with high accuracy. The problem of the on-line calculating load makes it necessary to introduce a somewhat simplified heat transfer model. A width-direction one-dimensional model in which the radial temperature distribution is assumed to be uniform was formerly used as excessive simplification. The one-dimensional model cannot accurately represent such physical phenomena as heat flux being restricted by the roll surface temperature. The new system reported here adopted a simplified two-dimensional FEM model that was developed by Hamauzu et al.[27] in which interpolation function approximates the radial temperature distribution with a few parameters. The roll wear model consisted of equations for estimating the roll wear profile from the rolling linear load and rolling cumulative length according to conventional findings.

3.3.4 Adaptive and plate thickness learning control

The elementary models comprising the control system invariably contains errors, such as material property estimation errors, temperature prediction errors and absolute accuracy errors due to model simplification. Adaptive control calculation and learning calculation perform the functions of determining these errors from the actual values collected by various sensors while rolling is under way and of correcting the preset controlled variables and learning model coefficients accordingly.

Adaptive and learning control can be divided by the timing of their execution into three types: (1) between-pass adaptive control, in which the roll gap, cross angle and other variables for the next pass are set and modified by using the rolling load, temperature and other variables of the previous pass; (2) plate thickness and crown learning control to be performed using gamma-ray thickness gages; and (3) between-slab learning control whereby when the rolling of one slab is completed, the model itself is modified to improve the setup accuracy for the next and subsequent slabs. A mill stretch model has an important role to play in plate thickness learning. In the mill stretch model adopted, the aforementioned roll deformation and backup roll chock oil film compensation are added to the measured mill stretch in the kiss roll condition (oil cylinder position variation measured with the top and bottom rolls in contact with each other). A sequential method of least squares that features excellent convergence and stability is employed as the plate thickness learning method, so that control accuracy can be improved online.

3.3.5 Within-plate shape control

In actual rolling, stabilization of the plate shape in the longitudinal direction is as important as improvement in setup accuracy by the process computer. Within-pass work roll bending control[28] by DDC was introduced for the purpose of reducing rolling load prediction errors and within-plate rolling load variations. Work roll bending is characteristic in that the mechanical plate crown can be adjusted as required to meet the actual metal-in situation, as compared with between-pass control by the cross angle. In addition to powerful between-pass crown control by the pair cross mill, work roll bending is provided with the function of finely forming the within-plate shape.

4. Results of Practical Application

The conversion of the finishing mill to the pair cross design enabled heavy-reduction (high-accuracy and high-efficiency) rolling. Heavy reductions materially improved mechanical properties and productivity, and substantially reduced the plate crown and improved the plate shape as a result of increased rolling control accuracy.

(1) Improvement in mechanical properties by application of heavy-reduction rolling

The application of heavy-reduction rolling improved various mechanical properties, facilitated the development of new products, reduced alloy consumption, eliminated some process steps, and stabilized production.

As one example, **Fig. 14** shows the effect of heavy-reduction rolling on the strength-toughness balance of Grade X80 sour gas line pipe steel (0.05%C-0.25%Si-1.3%Mn-Cr-Mo-Nb-Ti-Ca steel). Rolling with a heavy reduction of 20% in each pass improved strength and low-temperature toughness sufficient for the Grade X80 line pipe and permitted the commercial production of the Grade X80 line pipe.

(2) Improvement in productivity (decrease in number of passes) by heavy-reduction rolling

Fig. 15 shows an example of decrease in the number of rolling passes by heavy-reduction rolling. The plate crown was controlled

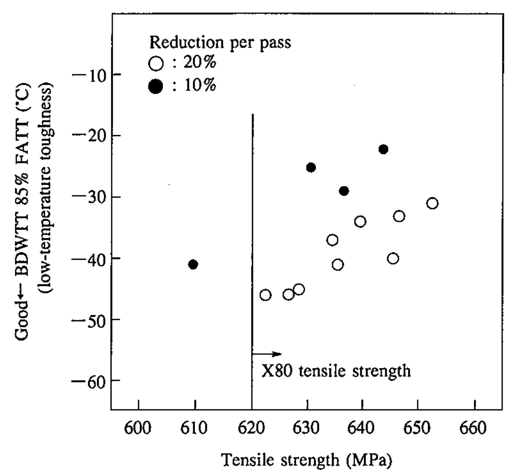


Fig. 14 Effect of heavy-reduction rolling on strength-toughness balance of X80 sour line pipe steel

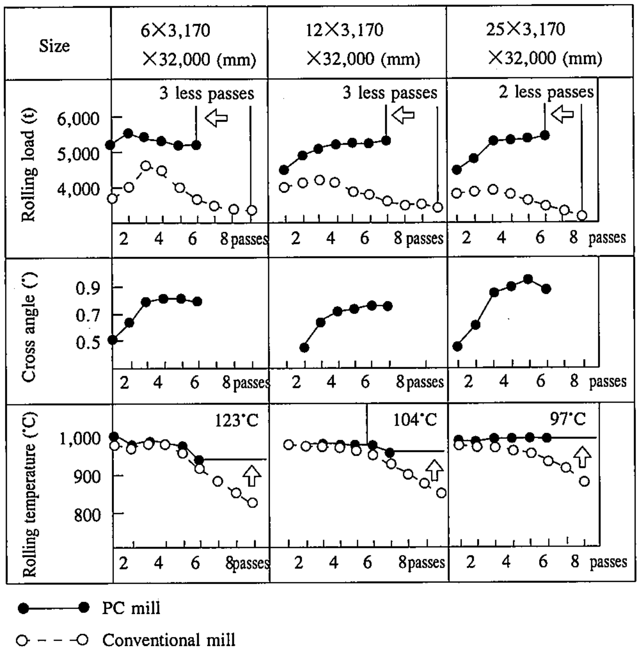


Fig. 15 Examples of heavy-reduction pass schedules after conversion to pair cross mill

independently of the plate thickness (rolling load) by taking advantage of the powerful crown control capability of the pair cross mill, and conventional light-reduction shape forming passes were eliminated. The avoidance of excessive drop in the rolling temperature in the final finish rolling stage also contributed to stabilization of the rolling operation.

(3) Plate crown reduction

Fig. 16 shows plate crown redution by plate width.
At conventional mills, work rolls have sine-ourved roll crowns to reduce plate crown caused by roll deformation. However, because the sine-curved roll crown has less effect on narrow plates than on wide ones, the crowns of narrow plates are larger than those on wide plates. Plate crown control independent of the plate width and rolling load was achieved at the pair cross mill.

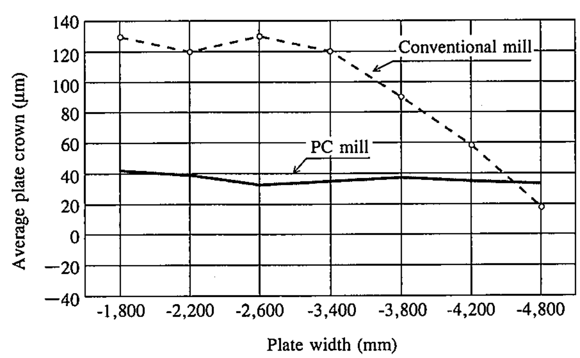


Fig. 16 Improvement in plate crown by plate width

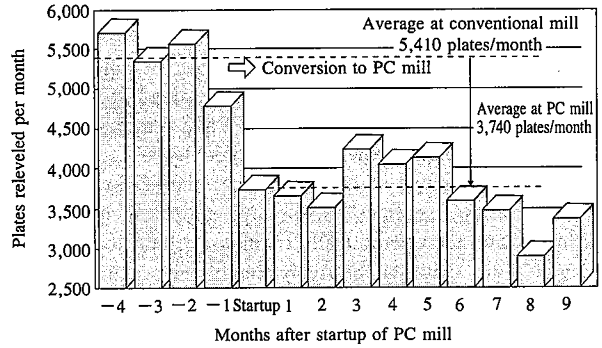


Fig. 17 Improvement in rolling shape

(4) Improvement in plate shape

Fig. 17 shows the improvement in the plate shape of plates. The releveling ratio of plates was significantly reduced by building and applying a rolling control system that embodied the above-mentioned plate shape and crown control theory. However, truly stable plate shape is not yet accomplished in the light-gage region of 6 mm or less. Future accuracy enhancement of the elementary models is one of the future challenges.

5. Conclusions

The pair cross mill introduced as the world's first for plate rolling at the Kimitsu Works of Nippon Steel is contributing to marked improvements in mechanical properties, productivity, yield, and quality through the realization of heavy-reduction (high-accuracy and high-efficiency) rolling. The development of heavy-reduction rolling metallurgy and rolling control technology have been introduced above as contributing factors for the development of the heavy-reduction rolling technology at the pair cross mill.

This development was awarded the "1996 Okochi Memorial Production Award" for the outstanding contribution of the pair cross mill toward the progress of production technology in industry.

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