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Recently, seamless tube has been expanding its application fields. Accordingly customers want further improvement in accuracy of tube dimensions. In order to improve the wall thickness accuracy of small-sized seamless tube, an on-line wall thickness gauge has been developed right after the stretch reducing mill as a finishing rolling mill. This wall thickness gauge is a full-automatic measuring system requiring no size change. A measuring principle has been established for tube as three dimensional material using γ-rays. This development has also made clear an optimal signal processing method on the statistical noise of γ-rays. Now, the wall thickness gauge is in smooth operation and is useful to rolling control by operators.

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Development of On-line Wall Thickness Gauge for Small Size Seamless Tubes*


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1 Introduction

In recent years, seamless tubes have been used in increasingly diversified applications, and higher dimensional accuracy has become necessary. At Kawasaki Steel's Chita Works, a multibeam type on-line wall thickness gauge[1)] using γ-ray projection onto medium-diameter seamless tubes (16″ plug mill) was developed in 1981 to meet the requirement for higher dimensional accuracy.

Small-diameter seamless tubes (7″ mandrel mill) were no exception. The development of an on-line wall thickness gauge that can measure the wall thickness of the small-diameter seamless tubes immediately after rolling was strongly desired as it would attain their higher wall thickness accuracy. The technique for the multibeam type on-line wall thickness gauge was improved, and a parallel-beam type on-line wall thickness gauge using gamma (γ) ray projection was developed. By positioning the gauge immediately behind the stretch reducing mill used for finish-rolling of small-diameter seamless tubes, the desired on-line development was attained.

Unlike the γ-ray projection type thickness gauge for plate and sheet, this parallel-beam type on-line wall thickness gauge required research and development on the fundamentals of size measuring techniques by γ-ray projection. The new on-line wall thickness gauge is now operating smoothly in the stretch reducing mill for small-diameter seamless tubes.

This paper describes the development of a general measuring principle for deformed three-dimensional materials, and reports the mechanism of high-accuracy measurement of the wall thickness of tubes traveling freely at high speeds, as well as the signal processing method adopted for the measurement.

2 Purpose of the Development and Specifications

As shown in **Fig. 1**, the stretch reducing mill used for

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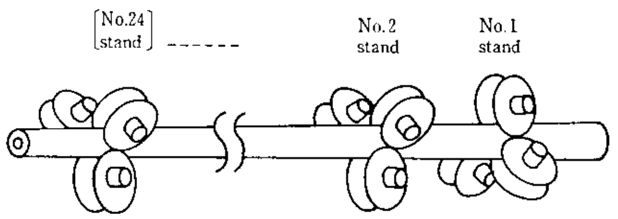

Fig. 1 Schematic illustration of rolling process of stretch reducing mill

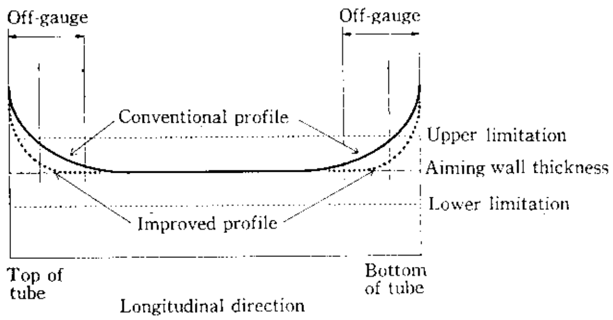

Fig. 2 Longitudinal wall thickness profile of tube after stretch reducing mill

finish-rolling of small-diameter seamless tubes finishes the shell to specified sizes by gradually reducing its outside diameter. When the outside diameter is reduced, metal flows in the wall thickness direction and longitudinal direction of the tube and, therefore, the wall thickness increases. To prevent this, a stretch tension is applied in the rolling direction to the tube while the rolling is underway and wall thickness is being reduced.

However, the reducer designing makes it unavoidable that the top and bottom of the shell receive less tension than the rest of the shell which come under normal rolling force. This results in the wall thickness profile as shown in **Fig. 2**, making the top and bottom portions worse. To obtain a dimensionally stable product, it is very important to know during rolling the starting point of the wall thickness increase.

Conventionally, a greater stretch is applied to the top and bottom of the shell than to the middle, and off gauge is reduced by a programmed control of the rotational speed of the rolls that produce this wall thickness deformation. With the conventional method, however, it may sometimes be impossible to set the optimum rotational speed of the rolls for all conditions of mill operation, because on-line measurement of the wall thickness profile immediately after rolling cannot be made in real time. The off gauge portions at the top and bottom are cropped off by the cold saw that cuts the rolled tube to the specified lengths. However, this crop length is based on figures obtained by previous operation or experiment, so that the possibility of the finished product containing off guage-error portions

Table 1 Specifications of on-line wall thickness gauge

Items		Specifications
Diameter	(mm)	21.0~177.8
Wall thickness	(mm)	2.0~ 35.0
Length	(m)	6~ 67
Tube speed	(m/s)	2~ 8
Tube temperature	(°C)	600~950
Tact time	(s)	Min. 15
Response		0.01 s or 100 mm
Accuracy		±0.1 mm 100 mm ϕ × 10 mm t
Allowance of swing	(mm)	±10

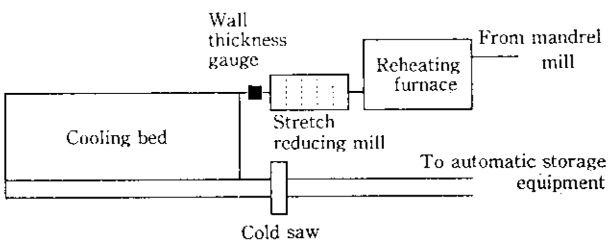

Fig. 3 Location of on-line wall thickness gauge after stretch reducing mill

cannot be completely eliminated.

To solve the foregoing problems, Kawasaki Steel has developed an on-line thickness gauge for small-diameter seamless tubes. The specifications of the equipment are shown in **Table 1**, and its location in the strech reducing mill is shown in **Fig. 3**.

3 Development of the Measuring Method

On-line wall thickness gauging presently in practical use apply the radiographic method and the electromagnetic ultrasonic method. The stretch reducing mill at Kawasaki Steel produces rolled products in a wider size range than those of other rolling mills. In addition, a large number of steel grades are used and, as given in Table 1, the rolling temperature range is also wide. Furthermore, minute oscillations of rolled tube on the delivery side of the stretch reducing mill may possibly hinder measurement. The authors reached the conclusion that to meet the specifications of measurement required for these operating conditions, it was decided best to apply the γ-ray projection method with which the company has technical experience in the manufacture of medium-size seamless tubes.

The authors therefore examined the specifications shown in **Table 2** to apply the γ-ray projection method for gauging small-diameter seamless tubes. The multi-beam method is capable of measuring the wall thickness

Table 2 Comparison and selection on measuring methods using γ-rays

	Multi-beam method	Fan-beam method	Parallel-beam method
Methods	For 16" seamless tube Detector Radiation source	For plate Radiation source Detector	Detector Radiation source
Points of measurement	3 points	Partial section mean wall thickness	Cross section mean wall thickness
Allowance of swing	±1.0 mm	Not permissive	Up to ± 10 mm
Selection	Rejection	Rejection	Adoption

of the cross-section of a tube in multiple places. Therefore, when the relationship between the γ-ray beam width and measuring accuracy determined for the multibeam method[1] was applied to small-diameter seamless tubes, it was found that a γ-ray beam of not more than 2 mm in width would be necessary. The exposing power of γ-ray beams of such a small beam-width is low, and sufficient γ-ray transmissivity cannot be obtained for heavy-wall sizes of the same wall thickness as found in medium-size seamless tubes. Since transmissivity is inversely proportional to accuracy, the required accuracy could not be obtained if the multibeam method was applied to small-diameter seamless tubes. The fan-beam method is structurally simple, and the techniques for thickness gauging of flat-rolled products can be applied. With this method, however, the average wall thickness of only part of the tube can be measured and the average wall thickness in the middle of the tube cannot always be measured when the tube oscillates. However, if γ-rays are projected onto the tube by approximating them to parallel beams, it is possible to measure the average wall thickness in the whole cross section of a small-diameter tube even if the tube oscillates. Therefore, the wall thickness measuring method by parallel beams of γ-rays was adopted for the on-line wall thickness gauging of small-diameter seamless tubes.

In developing this on-line wall thickness gauge, consideration was given to the equipment so that the gauge itself would be suitable for FMS (flexible manufacturing system) by allowing the calibration of the gauge, size change, etc., to be completely automated or unnecessary.

4 Measuring Principle

As with thickness gauges for plate and sheet, it was possible to apply Eq.(1), which represents the basic principle of thickness measurement by γ-ray projection, to the multibeam method for medium-diameter seamless tubes.

$$I = I_0 \exp(-\mu t) \quad \cdots\cdots (1)$$

where I is the transmissivity of a γ-ray, I_0 is the exposure of the γ-ray, μ is the absorption coefficient, and t is the thickness.

With the parallel-beam method for small-diameter seamless tubes, however, γ-rays are distributed and not ooncentrated as shown in **Fig. 4**. Therefore, the attenuation characteristics involve outside diameter D and wall thickness t as parameters, as shown in **Fig. 5**. Although

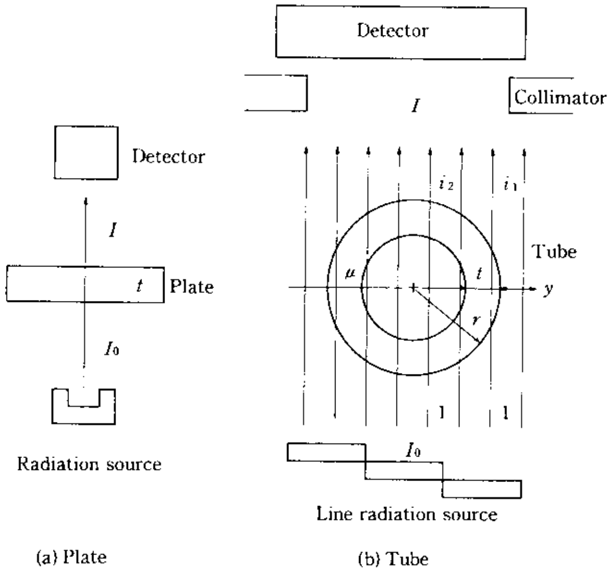

Fig. 4 Measuring principle of thickness

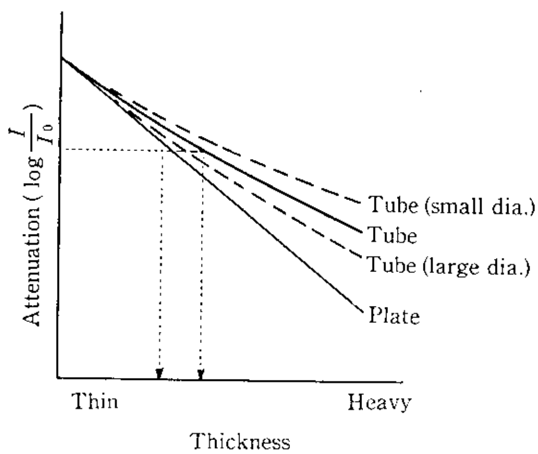

Fig. 5 Characteristic function between thickness and γ-ray transmissivity

this characteristic function is given by Eq.(2), it is necessary to calculate by Eqs.(3) and (4) the geometrical projection of the γ-rays, which depends on the position of the γ-rays that penetrate the cross section of the tube.

$$I = \frac{1}{r}\left[\int_{r-t}^{r} i_1 dy + \int_{0}^{r-t} i_2 dy\right] I_0 \quad \cdots\cdots\cdots\cdots (2)$$

$$i_1 = \exp(-2\mu\sqrt{r^2 - y^2}) \quad \cdots\cdots\cdots\cdots (3)$$

$$i_2 = \exp(-2\mu(\sqrt{r^2 - y^2} - \sqrt{(r-t)^2 - y^2})) \cdots (4)$$

where i_1 and i_2 are the relative transmissivity values of γ-rays in the cross-section of the tube, and r is the radius of the tube.

As is apparent from Eq.(2), there are a very large number of possible diameters, wall thicknesses and steel grades for the tube and, therefore, it is impossible to calculate them beforehand for tabulation purposes. Consequently, a system was adopted in which calculations are made each time the diameter, wall thickness or steel grade is changed.

As already mentioned the wall thickness gauge for tubes measures the transmissivity of γ-rays that penetrate three-dimensional materials and, therefore, for complex calculations compared with these for thickness guages plate and sheet are required.

5 Mechanism for γ-Ray Measurement

The most critical aspect in developing the γ-ray measuring system by the parallel-beam method was the method used to generate parallel beams. The measuring principle requires the space distribution of the γ-rays to be uniform and parallel in the areas where the γ-rays penetrate the tube. However, because γ-rays radiate in all solid-angle directions, it is necessary to approximate the radiation to be uniform and parallel. Furthermore, a margin of ±10 mm in measuring range is given to the maximum outside diameter measured, as shown in Fig. 4, in order to allow for minute oscillations of the tube and margins of measuring range of the measuring equipment. Therefore, those γ-rays that do not contribute directly to measurement must also be measured so that their effect can be allowed for.

On the delivery side of the stretch reducing mill, the rolling speed of the tubes is 8 m/s, as given in Table 1. To accurately measure the off-gauge lengths at the top and bottom of the tube, measurements should be taken at least at 100-mm intervals from the top of the tube. Therefore, it was necessary to develop a high-speed γ-ray sensor that could measure the transmissivity of γ-rays at about 10-ms intervals.

Generally speaking, the radiation source of measuring equipment using γ-rays should have a low intensity in consideration of safety. For a seamless tube, however, the γ-rays have to penetrate the cross section of the

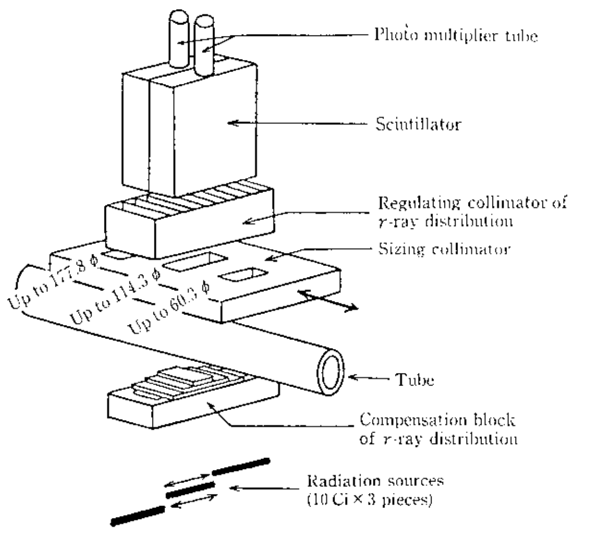

Fig. 6 Schematic structure of sensor by parallel-beam method

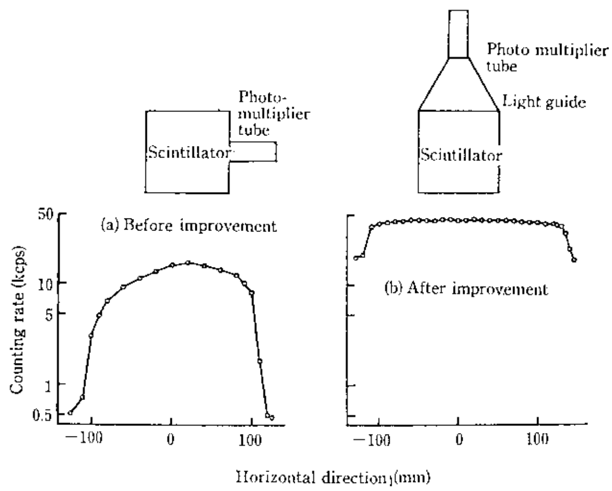

Fig. 7 Improvement of measurement accuracy by scintillator direction

tube, therefore, the exposure of the γ-rays is equivalent to that required for plate and sheet, so that a high radiation source intensity is required. To most effectively use the radiation source, therefore, a method was adopted in which the radiation source is expanded and contracted according to the diameter of the tube. An illustration of the mechanism for the sensor is shown in **Fig. 6**.

In conventional γ-ray sensors, the positional relationship between the scintillator and the photomultiplier tube is horizontal. In the present sensor, however, they are vertically arranged to make the detection characteristics uniform, as shown in **Fig. 7**. The regulating collimator for γ-ray distribution shown in Fig. 6 was used to control the space distribution of the γ-rays, making it possible to obtain the uniform space distribution shown

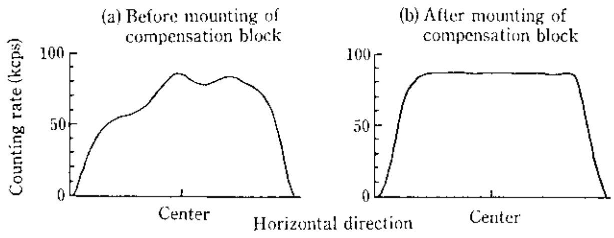

Fig. 8 Improvement of γ-ray distribution in measuring space by compensation block

in **Fig. 8**. This uniformity was verified by output signals from the sensor, which were obtained by horizontally moving a steel tube 26 mm in diameter and 7.5 mm in wall thickness.

6 Improving the Measuring Accuracy

6.1 Calculation Accuracy of the Relative Transmissivity of γ Rays

The relative transmissivity of γ-rays is calculated by Eqs. (2) to (4). Initially, the tube was divided equally in the cross-sectional direction, as shown in Fig. 4, and the distance over which each γ-ray penetrates the cross section was calculated. As is apparent from the cross-sectional shape of the tube, however, those γ-rays penetrating the tube near its two sides had markedly different transmissivity over very small changes in horizontal position. In contrast, those γ-rays penetrating the center of the tube had much more gradual transmissivity changes according to the horizontal position. In order to improve the calculation accuracy of the relative transmissivity for the γ-rays, the tube was divided in the cross-sectional direction as shown in **Fig. 9**, the zones near the two sides being divided finely and that around the center being divided coarsely. This enabled the calculation accuracy for heavy-wall sizes to be improved from several percent to less than 0.1%.

6.2 Reduction of Statistical Noise

The generation of statistical noise cannot be escaped in the measurement of γ-rays. Statistical noise is generated because γ-rays have the characteristics of particles, a γ-ray sensor counting the number of these particles. When penetrating a steel material, it is apparent from Eq. (1) that the longer the distance over which a particle penetrates the material, the greater the attenuation of the particle and the smaller the number of particles that reach the sensor. It is known that when the counting rate of γ-rays per unit time decreases, the statistical noise increases inversely to the square of the counting rate. Since the measuring accuracy decreases as statistical noise increases, it is necessary to reduce this statistical noise by some means.

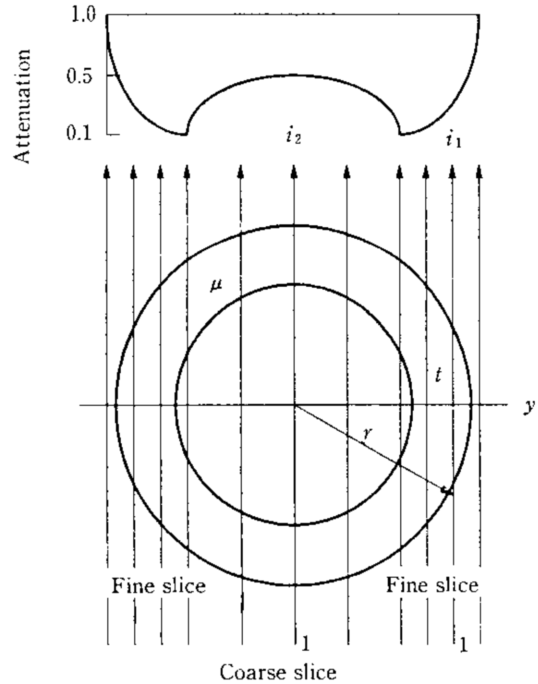

Fig. 9 Improvement of accuracy by relative γ-ray transmissivity calculation technique

It is apparent from the wall thickness profile in Fig. 2 of a tube rolled by a stretch reducing mill that the counting rate for γ-rays changes quite abruptly per unit time. In normal practice, a method for signal processing that can handle an abrupt change in the counting rate of γ-rays is not applied. However, in our system a Kalman digital filter[2] was applied to the γ-ray sensor, which is an optimum digital filter capable of varying the gain in signal processing as the counting rate for the γ-rays changes with time.

6.3 Verification of the Overall Accuracy

Figure 10 gives a comparison between measured values of a tube that was experimentally rolled to verify the measuring accuracy, these values being obtained with a manual ultrasonic thickness gauge, and those obtained by using the on-line wall thickness gauge. It is apparent that the measuring accuracy initially aimed at was achieved, and that the wall thickness profile at the top and bottom of the tube was correctly reproduced.

An example of the CRT screen used for operator guidance is shown in **Fig. 11**, the top and bottom of a tube being indicated in detail so that their positions from the tube ends is known. Information on six pieces of tube is simultaneously indicated so that the wall thickness profile in the same tube lot can be correlated.

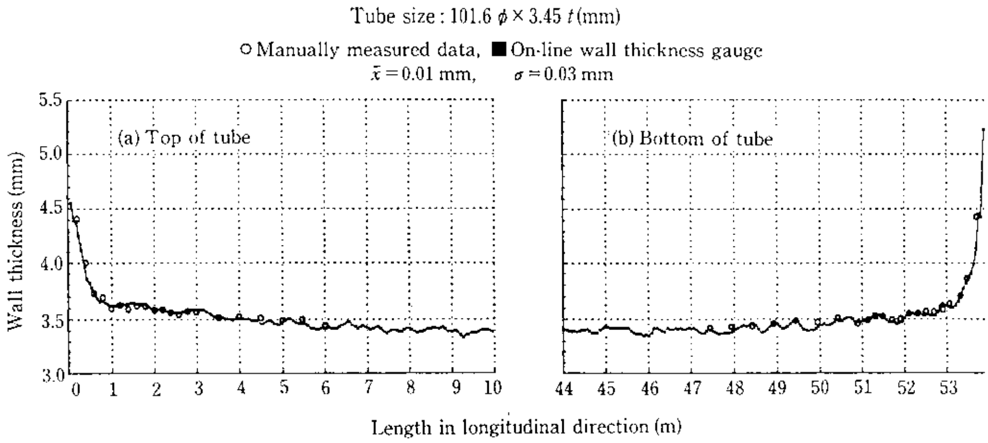

Fig. 10 Comparison of data measured by on-line wall thickness gauge with manually measured data

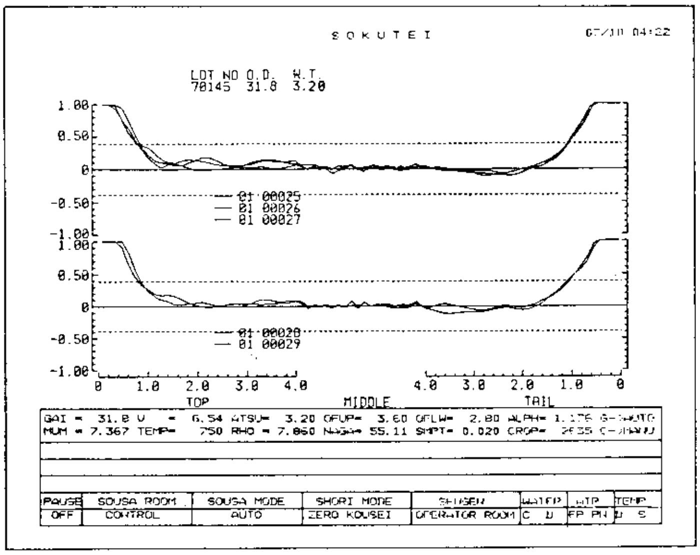

Fig. 11 Operator guidance of wall thickness information by VDT

7 Conclusions

The on-line wall thickness gauge for small-diameter seamless tubes was developed at Chita Works and put into successful use after introducing the measuring system for medium-diameter seamless tubes.

The following results were obtained from the development of this on-line wall thickness gauge:

(1) This FMS-oriented on-line wall thickness gauge does not require size changes for all sizes of small-diameter tubes.

(2) A general measuring principle for wall thickness by using γ-rays was established for steel tubes as three-dimensional materials.

(3) The optimum signal processing method for measuring the size of steel products by using γ-ray radiation was clarified.

At present, this on-line wall thickness gauge is being used on the delivery side of the stretch reducer in the small-diameter seamless tube mill to control the rolling operation.

The authors extend their sincere thanks to those staff of Fuji Electric Co., Ltd. who cooperated with them in the development of the hardware, etc. of this on-line wall thickness guage.

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