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Development of Steel Plate Manufacturing Technologies at Kawasaki Steel

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1 Introduction

Kawasaki Steel manufactures steel plates at its Mizushima Works using the world's largest class 4-high reversing mill, which is capable of rolling products with a maximum width of 5 350 mm. Since the plate mill began operation in 1976, computer control for various equipment and automation devices have been positively intoroduced with the aim of manufacturing high quality products with high efficiency.[1-3]

From the second half of the 1970s, following the Oil Crisis, through the first half of the 1980s, plate manufacturing technology made great progress in resource saving, including technologies for yield improvement, as represented by plan view pattern control, and energy saving, as represented by hot charge rolling. In the field of yield improvement, Kawasaki Steel was the first steelmaker in the world to develop and apply MAS (Mizushima automatic plan view pattern control system) rolling in a practical operation,[4] and advanced this technology into a trimming free plate production process in the latter 1980s.[5]

Among mechanical property control technologies, TMCP (thermo mechanical control process), which uses accelerated controlled cooling after rolling, was applied in a practical operation in the early 1980s, and has had an important effect in improving the performance of steel plates, including improvement of the weldability of high strength steels by reduction of the carbon equivalent, etc. Kawasaki Steel installed accelerated cooling device in 1983,[6] and has been supplying high performance steel plates for shipbuilding, construction, line pipe, and others.

Since the latter 1980s, the tasks required of plate manufacturing technologies have largely focused on the development of high performance steel plate manufacturing technologies, which respond to a higher level of customer requirements, and the development of FA (factory automation) technologies, which make it possible to improve the level of quality assurance. The report presents an outline of the progress in steel plate manufacturing technologies at Kawasaki Steel in recent years.

2 High Performance Steel Plate Manufacturing Technologies Responding to Customer Requirements

2.1 Plate Thickness Control Technology

Thickness accuracy on plate rolling improved dramatically with the introduction of hydraulic AGC (automatic gauge control) in the latter 1970s. Subsequently,

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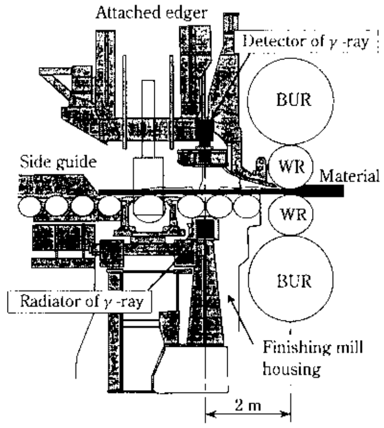

Fig. 1 Schematic view of proximate γ-ray thickness gauge

Kawasaki Steel undertook the challenge of achieving an even higher level of thickness accuracy by improving controllability, which was achieved by developing sensors based on a new concept and replacing control devices, applying a new control method to the unsteady-portions at the head and tail ends of plates, and other means.

The first of these efforts which deserves special mention was the proximate γ-ray thickness gauge, which was used for the first time in the world in 1987.[7] Separating the radiator and detector and attaching each to the mill housing separately, as shown in **Fig. 1**, made it possible to install this device in close proximity (2 m) to the finishing mill. The area around the plate rolling mill is an extremely severe environment for installing a precision device such as a thickness gauge, being characterized by high temperature, high humidity, and very large shock and vibration at the time of roll bite. These environmental problems were overcome by keeping the detector in a thermostat with a mechanical damper type shock absorber.

The hydraulic AGC system, which is extremely important as the actuator for thickness control, was renovated in 1994. Response was dramatically improved by adopting direct acting servo valves, which have excellent response and resistance to environmental factors, and by mounting the servos directly on the cylinders.[8] **Figure 2** shows the configuration and functions of the new AGC system. Functions which require high response are processed by an exclusive use controller in the hydraulic cylinder position control device, while other functions are processed by the DDC (direct digital control) of the screwdown system. In cylinder position control, a high speed cycle of 1 ms was realized by adopting a DSP (digital signal processor).[9] It might also be mentioned that, in this revamping, a dual AGC function, which is capable of controlling the right and left cylinder independently, and a cross control function, which compensates for differences in the response of the two cylinders, were also introduced. In addition, the controllability of monitor AGC, which is combined with the proximate γ-ray thickness gauge, was improved by adopting lost time compensation using tracking and identifying mill modulus error and gauge meter error during rolling.[10] **Figure 3** shows a block diagram of the new monitor AGC control system.

Thickness accuracy at the head and tail ends, in other words, in unsteady-state portions, can be broadly classified according to factors related to setup accuracy before AGC operation and factors related to response delay after AGC operation. Kawasaki Steel estimated the steep temperature changes at the head and tail ends which occur due to response delays after AGC operation, and developed a feed-forward system that compensates for

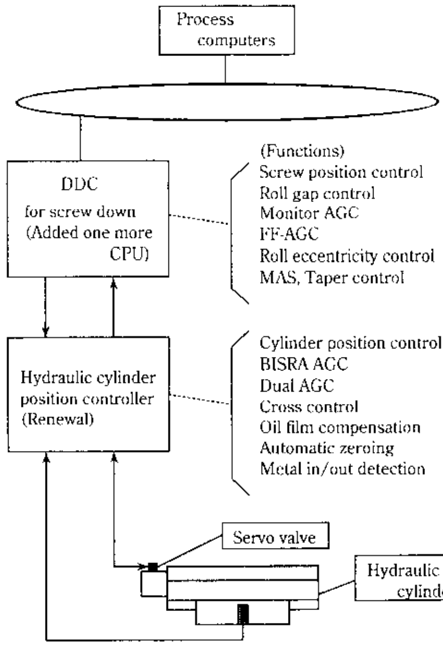

Fig. 2 Configuration of new AGC system

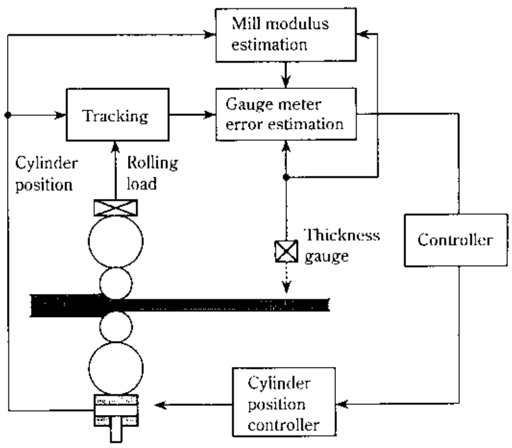

Fig. 3 Block diagram of new monitor AGC control

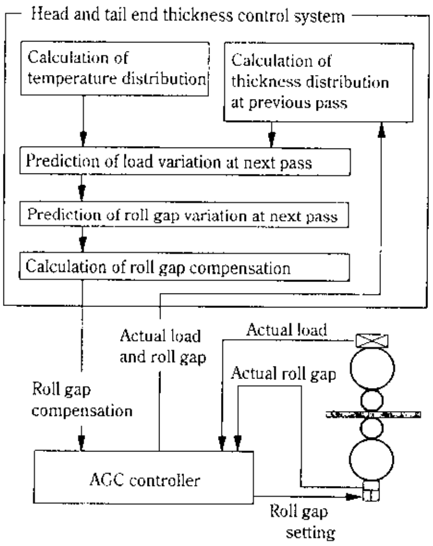

Fig.4 Configuration of head and tail end thickness control system

AGC response delays.[11] **Figure 4** shows the configuration of the control system. In estimating the temperature at the head and tail ends, a newly developed 2-dimensional analytic temperature model is used. Load variations are predicted form the estimated temperature distribution, the roll gap distribution is then calculated using the gauge meter method. Consequently, the amount of roll gap compensation is decided considering AGC response delay.

2.2 Improvement of Plate Width and Length Accuracy

In applications such as tanks and car carrier decks, recutting by the user is not necessary if the plate width and length accuracy are satisfactory. Because a higher level of dimensional accuracy than that in the JIS standard had long been desired in such applications, Kawasaki Steel carried out a variety of development work aimed at realizing the required accuracy.

As mentioned previously, Kawasaki Steel developed and applied the trimming free plate production process in the second half of the 1980s as a plan view pattern control technology.[5] In this process, in order to make a high level of width accuracy into plates in the rolling stage, it is necessary to use a milling machine rather than the conventional side shear as the shearing line equipment for finishing the plate width. Therefore, in 1987, a milling machine was installed between the side shear and the end shear.[12,13] **Table 1** shows the specifications of the milling machine. The cutter is a helical milling type, which is inclined 25° in the direction of forward plate movement, so enables a maximum cutting depth of 20 mm per side under high feed speed. **Figure 5** shows examples of the product width accuracy in plate width finishing when the milling machine is used in the

Table 1 Specifications of milling machine

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

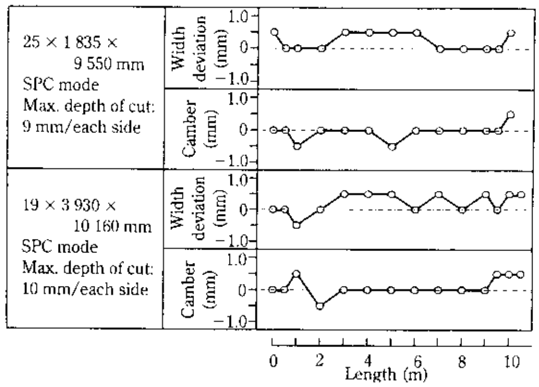

Fig. 5 Cutting accuracy of SPC mode by milling

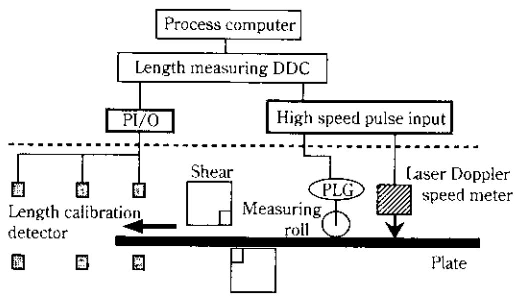

Fig. 6 System configuration of plate length meter

SPC (straight position control) mode. This process realizes a high accuracy of ± 0.5 mm in both width deviation and straightness in the longitudinal direction, which had been impossible with conventional shear cutting, and thus makes it possible to respond fully to the customer requirement of omitting recutting.

Kawasaki Steel also has been studying to improve product length accuracy. Because it was necessary to improve the accuracy of shearing with the end shear, a new method of measuring the plate length to determine the shearing position was developed as a replacement for the conventional measuring roll method, and was applied to the actual operation in 1997.[14] **Figure 6** shows the configuration of the new length measurement

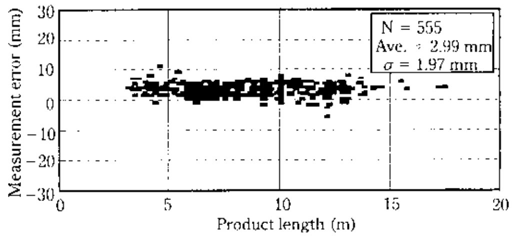

Fig. 7 Accuracy of shear cutting by new plate length meter

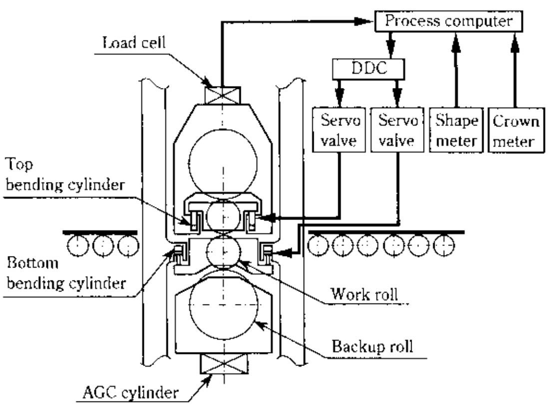

Fig. 8 Structure of shape control system

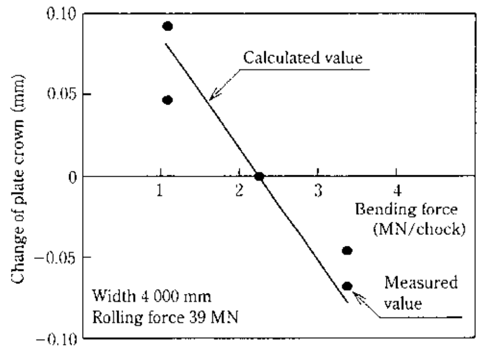

Fig. 9 Comparison of plate crown between experimental and calculated results by simulation model

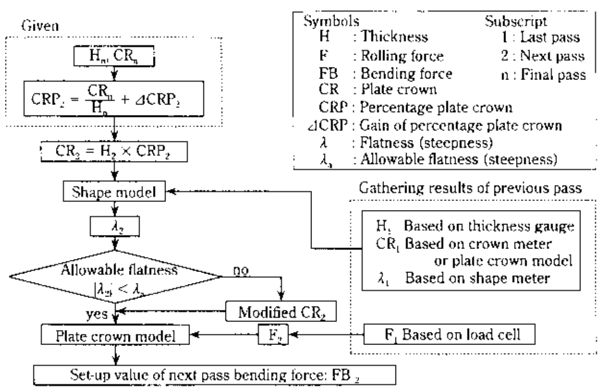

Fig. 10 Set-up algorithm for work roll bending force based on shape meter data

system, which combines a laser Doppler speed meter, length calibration detectors and measuring roll mechanism. This system realizes a length measurement accuracy of ± 0.02%, making it possible to obtain the high level of product plate length accuracy shown in **Fig. 7**.

2.3 Flatness Control Technology

In recent years, in line with progress in automation and improved efficiency in the processing of steel materials by customers, plate flatness has assumed increasing importance. Kawasaki Steel has carried out development to improve flatness in various fields of technology, including rolling, cooling, and leveling.

As a technology for flatness control in the rolling stage, a new control technology in which the work roll bending force is controlled based on actual measured flatness data was developed and applied in 1992.[15–17] The control system, as shown in **Fig. 8**, comprises a shape meter using the scanning type of semiconductor laser, which is capable of measuring the steepness of hot plates during rolling from a position 11 m from the finishing mill, a three head γ-ray thickness gauge (crown meter), a load cell and other sensors, a process computer and other computers, and a work roll bending device which can apply a maximum bending force of 3.4 MN/chock (control range: 2.2 ± 1.2 MN/chock). In order to confirm the plate crown control capability of the work roll bending method, an aluminum press experiment was performed with the actual plate mill. **Figure 9** shows the amount of change in the plate crown corresponding to the bending force with a 4 000 mm wide plate. A plate crown change of 0.15 mm could be obtained with a bending force change of 2.4 MN/chock, demonstrating that not only flatness control, but also crown control, is possible with wide plates. **Figure 10** shows the set-up algorithm for work roll bending force.[18] The bending force is set in the during passes aiming at the target crown in each pass. As rolling approaches the final pass, the bending force is set so as to obtain satisfactory flatness based on the measured data from the shape meter. The shape model used in the algorithm is reduced to a formula using a shape change coefficient and entry plate elongation difference ratio inheritance coefficient. The shape change coefficient was modeled using data from the actual rolling, which were collected with the new shape meter.

At present, accelerated controlled cooling after rolling can be considered the key technology to plate material quality control and therefore has assumed increasing importance. However, from the viewpoint of process technology, the problems of shape defects caused by

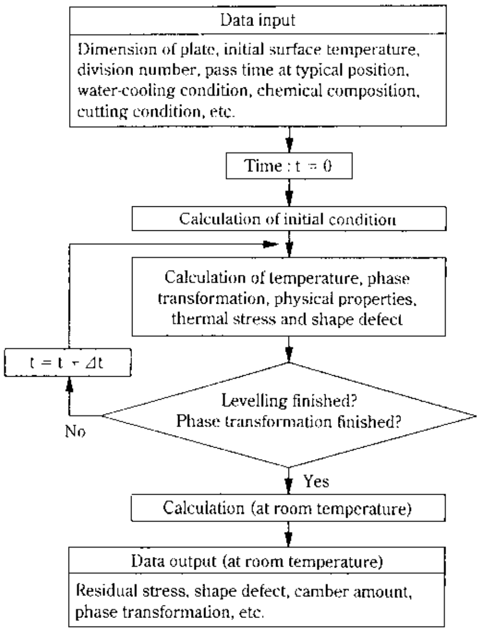

Fig. 11 Flow of the thermal stress and shape defect simulator

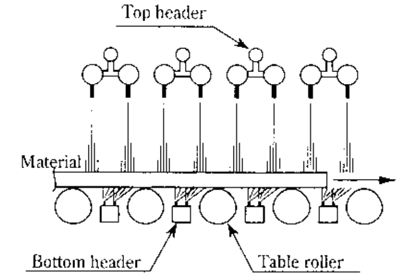

Fig. 12 Water-cooling device (ACC, #4 zone)

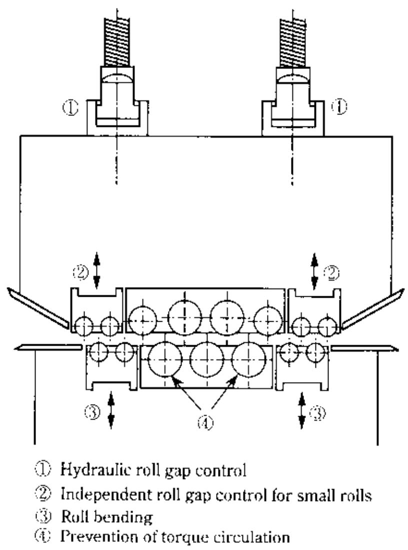

Fig. 13 The main functions of the new hot leveller

nonuniform cooling and camber and warp due to the release of residual stress during longitudinal cutting remained to be solved. To obtain guidelines for operational technology aimed at solving these problems, Kawasaki Steel developed an analytical simulator which simultaneously estimates the temperature distribution, thermal stress, and changes in the shape of plates from the cooling conditions after rolling.[19] **Figure 11** shows the flow chart of the simulator. The cross-sectional dimensions of the plate, initial surface temperature, water cooling conditions, chemical composition, longitudinal cutting conditions, and other conditions are input, and after adjusting for the effects of hot leveling and phase transformation, the residual stress at room temperature, shape defects, and amount of camber are calculated. Based on these analytical results and experimental results, a partial revamping of the accelerated cooling equipment was carried out in 1995.[20] Of the total cooling zone length of 40 m, the water flow rate in the 10 m following the mill was increased to 2.2 times the former amount, and inclined elliptical spray nozzles were adopted in the bottom headers, as illustrated in **Fig. 12**, to prevent water from riding on the head end and crosswise edges of plates. In addition, an air water-cut device was installed at the delivery side of the cooling zone. These measures were taken to ensure a high level of uniformity in cooling.

In the hot leveling process, the hot leveler was renovated in 1988 in order to solve the problem of inadequate leveling capacity with high strength materials, which inevitably occurs in low temperature leveling of TMCP steels and similar products.[21] **Figure 13** shows an outline of the new equipment. The maximum leveling force is 40.2 MN. Among the total of 15 leveling rolls, small diameter rolls with a diameter of 190 mm and a pitch of 200 mm were adopted at the entry and delivery sides for use in leveling thin plates. When heavy gauge, high strength materials are leveled, the upper small diameter roll groups are retracted upward. The lower small diameter rolls are equipped with roll bending device, which have improved the effectiveness of leveling partial shape defects in thin plates. Hydraulic cylinder position control devices make it possible to control the roll gap during leveling. In addition, the lower large diameter rolls are equipped with clutches which are switched to the idle position after roll bite. This prevents torque circulation, making it possible to level heavy gauge, high strength materials with high leveling force.

3 Factory Automation Technologies Enabling Higher Level of Quality Assurance

With the aim of improving the level of quality assurance by measuring the dimensions and shape of 100% of product plates, Kawasaki Steel undertook the develop-

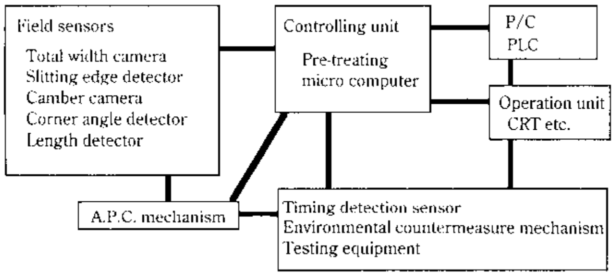

Fig. 14 System configuration of the plan view shape meter

ment of an automatic inspection system which is capable of performing high accuracy dimension and shape measurements using various sensing techniques.

Plate thickness inspection has long been performed based on measured values obtained with the γ-ray thickness gauge. Kawasaki Steel carried out an equipment renovation in 1990 in which it adopted a high speed/response gauge that uses photomultiplier as the detectors, and at the same time, also adopted a three head type.[22] This has made it possible to perform simultaneous three point measurements in the plate crosswise direction within a very small measurement area, and thus has greatly improved the reliability of thickness assurance.

As the inspection device for flatness, a flatness meter which uses laser displacement meters was introduced in 1992.[23] The laser displacement meters are arranged in two rows in the direction of plate transport, with 30 units in the crosswise direction. By giving consideration to the optimum algorithm, which eliminates the influence of plate bouncing in calculations of shape defects, it is possible to calculate highly accurate shape defect date for the entire surface area of a plate in less than 1 s.

For high accuracy, automatic measurement of various types of dimensional and shape data, a plan view shape meter was developed and introduced in 1994.[24] Four items can be measured with this meter, these being length, width, camber, and the squaring angle. The system configuration of the plan view shape meter is shown in **Fig. 14**. In full width measurements, because the measurement range is changed to a maximum of 4 350 mm, high response was secured by using multiple groups of one-dimensional CCD cameras and lower light sources. The slitting edge detector was configured using a scanning type two-dimensional distance meter to give the system excellent resistance to external disturbances such as bouncing during plate transportation. For other detectors, general purpose cameras, image processing devices, laser devices, and others were selected depending on the use environment, realizing high accuracy and high reliability.

The changes in the methods of dimensional and shape inspections following the renovation of the γ-ray thickness gauge and the introduction of the flatness meter and plan view shape meter are shown in **Table 2** in comparison with the conventional methods.[25]

Table 2 Comparison of inspection methods

Inspection item	Conventional method	New method
Thickness	2-head γ-ray thickness gauge	3-head γ-ray thickness gauge
Width	Shearing device Plan view meter for as-rolled plate Inspection by operator	Plan view shape meter
Length	Shearing device Inspection by operator	Plan view shape meter
Camber	Inspection by operator	Plan view shape meter
Squaring angle	Inspection by operator	Plan view shape meter
Flatness	Inspection by operator	Flatness meter

4 Conclusion

The following high performance steel plate manufacturing technologies and FA technologies have been developed by Kawasaki Steel since 1987 to respond to a higher level of customer requirements and improve the level of quality assurance:

(1) Plate thickness control technology was improved by installing a proximate γ-ray thickness gauge at a distance of 2 m from the finishing mill, remodeling the hydraulic AGC system, and developing a new control method for the unsteady-state portions at the head and tail ends of plates.

(2) The width and length accuracy of products was improved by introducing a milling machine and developing a new plate length measurement system.

(3) Flatness was improved by developing a shape control system which sets the work roll bending force on the basis of data obtained with a shape meter located near the mill, revamping the accelerated cooling equipment to secure uniform cooling, and renovating the hot leveler.

(4) The level of quality assurance was improved by renovating the γ-ray thickness gauge, introducing a flatness meter, and developing a plan view shape meter.

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