1. Introduction

Steel plates are being used under increasingly tough conditions with the latest increase in energy demand. Such tough use conditions include those in arctic regions and deep waters; accordingly, low-temperature toughness, ultra-heavy gauge, and other new property items came to be required for the product in addition to high strength, which fact calls for innovative process technologies. In view of growing demand for plate products, new plate mills have been constructed and the production capacities of various others in China and Korea. Consequently, Japanese plate manufacturers have to further cut their production costs. In consideration of such latest market change, Nippon Steel Corporation and Sumitomo Metal Industries Co. Ltd., the predecessors of Nippon Steel & Sumitomo Metal Corporation, developed wide varieties of technologies for plate manufacturing processes. The present paper outlines distinctive ones of such technologies.

2. Slab Heating Control

As reheating furnaces were added to the plate mill lines to meet the increasing demands for heavy plates for energy-related applications, improvement of fuel consumption became an important issue. To reduce unit consumption of fuel, automatic combustion control models have been developed. Advanced numerical models have been worked out to reduce energy consumption, raise product yield, and enhance process control accuracy. The companies developed their own versions of thermo-mechanical control processes (TMCP) and equipment capable of accurately and evenly cooling plates within a wide range of cooling rates. Advanced vertically integrated quality control systems support the plants to appropriately respond to customer requirements in a timely manner.
center and the lower surface) in the middle furnace position. For example, in the case of slab j in Fig. 2, the temperature rise $\Delta T_{f,3}$ in the No. 2 heating zone (2HZ) and the same $\Delta T_{f,4}$ in the soaking zone (SZ) are determined by the linear programming based on (a) the difference between the final slab temperature $T_{m0}$ expected at position $k = 3$ and the target discharge temperature $T_{m\text{aim}}$, (b) the difference between the expected soaking degree $T_{sc0}$ and the target soaking degree $T_{sc\text{aim}}$, (c) the difference between the expected slab temperature $T_{mk0}$ and the aimed slab temperature $T_{mk\text{aim}}$ at $k = 3$, and (d) the difference between the expected soaking degree $T_{sck0}$ and the aimed soaking degree $T_{sck\text{aim}}$ at $k = 3$.

Figure 3 shows an actual temperature record of a reheating furnace working under automatic combustion control. The model makes it possible to get the target slab discharging temperature without insufficient heating by minutely controlling the furnace temperature in the 2HZ. As the application ratio of the automatic control increases, the unit fuel consumption has improved by 2.5% from that by conventional manual control.

### 3. High-precision Rolling Control

High-functionality plates, typically those of high-strength steels, are manufactured usually by applying the thermo-mechanical control process (TMCP) to steels containing alloy elements in high quantities. Because their hot deformation resistance is very high, the number of rolling passes increases and it is hard to obtain high dimensional accuracy in terms of gauge, flatness, etc. In addition, because of high contents of alloy elements, unit steel cost is high, and a small decrease in production yield results in considerable loss. Some examples of measures taken in plate rolling to secure desired quality of high-functionality products are presented in this subsection.

#### 3.1 Shape control

Controlled rolling (CR) of plates in Japan started in the 1960s. As it became widely practiced, the increase in the rolling load due to low-temperature rolling became conspicuous, and equipment such as the mill housing was damaged. To prevent such troubles, plate mills became larger through reinforcement of housings and other measures. More recently, new shape-controlling mills such as pair-cross (PC) mills were built, which has made it easier to practice controlled rolling at high reduction and achieve good flatness and dimensional accuracy.

Figure 4 shows a conceptual diagram for setting the pass schedule of plate rolling. In step 1 (in circle in the diagram), the rolling load at the final (n-th) pass is defined based on the product thickness and the target plate crown, then in step 2, the reduction to obtain the final rolling load is calculated, and the plate thickness $h_{n-1}$ at the exit from the previous ((n−1)-th) pass is determined, and in step 3, the rolling load at the (n−1)-th pass is determined such that the crown ratio (as defined in Fig. 5) is kept unchanged and flatness is not disturbed. The entire pass schedule for a slab is determined by thus repeating steps 2 and 3 backwards from the final pass (pass scheduling for constant plate crown). Naturally, if the calculation result exceeds the upper limits of the rolling load, torque, etc. of the mill, they must be adjusted to fall within the mill capacity.

For heavy-reduction rolling of plates, it is necessary to adequately control the plate crown at the final pass (determined in step 1) and keep the crown constant (step 3 above), and the use of shape-controlling mills capable of changing plate crown during rolling is increasing for this reason; in fact, Nippon Steel & Sumitomo Metal operates a back-up roll bending (BURB) system at Nagoya Works and a PC plate mill (shown in Fig. 6) at Kimitsu Works.

A PC mill controls plate crown by turning the upper set of rolls (work roll (WR) and back-up roll (BUR)) horizontally in one direction and turning the lower set of rolls (same) in the opposite direction such that they cross each other on the mill center line. The roll pass schedule calculation for a PC mill is the same as that for a conventional one explained above in that it goes backwards from the final pass to the first. However, taking advantage of the large crown control capacity of the mill to be free from the limitation of rolling load to keep plate crown constant, the reduction at each pass is in-
creased and the number of passes is smaller. Figure 7 compares the pass schedules before and after the introduction of the PC mill; the number of passes has been decreased by two to three for each slab. This has significantly improved productivity, and in addition, made it possible to roll thin gauge plates stably owing to the lower temperature drop.

Heavy-reduction rolling is also effective at improving product quality. Figure 8 shows the effect of the reduction ratio on the strength–toughness balance of steel plates for API X80 sour-resistant line pipes; tensile strength and low-temperature toughness have been improved by increasing the reduction at each pass from 10% to 20%.

3.2 Yield improvement

As the steel cost of high-functionality plates is high as stated earlier, yield improvement is essential for cost reduction. Two important yield improvement measures peculiar, i.e., geometry control and edge bulging control, which are to plate products are presented below.

3.2.1 Planar shape control

Common rolling procedures for steel plates are given in Fig. 9. The most characteristic feature of plate rolling is broad-side rolling with the slab turned by 90° on the roller table, and in this relation, control of plate width and planar shape is decisive for improving yield.

A technique called “draft alteration before turn (DAT)” was introduced to the plate mills of Kimitsu and Oita Works; it is a method for controlling planar shape by applying thickness difference in the length direction by using automatic gauge control (AGC). More recently, for more accurate shape control, an attached edger has been installed at each of the plants.

The plate mills of Nagoya and Kashima Works use detached edgers for planar shape control; that of Kashima Plate Mill is a hydraulic edger capable of changing width reduction during a rolling pass. This is effective for short-stroke edger rolling to prevent head and tail narrowing or width shortage, which is likely to occur through conventional practice. The principle of the short-stroke edger practice is explained in Fig. 10. The narrowing at the head and tail is minimized by decreasing width reduction at the head and tail of a plate to increase production yield.8, 9 Figure 11 shows the yield improvement effect of short-stroke edger rolling. The yield has been improved owing to the less crop loss and edge trimming than by...
conventional fixed edger pass rolling.

3.2.2 Estimation of edge bulging and its reduction

The number of rolling passes increases as steel strength increases, and bulging of plate edges as shown in Fig. 12 (called double bulging) increases as the number of passes increases, leading to larger yield loss. Studies on bulging shape prediction models are being conducted to clarify the mechanism of its formation.10–13 Table 1 summarizes the growth of edge bulging during plate rolling. The bulging becomes larger as the product thickness increases and the reduction at each pass decreases; it is larger near the tail end at each pass. All these indicate that large double bulging occurs at the slab head and tail during broadside rolling, which is done while the slab is still thick. In particular, in rolling of high-functionality plates, the reduction in each pass tends to be small and the bulging is likely to be large as the hot deformation resistance of the steel is high.

An example of bulging shape obtained through FEM analysis is given in Fig. 13. The sectional shape can be approximated accurately using the following quartic equation:

\[ y(x) = ax^4 + bx^2 \]  

where \( x \) is a dimensionless figure of the distance from the thickness center divided by a half of the plate thickness, \( y \) is the bulging at position \( x \) assuming that the bulging at the thickness center is 0, and \( a \) and \( b \) are coefficients, which can be obtained from \( \delta W_m \), \( \delta W_s \), and \( D_m \) in Fig. 13.

\[
\begin{align*}
  a &= \frac{\delta W_m D_m^2 - \delta W_m}{D_m^2 (1 - D_m^2)} \\
  b &= \frac{\delta W_n - D_m^2 \delta W_s}{D_m^2 (1 - D_m^2)}
\end{align*}
\]

The above three parameters that define the bulging shape can be expressed using the following rolling parameter \( \psi \):

\[
\psi = \frac{\ell_d}{H_i} = \sqrt{R/H_i} = \frac{\sqrt{R \cdot \Delta H}}{H_i}
\]

where \( \ell_d \) is the contact arc length, \( H_i \) the entry plate thickness, \( H_e \) the exit plate thickness, \( \Delta H \) the reduction, and \( R \) the work roll diameter.

Edge bulging shape per pass was estimated by FEM analysis changing rolling conditions, and the values of \( \delta W_n \), \( \delta W_s \), and \( D_m \) were determined for the bulging shape thus obtained. Figure 14 shows their relationship with the rolling parameter \( \psi \). Regression equations were formulated on the basis of the result of the above in the range of \( \psi \) from 0 to 1, and a formula for predicting the bulging shape has been worked out. A similar formula applicable to the bulging in the head and tail ends of a plate has also been worked out in the same manner.11

With a plate mill equipped with an edger stand, it is necessary to predict the bulging shape change due to edging (width reduction).12
The result of a laboratory test on the double bulge remaining after an edging pass; it is possible to express the size of bulging after edge rolling as a function of the ratio of sectional area reduction $V_R \times D_m$. It is clear from Fig 15 that even after an edging pass at a sectional area reduction ratio of 1.0 or a reduction equal to the formation of double bulging, the ratio of remaining bulges stays below 1.0. This indicates that to completely wipe out the double bulges by edging, a reduction 1.5 times the bulging or more must be applied.

As has been explained above, predicting the edge bulging shape after rolling passes became possible. To decrease the bulging by high-reduction edging, the prediction accuracy was verified through test rolling of hard steels with which the size of edge double bulging tends to be large (see Fig. 16). However, note that the planar geometry is affected by the change in the edge rolling condition to decrease the edge bulging, and it is necessary to find out an optimum rolling condition to obtain good planar geometry with edge bulging as small as possible, which is yet to be studied.

### 3.3 Manufacturing special-shape plates

Manufacturing plates of different dimensions in one piece is a recent commercial practice of plate rolling. This is done by combining products of different thicknesses or widths in a same slab to increase slab weight and raise productivity.

In shipbuilding and other industries, steel plates having two or three thicknesses lengthwise or gradually changing thickness (longitudinally profiled (LP) plates) are used to eliminate welding work or reduce structural weight. Longitudinally profiled plates are produced by gradually changing the mill screw down according to the desired taper. Nippon Steel & Sumitomo Metal can manufacture different types of such special-shape plates as given in Fig. 17.

Figure 18 shows the methods of rolling differential-thickness plates. Different methods are employed depending on the thickness difference: type 1 is suitable when the difference is small, and types 2 and 3 are used as the difference increases. Longitudinally-profiled plates are rolled under tracking of longitudinal position of a plate and continuously changing the roll gap. Here, absolute gauge-meter AGC is instrumental in accurately obtaining desired taper shape in the longitudinal direction; it defines the plate thickness at the mill exit on the basis of the change in rolling load as the roll gap is changed.

When handling special-shape plates, small deviation in the plate positioning in the shearing process will lead to significant gauge error; for this reason, these plates used to be gas-cut off line. Recently on-line cutting has been made practicable thanks to high-precision sensors such as laser thickness meters.

### 3.4 Schedule-free rolling

The width of plate products ranges from 1 to 5 m. To minimize the deterioration of plate crown and flatness caused by work roll
profile change due to its wear and heat crown, plates are rolled in a one-roll campaign in descending order of width; this rolling order is known as a coffin pattern. However, high-functionality plates are often ordered in small lots, their reheating temperature is different from that of ordinary products, and they often require slow cooling after rolling. If they are to be rolled according to the coffin pattern, they will hinder smooth production and energy saving: the tonnage per roll campaign may decrease, and the charging temperature of hot-charge slabs to the reheating furnaces lowers because of waiting for their roll chance. Considering such problems, measures for schedule-free rolling without the width restriction have been developed and introduced (see Fig. 19).

An on-line roll dressing system using abrasive jet was developed at Kashima Works, which made schedule-free rolling viable. The method consists of spraying abrasive powder with high-pressure water onto the work roll surface. The spray nozzle developed for the system is shown in Fig. 20; to prevent the piping from clogging, the water and the abrasive powder are fed via separate routes, and mixed immediately before being sprayed.

Figure 21 shows an example of roll profile improvement by the roll dressing system fitted to the plate finishing mill of Kashima Works. The dressing is applied to smooth out surface unevenness in predicted roll wear profile, and at actual profile measurement after rolling operation, the roll surfaces were found to be substantially free of unevenness. Thus the system proved effective at expanding roll chances, reducing the frequency of work roll changes to a half, and raising the working rate of the mill.

An on-line roll grinder (ORG) system has been introduced to the plate mill of Oita Works to remove the local wear of work rolls due to rolling of plate edges. Figure 22 schematically illustrates the ORG system. Two grinder heads mounted on a frame on the down-stream side of the mill housing are provided for each work roll; flat-disc grinding wheels are selected for long service life. In plate rolling, short rolling passes succeed one after the other at short intervals, and grinding between passes is difficult; therefore, the rolls are ground during the interval between slabs or during the slab turn after broadside rolling (see Fig. 23).
A process named the Sumitomo High Toughness (SHT) Process, developed by Sumitomo Metal, has led to the development of many such technologies in Japan. The forerunners of Nippon Steel & Sumitomo Metal developed many such technologies by themselves. TMCP was developed in Japan; the forerunners of Nippon Steel & Sumitomo Metal developed many such technologies by themselves. A process named the Sumitomo High Toughness (SHT) Process was introduced to Kashima Works in 1975. It was unique in that desired material structure was obtained during plate rolling by cooling to below a transformation point and then reheating to prescribed temperature. However, because it involved additional steps to heat and roll the plates for a second time, it was inconvenient for production increase, and it is not practiced today.

Another technology to control material structure by on-line accelerated cooling alone was developed, and accordingly an on-line direct quenching (DQ) facility was installed at Kashima Plate Mill Plant in 1979. Then, what would become the prototypes of the present accelerated cooling equipment were constructed at Kashima and Kimitsu Works in 1983. The inventor companies named their respective processes differently; the process of Kimitsu was called the Continuous on-Line Control (CLC) Process, and that of Kashima was called the Dynamic Accelerated Cooling (DAC) Process.

The CLC process is characterized by hot leveling and cooling under restriction. A new type of cooling nozzle was developed in 2005 as an improvement to the CLC, which enabled homogeneous cooling even at low cooling rates; then, a new cooling facility capable of homogeneous cooling across a wide range of cooling rate, named the CLC-μ, was installed at Kimitsu (see Fig. 25).

Likewise, DAC was also improved; in 2010, the then Sumitomo Metal Industries combined a high-precision cooling model of its own development with MULPIC, European equipment for accelerated cooling used at many plate mills worldwide, and constructed a new cooling system called DAC-n (see Fig. 26) to realize homogeneous cooling and enhanced accuracy of the cooling-end temperature.

Both these facilities have been instrumental in stably manufacturing high-end products such as the plates for super-high-strength line pipes of API X100 or higher grades, those for sour-resistant, thick-wall line pipes, off-shore structures, penstocks, and high-Ni plates for LNG tanks.

4. Thermo-mechanical Control Process (TMCP)

The thermo-mechanical control process (TMCP) to control heating, rolling, and cooling of steel on line to improve strength, toughness, weldability, and other property items is widely practiced in steel plate production. Many of the fundamental technologies of the TMCP were developed in Japan; the forerunners of Nippon Steel & Sumitomo Metal developed many such technologies by themselves. A process named the Sumitomo High Toughness (SHT) Process was introduced to Kashima Works in 1975. It was unique in that desired material structure was obtained during plate rolling by cooling to below a transformation point and then reheating to prescribed temperature. However, because it involved additional steps to heat and roll the plates for a second time, it was inconvenient for production increase, and it is not practiced today.

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the work rolls and the BUR sections using load cells, (2) estimates the transverse distribution of the load between the plate and the work rolls from the readings of the load cells, and (3) controls the positions of the BUR sections during processing such that the transverse load distribution becomes even.

6. Production Scheduling

To maintain a production quantity, secure a reasonable profit margin, and expand the share in the steel plate market under oversupply from countries such as China, it is now imperative for Japanese steelmakers to strengthen not only cost competitiveness but also non-cost competitiveness, which includes higher product performance and functionality to meet customer requirements, ability to propose solutions covering up to the final use of the products and delivery capacity (short delivery and shipment-ready ratio). The measures taken to enhance delivery capacity are explained below.

As a matter of policy, Nippon Steel & Sumitomo Metal covers, all the plate market sectors from general-purpose to high-end products. Consequently, the ratio of products that require finishing after rolling is increasing, and the bottleneck process in the plate mill plant changes from time to time depending on the product mix. To maintain high shipment-ready ratio and minimize the opportunity loss of every production facility (or maximize marginal profit), the Company has developed various techniques to optimize input for quarterly and monthly production plans and breaking them down into weekly and daily schedules.

6.1 Development of production time prediction

The production time of each plate order depends on the pattern of necessary finishing processes. Considering this, to define the process route pattern of each order, decision trees have been composed on the basis of past operation data (see Fig. 27). A model has been developed to estimate the production time for a process route pattern (i) (mean processing time $\mu_i$ and its standard deviation $\sigma_i$) has been formulated combining the decision trees and the processing time parameters for each process (j) (mean processing time $\mu_j$ and its standard deviation $\sigma_j$), which are derived also from past operation data (see equation (4)). Work tools have been provided to support the people responsible for order input. All these in combination made it possible to optimally input orders to the quarterly and monthly production plans, maintain the shipment-ready ratio high, and shorten the average production time of orders by one to three days.

$$\mu_i = \sum p_i \mu_i, \quad \sigma^2_i = \sum p_i \sigma^2_i$$ (4)

$P_i$: if or not process route pattern i includes finishing process j

$\mu_j$: mean processing time at process j

$\sigma_j$: standard deviation of processing time at process j

6.2 Development of optimum converter-caster scheduling

Customers’ orders compiled in the above manner into quarterly and monthly production plans avoiding bottlenecking are then broken down into weekly and daily rolling and processing schedules without bottlenecking. A method has been developed also for tapping/casting scheduling to maximize the number of sequential heats (lot) of a steel grade in consideration of the plate production schedule. Tapping/casting tonnage for each lot defined by steel grade and plate processing pattern is set by mixed integer programming so as to minimize the evaluation index (equation (5)) covering the number of sequential heats of the converter, the tapping/casting deadline date, and even loading of plate finishing processes under the conditions of equipment capacity and other restrictions.

$J_1 = \sum \delta_i \cdot \text{number of steel grade changes at casting}$

$J_2 = \sum \left( \sum \delta_i \cdot \text{late delivery} \right)$

$J_3 = \sum \left( \sum \delta_i \cdot \text{overflow exceeding capacity of plate finishing processes} \right)$

$W_p, W_w, W_f$: weighting factors

$x_{ij}$: number of steel grade changes at casting

$\delta_i$: number of finishing processes

$\delta_i$: number of steel grade changes at casting

$\delta_i$: number of finishing processes

Evaluation function

$J = W_1 J_1 + W_2 J_2 + W_3 J_3$ (5)

Sequential heats of the converter, the tapping/casting deadline date, and even loading of plate finishing processes under the conditions of equipment capacity and other restrictions.

7. Enhanced Quality Control

Quality identification in producing plates of widely varied speci-
fications and sizes and correctly assign them to individual orders is essential for securing customers’ confidence. Requirements of customers are becoming increasingly varied as stated earlier. On the other hand, because of the generation change of employees at production plants, difficulty in quality identification is increasing. In consideration of the situation, a quality identification control system has been constructed based on information communication technology (ICT) to improve customers’ confidence and productivity of the plate finishing processing. The ICT employed here features digital micrometers, data transmission terminals, and speech recognition devices based on a personal digital assistance (PDA) system (see Fig. 29). The introduced quality identification control system assures reliable work structure of quality identification and has reduced the time for plate finishing processing to half of what it was in the past.

8. Closing
As described, advances of different production and control technologies have enabled manufacturing high-functionality plate products for various applications. In addition to the efforts to produce high-end products smoothly, stably, and at lower costs, it is necessary for us to bend efforts on technical development to offer plate products of higher grades combining multiple functionalities such as sour-resistant X80 plates and those for high-heat-input welding excellently in low-temperature toughness.

The principal subjects to attain this end include:
(1) Further advance of the TMCP technology to ensure good flatness stably in slow to rapid cooling,
(2) Incorporation of desired material quality in products through vertically integrated processes from steelmaking—casting of slabs excellent in surface and internal quality,
(3) New technologies to enable manufacturing high-functionality steel plates at lower costs (high-precision rolling, uniform cooling, etc. to attain an extreme in product yield), and
(4) Optimum production control system to deliver products to customers in a timely manner.

None of these is achievable in a short period, but we shall continue bending efforts to accelerate technical breakthroughs to better respond to customers’ requests making the most of the technology that has been accumulated.

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