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Development of Laser Thickness Gauge in Steel Plate Shearing Line†

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Abstract:

JFE Steel has developed a laser thickness gauge for the purpose of guaranteeing the full-length thickness of steel plates, at the plate mill shearing line in East Japan Works (Keihin). The laser thickness gauge with high response and high measurement resolution provides thickness measurement of the overall length, including the top edge of the steel plate being conveyed. The laser thickness gauge is susceptible to the effect of mechanical deformation due to temperature changes, and vibration. In order to ensure the necessary performances, an on-line calibration method was proposed and applied, and a real operational plate thickness gauge was successfully developed.

1. Introduction

A laser thickness gauge was developed for the plate mill shearing line in East Japan Works (Keihin), JFE Steel and is now in operation. In this device, responsivity and measurement accuracy are improved in comparison with the conventional γ-ray thickness gauge, and highly accurate thickness measurement of steel plates during conveying is now possible, including the top edge of the steel being conveyed. This device is contributing to improvement of the level of quality assurance.

This paper describes the results of studies of securing responsivity and measurement accuracy and methods for ensuring durability and reliability which were carried out in the development, together with the results of offline and online evaluations with the actual device.

2. Laser Thickness Gauge

2.1 Principle

The main specifications required in a laser thickness gauge are shown below.

(1) Measurement Object
  a. Plate thickness: 5–50 mm
  b. Plate width: 1 500–5 250 mm
  c. Plate length: 6–27 m
  d. Plate conveying speed: Up to 90 m/min

(2) Measurement Positions: 3 points in plate width direction (Both edges and center)
  Continuous measurement in plate longitudinal direction (Profile)

(3) Measurement Accuracy (Offline, $\pm 2\ \sigma$): $\pm 30\ \mu$m
  (Accuracy conforms to that of the existing γ-ray thickness gauge.)

(4) Dead Zone (Tip): $<$30 mm
  Plate Conveying Speed: 90 m/min

In online thickness gauges for steel plates, including heavy plates, γ-ray or X-ray thickness gauges have mainly been used as the conventional technology. In these thickness gauges, γ-rays (X-rays) from a radiation source are irradiated on the object steel plate, the γ-rays (X-rays) which are transmitted through the plate are detected by a detector, and calculation/measurement of the plate thickness is performed based on the attenuation of the γ-rays (X-rays) transmitted through the plate. Stable plate thickness measurement is possible because this system is relatively impervious to the effects of external disturbance factors such as dust, steam, etc. and changes in the positions of the pass line and sensors (radiation source, detector).

However, due to the large irradiated beam diameter (up to approximately φ40 mm) and the low responsivity (up to 50 ms) of the γ-ray method, as shown in **Fig. 1**, this method has the drawback that measurement accuracy deteriorates at the top edge portion of the plate being conveyed. Therefore, in order to perform accurate thickness measurement of the top edge portion, it is necessary to reduce the conveying speed or stop the plate.

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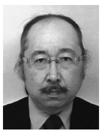

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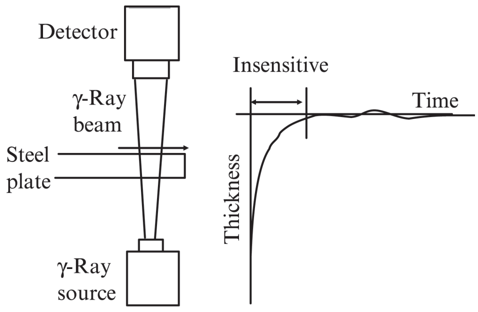


Fig. 1 Response of γ-ray thickness gauge

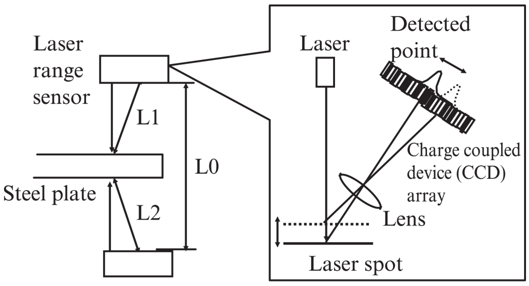


Fig. 2 Thickness gauge with laser range sensor

Moreover, due to the principle of measurement, γ-ray attenuation increases when the plate thickness increases, resulting in degradation of measurement accuracy.

As shown in **Fig. 2**, the laser thickness gauge[1] uses triangulation-type laser distance meters, which achieve unit high measurement accuracy (to level of several micrometers). Two opposing laser distance meters are positioned and fixed on a vertical axis on the top and bottom surfaces of the steel plate, and the plate thickness d is calculated from the distances to the plate surface (L1, L2) and the distance between the installation positions of the two distance meters (L0) (Plate thickness: $d=\mathrm{L0}-\mathrm{L1}-\mathrm{L2}$).

With laser thickness gauges, the diameter of the laser spot which is the measurement point is small (no more than φ1 mm), and it is also possible to perform measurements with high responsivity (several microseconds). Highly accurate measurement of the plate thickness profile over the full length is possible, including the plate top edge portion, even with plates which are being conveyed.

Because laser distance meters are easily affected by dust, steam, etc., it is difficult to apply this technology to lines with severe environments, for example, to measurement of high temperature steel plates and the like. However, application is possible under good environmental conditions with cold objects (up to 300°C), for example, at the plate shearing line.

Moreover, as shown in **Fig. 3**, unlike the γ-ray thickness gauge, accuracy is not affected by the thickness of

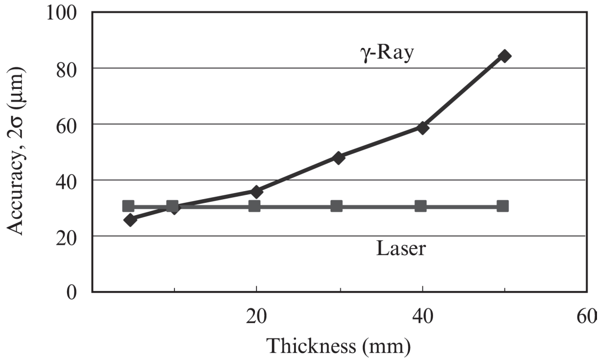


Fig. 3 Accuracy of thickness gauge (Online)

the measurement object. Thus, it is possible to realize stable plate thickness measurement.

2.2 Accuracy of Laser Thickness Gauge

As mentioned above, in laser thickness gauges, the distance to the object surface is measured by a pair of opposing laser distance meters positioned on the two side of the measurement object. Therefore, changes in the relative position/angle, etc. between the laser distance meters and the object during measurements have a large influence on measurement accuracy.

The main factors which influence measurement accuracy are listed below.

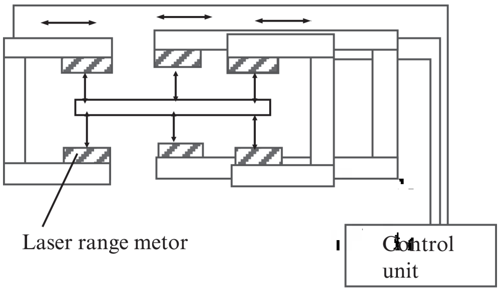
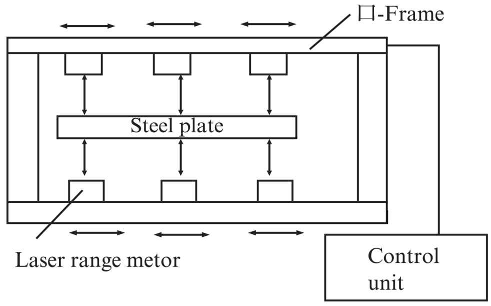
(1) Error of Laser Distance Meters (Offline Accuracy)
- a. Characteristics and deviation (linearity, noise)
- b. Temperature drift (offset/linearity change)

(2) Error of Laser Distance Meters (Online Error)
- a. Changes in distance meter position and angle
  Changes in position and angle due to thermal expansion of the frame (structure) holding the distance meter, etc.
- b. Change in angle of steel plate
  Changes in the relative position and angle between the steel plate and distance meters due to strain, vibration, etc. of the plate itself
- c. Surface properties of steel plate
  Changes in the values detected by the distance meters due to changes in the condition of reflection and diffusion of laser light at the steel plate surface
- d. Influence of space between steel plate and distance meter
  Variations in laser light due to thermal fluctuations in case the temperature of the steel plate is equal to or higher than the ambient temperature

2.3 Equipment Configuration of Laser Thickness Gauge

In a laser thickness gauge, two laser distance meters are arranged on a straight line which is perpendicular

Table 1 Comparative table of laser thickness gauge

	C-Frame	冂-Frame
Configuration	Laser range metor is fixed on C-frame. 	Laser range sensor is moved on 冂-Frame. 
Merit	High accuracy	Small space
Demerit	Large space required Large frame required	Low accuracy Measurement error caused with indivisual move of laser unit

with respect to the top and bottom surfaces of the steel plate. To secure accuracy, the measurement directions of the two distance meters must coincide, and a mechanism which moves the distance meters to the instructed measurement position in the plate transverse direction is also necessary. Thus, it is necessary to study a device with functions and structures for holding and moving the laser distance meters.

Table 1 shows the examples of the frame shapes for arranging and holding the distance meters.

In the gate-frame type, a fixed gate-type frame is installed, and the frame has the function of moving only the opposing pair of laser distance meters on the top and bottom surfaces of the plate. It is easy to secure frame strength and prevent frame deformation, and it is possible to reduce the equipment installation space, even in case of multi-point measurements. However, if the top and bottom distance meters are moved, it is necessary to ensure accurate movement by coupling the top and bottom laser distance meters, and measurement errors due to misalignment of the optical axes of the top and bottom distance meters occur easily.

In the C-frame type, the opposing laser distance meters are fixed at the top and bottom tips of the C-frame, and the C-frame itself is moved while maintaining the positional relationship of the top and bottom distance meters. Since misalignment of the optical axes is not a problem, measurement accuracy is easily maintained. However, because this is a cantilever support method, a large-scale C-frame is necessary in order to prevent deformation.

Moreover, for simultaneous measurement of multiple points, it is necessary to support and move multiple C-frames, but this results in a large-scale device and mechanism, and requires a large installation space.

With both types, countermeasures to minimize error are necessary because misalignment of the position and angle (optical axis) of the laser distance meters occurs accompanying mechanical deformation and expansion and contraction of the frame due to thermal expansion.

Conceivable methods for reducing the influence of error include reducing deformation by increasing the stiffness of the frame itself and preventing deformation due to temperature change by performing temperature management, for example, by cooling (water cooling) the entire frame structure, but these methods are not practical, as they increase the size and complexity of the frame structure and the necessary temperature management (control) is difficult.

In the developed laser thickness gauge, the C-frame type was adopted from the viewpoint of securing basic accuracy, and on the precondition that moderate deformation of the frame will occur due to thermal expansion, etc., short-time deformation caused by vibration of the frame structure, etc. is reduced by securing frame stiffness. Assuming that gradual long-time variations/deformation caused by temperature changes can be minimized by performing calibrations periodically, an online calibration mechanism was proposed and applied.

At the plate shearing line, steel plates are conveyed with an interval between the preceding and following plates. Therefore, after reducing the effect on the efficiency of plate conveying and shearing operation, it was judged that calibration is feasible by performing calibrations between plate conveying operations.

Because the new device is premised on online calibration, in the C-frame itself, it was sufficient to secure the stiffness necessary to prevent short-time vibration and deformation and to provide a simple heatproof structure to suppress the effects of heat due to the radiant heat from the object of measurement, etc. As a result, it was possible to design a compact C-frame and relax the specifications required in its fabrication.

In the actual design, design of the structural parts, including the C-frame, was performed so as to minimize revamping of existing equipment such as tables at the plate conveying line, etc.

3. Laser Thickness Gauge for Plate Shearing Line

3.1 Equipment Composition and Layout

At a plate shearing line, plate thickness assurance is performed by measuring the plate thickness of steel plates being conveyed at 3 points (both edges and center of plate) in the plate transverse direction and calculating the crown shape, etc. in the transverse direction. Therefore, it is necessary to install 3 pairs of laser distance meters (C-frames) and to move the measurement points of the distance meters (C-frames) corresponding to the width of the plate being conveyed.

At the plate shearing line at East Japan Works (Keihin), plates are conveyed with one side of the line (drive side, DS) as a reference. Measurements of 3 points in the transverse direction can be performed if 3 C-frames are arranged in 3 lines in the plate conveying direction (longitudinal direction) and a mechanism for moving the stroke corresponding to the respective measurement position ranges is provided. However, in case of an arrangement in which the C-frames are inserted from one side of the line, C-frames with a stroke at least as long as the total line width are necessary, resulting in large-scale C-frames and auxiliary equipment as well as increased mechanical error accompanying the larger size.

Therefore, in the design adopted here, as shown in **Fig. 4**, the two plate edges are measured by arranging 2 compact C-frames for edge measurements on the opposites sides of the line, and the plate center is measured by a C-frame having a stroke of 1/2 of the line width. A compact design, including the total layout, was realized by arranging the C-frame for measurement of the plate center on the downstream side in close proximity to the C-frames for edge measurements.

After making the C-frames as compact as possible, preconditioned on online calibration, as mentioned in Section 2.2, a structure in which the C-frames are suspended from gate-type frames was adopted. As a result, stabilization is achieved by the self-weight of the frames, and installation of guide rails, etc. on the ground surface side is not necessary.

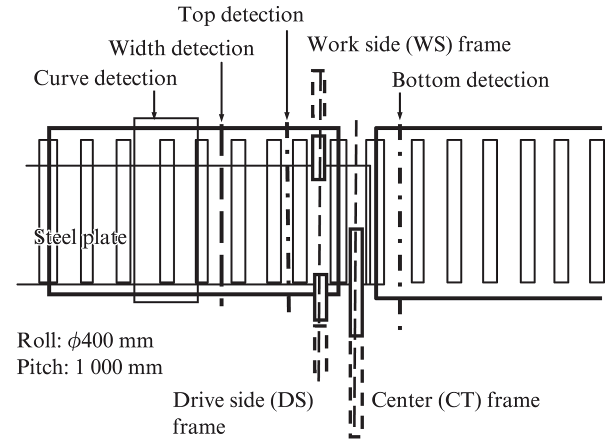


Fig. 4 Structural drawing of facilities

3.2 Applied Technologies and Mechanisms

(1) Online Calibration Mechanism

In this device, an online calibration mechanism was proposed and applied in order to perform calibrations of the positions and angles of the distance meters by using the time between conveying of steel plates.

The online calibration mechanism comprises a mechanism by which existing calibration pieces are inserted at the position of the steel plates between measurements (conveying) of the plates, and calculation and correction treatment of variations in the positions and angles of the distance meters due to thermal expansion, etc. based on the results of measurement of the inserted calibration pieces.

In online calibration, it is possible to perform calibrations with good accuracy by measuring multiple calibration pieces with different thicknesses or measurement surface angles. However, it is difficult to incorporate this method in the actual equipment, as it is necessary to exchange multiple calibration pieces in a short time, and this would increase the scale and complexity of the online calibration mechanism unit.

It is possible to perform calibrations of the distance meters if the position or angle of the calibration piece positioned between the distance meters can be changed continuously, but in this case, it is necessary to perform setting of the position and angle of the calibration piece accurately, which would invite greater complexity in the mechanism unit and its control. Therefore, in the mechanism which was proposed and applied in this thickness gauge, calibration pieces of equal thickness are attached at different positions and angles on the side of a cylinder, and the calibration pieces (measurement positions) are exchanged continuously by rotating the cylinder around a fixed axis, making it

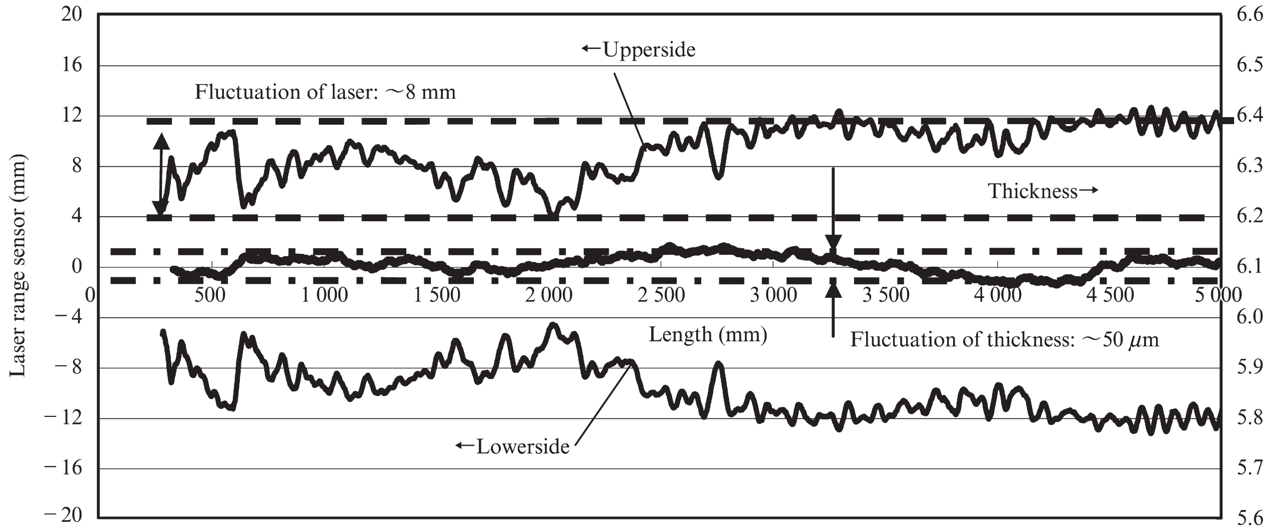


Fig. 5 Reduction of influence of steel plate vibration

possible to collect a large volume of data with high efficiency in a short period of time.

As the actual online calibration mechanism unit has a mechanism which retracts during plate measurements, it is possible to perform calibrations without a influence on plate conveying by performing movement, rotation (measurement) and retraction of the calibration pieces (cylindrical part) during the time from completion of one measurement until the next plate advances.

(2) High Speed Simultaneous Measurements

At the plate shearing line of Keihin District where this equipment is installed, plates are conveyed on rolls with a 1 m pitch, resulting in large vibration (jumping and vibration due to contact with the rolls) of the top and tail ends of the plate accompanying conveying. This causes variations in the timing of measurements by the opposing distance meters, and may possibly become an error factor.

In order to reduce variations in the timing of the measurements by the opposing distance meters when plate vibration occurs during conveying, the influence of vibration (displacement) is reduced by applying distance meters which are capable of performing high speed (10 kHz), synchronous measurements.

Figure 5 shows an example of the measured data from the distance meters and the result of the calculation of the plate thickness. As shown in the results of the measurements by the distance meters, although high speed vibration (displacement) of the steel plate occurred, the distance displacements are mutually complementary and plate thickness measurement is possible.

4. Accuracy and Performance of Laser Thickness Gauge

4.1 Offline Measurement Accuracy

The following presents the results of an evaluation of measurement accuracy when test pieces and sample plates were measured at room temperature under a static condition.

(1) Test Pieces for Accuracy Verification
Thickness of measured plates: 10/22/34/46 mm
Surface condition: Diffusing surface (Uniformly processed surface)
Measurement accuracy (Deviation): 2 σ=18 μm

(2) Measurement of Steel Plate Samples
Thickness of measured plates: 10/12/22/30 mm
Surface condition: Diffusing surface and glossy surface (Depending on sample)
Measurement accuracy (Deviation): 2 σ=23 μm

For the samples, the average of multiple measurement results at different positions on the surface (same plate thickness, different measurement surface) are shown. Offline accuracy could be secured with no problems.

In comparison with the test pieces for accuracy verification, deviations in accuracy depending on the sample occurred with the actual steel plate samples. This occurred due to variations in the condition of laser light diffusion due to differences in the surface condition of the sample steel plates.

4.2 Results of Online Measurements

Online measurements were performed with the laser thickness gauge installed at the plate mill shearing line in East Japan Works (Keihin), and the performance of the device was evaluated.

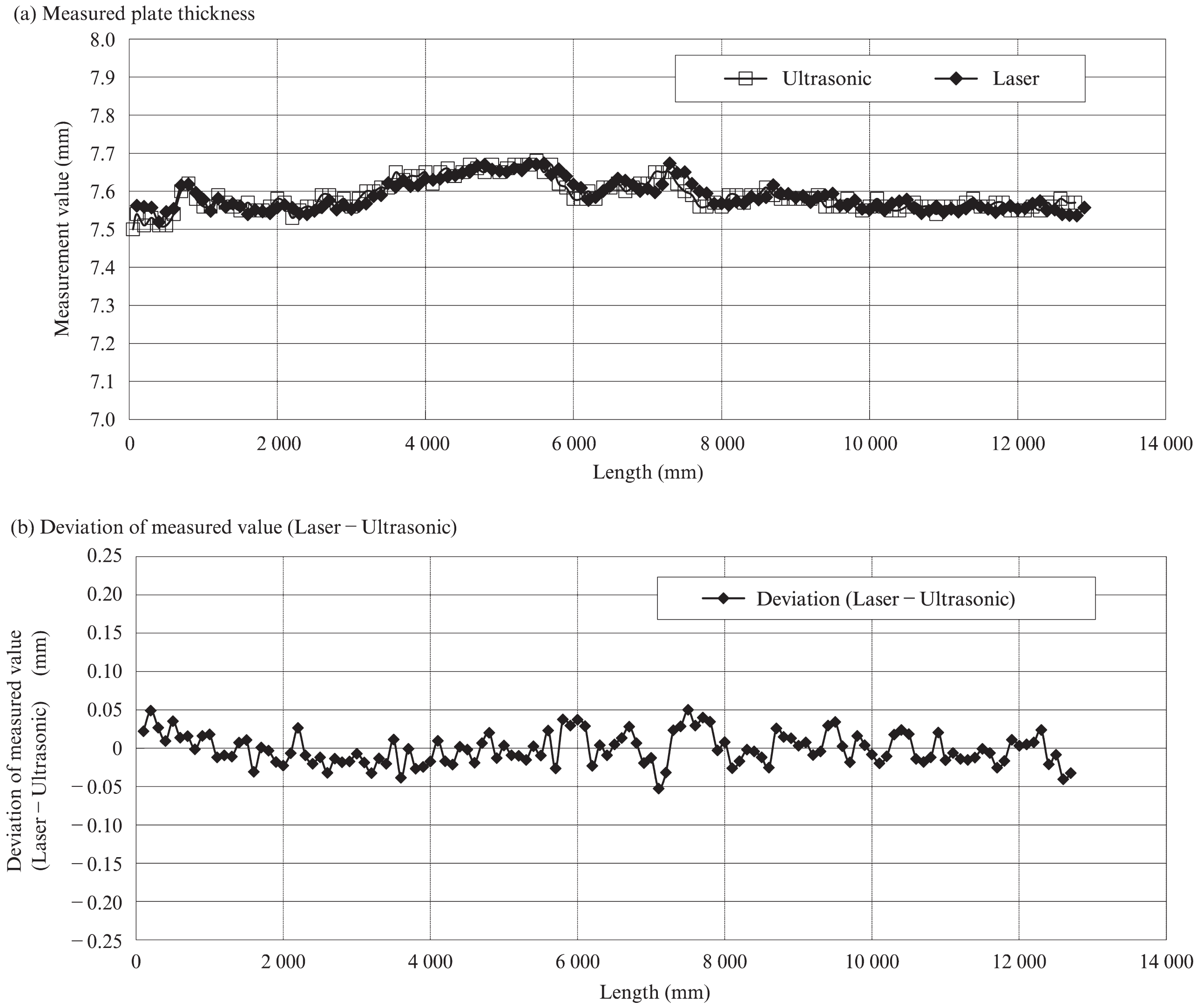


Fig. 6 Measurement result of test plate

(1) Measurement Accuracy

a. Measurement objects

• Test material: Cold measurement

• Operational (rolling) material: Hot (up to 300°C) measurement

b. Measurement results

The evaluation of the measured plate thickness was performed by deciding comparison points in the steel plate and comparing the results with the results of manual measurements (offline cold measurement by ultrasonic thickness meter).

As results of the accuracy evaluation test with the test material, **Fig. 6** shows a comparison of the results with the laser thickness gauge and manual measurement (ultrasonic thickness meter). (In this figure, (a) shows the results of the respective measurements and (b) shows the deviation between the measured values.)

As shown in Fig. 6, although there are deviations between the measured values of the laser thickness gauge and manual measurement, good agreement between the plate thickness profiles could be confirmed.

The cause of these deviations is considered to be variations in the comparative measurement positions, which occurred because the measurements with the laser thickness gauge were performed during plate conveying but the manual measurements were performed offline.

Similar measurement results were also obtained with the operational material.

(2) Measurement Responsivity

Plate thickness measurement begins from the point in time when the measurement point (laser spot) of the laser thickness gauge strikes the top edge of the steel plate being conveyed. Because good agreement was also obtained between the results of measurements of the top edge (position 50 mm from the leading edge) by the laser thickness

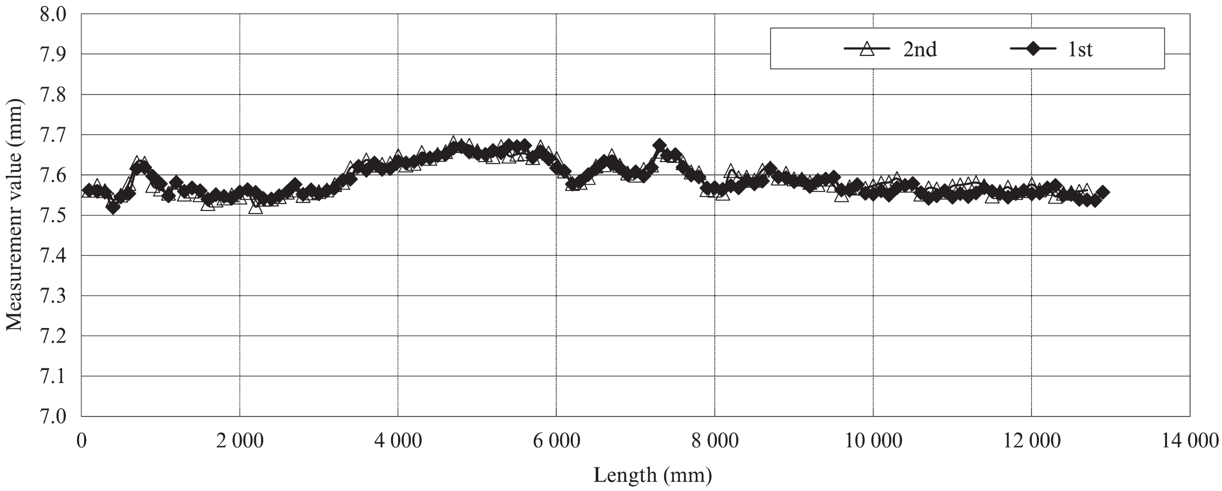


Fig. 7 Test result of repeatability

gauge and the manual measurement results, accurate measurement of plate thickness from the extreme top edge of steel plates is possible. This result confirmed the fact that high responsivity can be secured in comparison with the conventional γ-ray plate thickness gauge.

(3) Measurement Repeatability

Figure 7 shows the results of multiple measurements of the same steel plate.

After the 1st measurement was completed, the plate on the conveying line was conveyed in the opposite direction and measurement was performed again. The graph also shows the deviation in comparison with the results of manual measurement, which was performed after the online measurements.

The measured results in these multiple measurements showed good agreement (deviation of measured values at each measurement point: $< 10\ \mu$m), confirming the repeatability of measurements.

5. Conclusion

A laser thickness gauge for the plate mill shearing line in East Japan Works (Keihin), JFE Steel was developed and applied in actual equipment. (The design, manufacture and adjustment after installation of the actual device were performed by JFE Electrical & Control Systems.) In the development, an online calibration method was applied practically in order to secure measurement accuracy, which is an issue with the laser method, and performance equal or superior to that of the existing γ-ray thickness gauge was secured. The laser thickness gauge also enables measurement of the full length of steel plates, including the plate top edge, which had been difficult to measure in conventional γ-ray thickness measurement, and could contribute to improvement of the level of quality assurance.

In the future, development to dimensional measurement and shape measurement utilizing laser distance meters will also be possible.

Reference

1) The papers of Technical Meeting on Metal Industries Division, IEE Japan. 2010-12-17, MID-10-026.