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Development of Pipe with High Precision and High Strength for Automotive Propeller Shaft

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Abstract:

The deformation behavior of electric resistance welded (ERW) pipes in the sizing process was investigated in detail by both three dimensional elasto-plastic finite element analysis and experiments. The purpose of this investigation was to clarify the effect of yield strength at the welded seam on the pipe end deformation, which deteriorated a pipe end roundness after the pipe was cut. It was found that the pipe end deformation caused by a non-uniform distribution of the seam strength in a circumferential direction could be controlled by changing the ratio of the radius of top-bottom rolls to the radius of side rolls on the 4-roll sizer. It was also confirmed through calculations and experiments that, in case of the seam strength being greater than the other portion, decreasing the radius of top-bottom rolls in size rather than that of side rolls resulted in improving the pipe end roundness. It has been attained by applying this technology that the high precision and high strength pipes for automotive propeller shaft can be manufactured at low cost.

1. Introduction

To help address environmental problems, automotive steel pipes are shifting to high strength, thin wall and high precision pipes, with the movement toward lighter pipes to enhance fuel economy or pipes to withstand increasing engine power. To enhance fatigue strength, steel pipes for propeller shafts in particular are changing from the conventional girth weld by arc welding to a welding process by friction welding. The friction welding process requires dimensional accuracy at pipe ends [1], and thus runout accuracy is critical for safe running with high speed revolution at high speed range. As thin wall, high precision (690 to 780 MPa) [2] products become increasingly necessary, steel pipes of high dimensional accuracy within 0.1 to 0.2 mm by the method of evaluation including bends and roundness are required.

To achieve this dimensional accuracy enhancement, it can be thought that the process of heat treatment is added as the final process to reduce residual stress. However, there are problems of decreasing yields such as bends or the deterioration of pipe roundness caused during heat treatment and the elimination of bends or cutting of pipe ends in finishing processes. Products therefore need to be manufactured with a high roundness at low cost with welding.

This report describes an analysis method in which sizer forming is simulated precisely to measure quantitatively the effects of yield strength at the welded seams of steel pipes on the pipe end deformation. The introduction of a 4-roll sizer in place of the conventional 2-roll sizer in the sizing process increases manufacturing precision and enables high strength pipes to be produced for propeller shafts. Therefore, we also describe the results here.

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2. Analysis of Pipe End Deformation

2.1 Method of analysis

The problem of residual stress with respect to dimensional accuracy such as roundness is becoming significant in thin wall structural steel pipes for machines including propeller shafts. When a thin wall of t/D = 3% or less and high strength electric resistance welded (ERW) pipes in particular are cut to their regular size after pipe manufacturing, "pipe end deformation (cutting deformation)" has a completely different configuration from the pipe center (pipe body) at the pipe end, causing problems (see **Fig. 1**).

Fig. 2 shows an enlargement of displacement in a wire-frame view of the configuration of the end of a cut pipe, which is measured at intervals of 20 mm from 10 mm at the pipe end to 230 mm with a roundness measuring machine. A thin wall material of t/D = 2.1% causes a large deformation, while that of t/D = 5% seldom causes deformation. This gives the maximum amount of deformation Δr_{max} after cutting at the initial radius when the contraction percentage ε_D of the outside diameter is changed with a 2-roll sizer; this phenomenon occurs in thin wall material without depending on the contraction percentage [3,4]. To clarify the phenomena, the calculation of 2-roll and 4-roll type sizers was performed using the isoparametric element of eight nodal points capable of expressing the bending deformation of the general finite element method code MARC. To determine the pipe end deformation, analysis was carried out by cutting pipe ends after sizer forming and a model used to simulate the occurrence of pipe end deformation (see **Fig. 3**). Pipe outside diameter, wall thickness, roll radius and caliber diameter were set to D, t, R_d and D_R, respectively. The pipe was fixed to move the patched surface of a rigid body corresponding to a roll with it rotated, and the friction of the pipe and roll as well as the initial residual stress of the pipe were neglected. The axial speed of the roll was set to u_x, and axial angular speed of the roll was set to ω_1 and ω_2 respectively. Allowing for the symmetry for the pipe body, the circumferential 90° of a quarter (1/4) pipe and the axial 400 mm were divided into 18 degrees and 80 parts respectively, a layer was established in the direction of wall thickness, and the element number was set to 1,440. Restricting boundary conditions in the direction of x were given to the end face of the pipe at the roll-out side. As shown in **Fig. 3** for the analytic model, the balance of stress was calculated after the elements of length of outside diameter portion D were deleted to eliminate the effect of the pipe end of the unsteady area affected by roll bite after forming of a pipe of 75.0 mm in outside diameter and 400 mm in length, and the pipe end deformation was determined.

Tables 1 and **2** give the analytic conditions of 2-roll and 4-roll. For the 4-roll, the ratio of top-bottom roll radius Rdt to side roll radius Rds (Rds/Rdt) was changed to determine the effects on pipe end deformation. Since the end deformation of a pipe depends on the amount of roll pressure drop (amount of contraction), it was defined as $\Delta r_p = \Delta r_1 - \Delta r_2$, where the displacement from the initial radius to the maximum radius is Δr_1 and that from the initial radius to the minimum radius is Δr_2 as

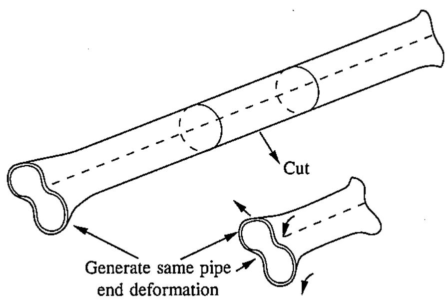

Fig. 1 Pipe end deformation

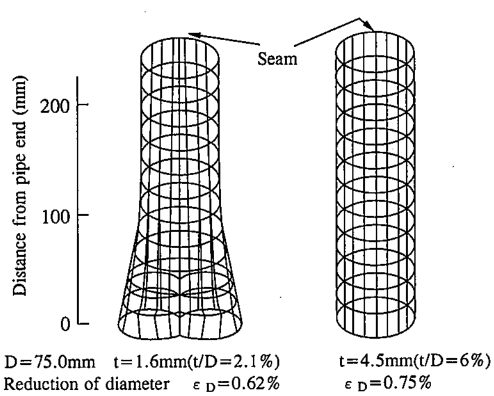

Fig. 2 Configuration of pipe end deformation (×20 magnification)

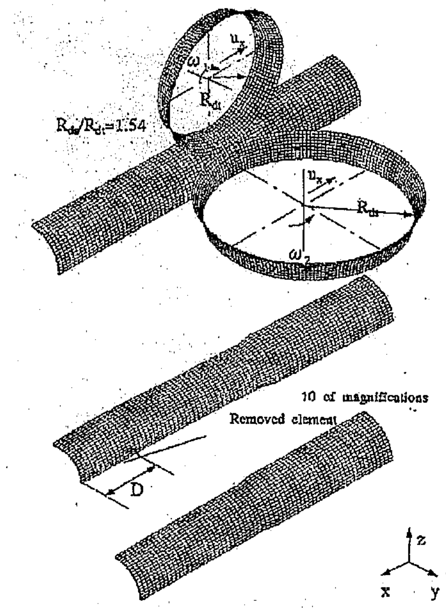

Fig. 3 Model of the Finite Element Method used in analysis

Table 1 Material characteristics

Mechanical property	MPa
Yield Stress σ_Y	500
Coefficient of work hardening H	800
Young's modulus E	210,000

Table 2 Dimensions used in calculation

Diameter D (mm)	Thickness t (mm)	Top roll radius R_{dt} (mm)	Side roll radius R_{ds} (mm)	Caliber diameter D_R (mm)
75.0	1.6	100 65 25	100	74.26 74.64

shown in **Fig. 4**. $\Delta r_p > 0$ and $\Delta r_p < 0$ represent the deformation of a longitudinal ellipse and lateral ellipse, respectively.

2.2 Results of analysis

Fig. 5 shows the results of analysis of the state of the pipe end being affected by the biting area and the pipe end deformation when the pipe end is cut. The figure indicates that the state of the pipe end constituting an unsteady area in biting causes larger deformation than the pipe end after cutting. It also indicates that lateral pipe end deformation presenting a problem with 2-rolls decreases as the ratio of the radius of top-bottom rolls to that of side rolls approaches 1. **Fig. 6** shows the relationship between the ratio of the radius of top-bottom rolls to that of side rolls and the absolute value of the amount of pipe end deformation. 4-rolls of different diameter cause less pipe end deformation ($|\Delta r|$) than 2-rolls, but pipe end deformation increases the

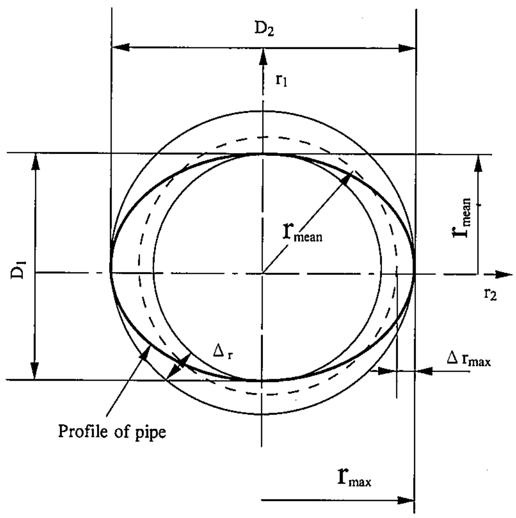

Fig. 4 Definition of pipe end deformation

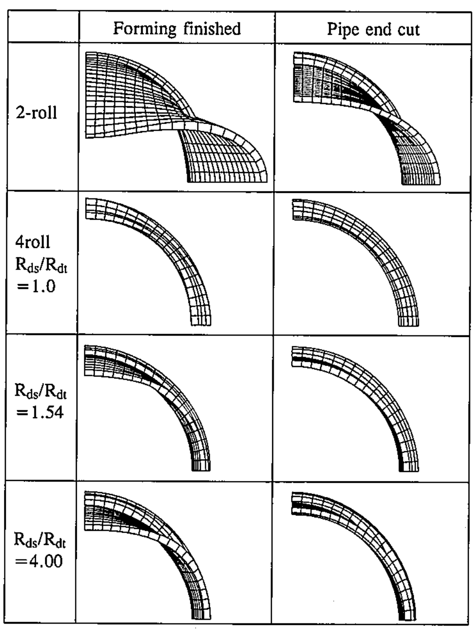

Fig. 5 Configuration of pipe ends by analysis (×10 magnification)

radius by at the area with a large roll radius. This is the same as for the mechanism caused in the case of 2-rolls, where the radius increases in the roll flange with a large roll radius of curvature and where it decreases directly below the roll with a small roll radius of curvature. This phenomenon is caused by the uneven distribution of residual stress because the large diameter portion of the roll is not drawn in the longitudinal direction[4].

3. Effect of Yield Strength at the Welded Seam on the Pipe End Deformation

3.1 Method of analysis

In electric resistance welded (ERW) steel pipes, the yield strength in the vicinity of welds is subjected to heat history due to electric resistance welding, resulting in a different strength from the base metal.

Therefore, even when die forming which serves as axis symmetric forming or 4-roll forming is performed, the welded seam provides a specific point for material strength, causing pipe end deformation. Accordingly, the effect of a welded seam was studied for the case where drawing was performed with 4-rolls of

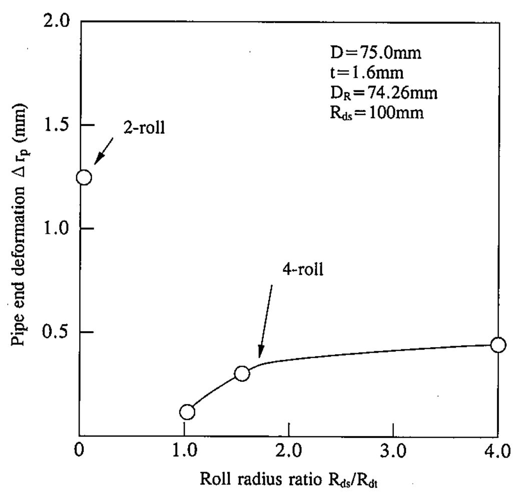

Fig. 6 Relationship between pipe end deformation and roll radius ratio of 4-roll

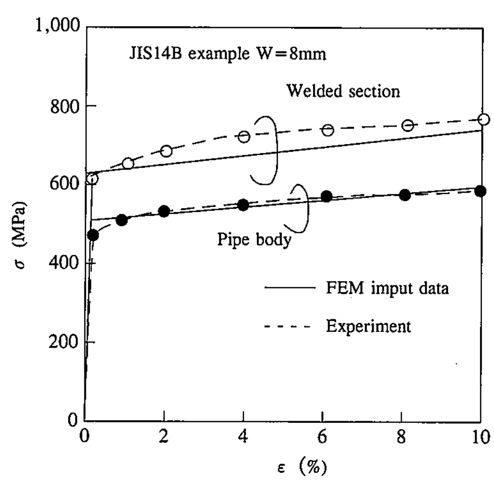

Fig. 7 Stress-strain curve of welded section and base metal

equal radius with respect to pipes of seam strength 100 MPa higher than other areas. Using the stress-strain relationship shown in **Fig. 7**, the distribution of seam strength was calculated together with the experiment conditions using the model in **Fig. 8**.

3.2 Results of analysis and discussion

For hard seams, longitudinal pipe end deformation with a high strength seam along the length occurs as shown in the upper part (1) of **Fig. 9**. This is caused by tensile stress occurring relatively in the axial direction of the seam without the seam being stretched because it is not plastic-deformed in the axial direction.

Fig. 10 shows the results of comparison with experiments on the effect of the amount of contraction. The calculated results were the same as those of the experiments, and an increased contraction showed a trend toward slightly larger pipe end deformation.

A roll radius ratio R_{ds}/R_{dt} was thus studied as a way of preventing pipe end deformation due to the difference in weld strength. Provided that the roll radius ratio R_{ds}/R_{dt} = 1.54 with respect to the 4-rolls of equal radius R_{ds}/R_{dt} = 1.0 from **Fig. 7**, the longitudinal pipe end deformation can be expected to be caused by the effect of seam strength of about 0.25 mm, and so the prevention of deformation was studied from the calculation (see the lower part of **Fig. 9**).

For rolls of equal radius, the radius increased only in the seams, while the pipe end deformation could be eliminated by making the top-bottom rolls symmetric to decrease the radius (R_{ds}/R_{dt} = 1.54). The pipe end deformation caused by the distribution of seam strength can be minimized by changing the roll radius ratio.

4. Improvement Effects Using 4-rolls of Different Radii

4.1 Method of experiment

Experiments were conducted to check the offset of pipe end deformation caused by the difference in welded seam strength using rolls of different radii for 4-roll sizers. In the experiments, single-stage forming by a 4-roll sizer was performed using two types of roll calibers as shown in **Fig. 11**. The construction of the 4-roll sizer is such that the radius of the side roll is smaller than that of the top-bottom roll. The amount of roll pressure drop was changed to adjust the change of contraction percentage. The configuration of the pipe body deteriorates as it gets out of the proper contraction percentage of caliber, and forming was performed aiming at a contraction percentage of outside diameter of 0.1, 0.9, and 1% or so. The pipe end was cut to 1 m after forming, and the configuration of the pipe end was measured at intervals of 20 mm from 10 mm at the pipe end to 230 mm with a roundness measuring instrument capable of measuring the absolute radius by the least squares method. To determine the effect of the positional relationship between the roll radius and welded seam on the pipe end deformation, the seam was aligned with the top-bottom roll (large radius) and the side roll radius (small radius).

4.2 Results of experiments and discussion

Fig. 12 shows the measurement results of the configuration of pipe end face after forming in a wire-frame view.

For the small radius of rolls with the seams aligned with the side rolls (θ = 90° : R_{dt}/R_{ds} = 1.54), the pipe end deformation decreased. On the contrary, when the welded seam is aligned

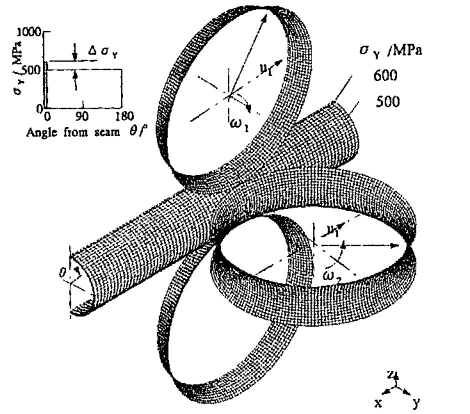

Fig. 8 Model of Finite Element Method allowing for welded seam

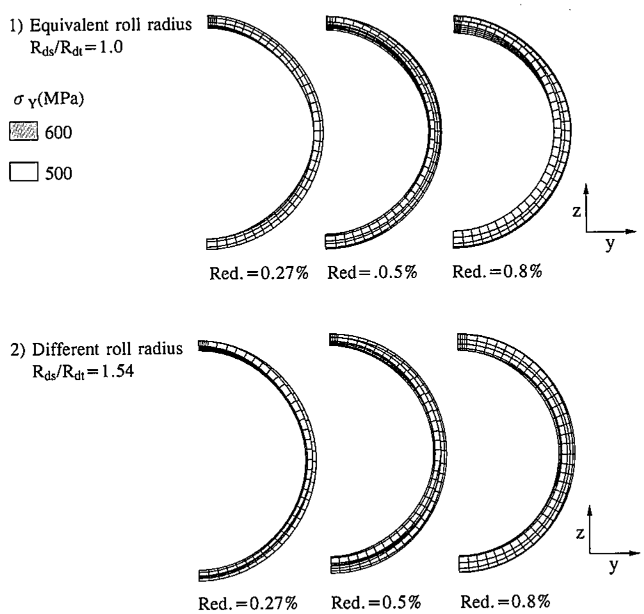

Fig. 9 State of pipe end deformation by analysis (×10 displacement magnification)

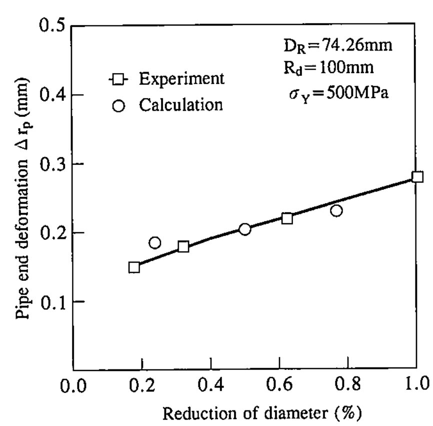

Fig. 10 Relationship between pipe end deformation and amount of contraction when welded seam is harder by 100 MPa

with the area with large roll radius ($\theta = 0°$: $R_{dt}/R_{ds} = 0.66$), the pipe end deformation caused by the difference in roll radius is superimposed and increased.

Fig. 13 summarizes the effects of contraction percentage, showing that the pipe end deformation is prevented in the vicinity of the contraction amount of design caliber (1.0% contraction at $D_r = 74.26$ mm).

From the above results, when seam strength is increased by about 100 MPa, a roll radius ratio R_{dt}/R_{ds} of at least 1.54 may be used. It was also shown that the pipe end deformation could be offset in the vicinity of the contraction amount of design caliber. Even when there is a difference of strength between the welded seam and base metal, the change of the roll radius and application of the technology to each steel type allow high precision products to be manufactured with welding. Products from 690 to 780 MPa or so can be manufactured at present.

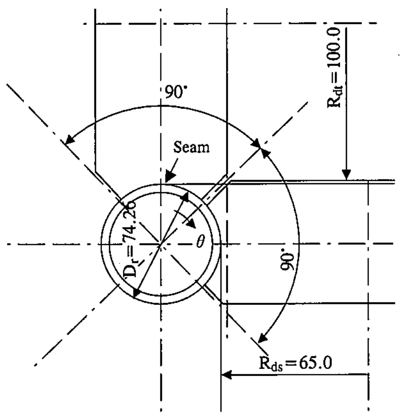

Fig. 11 Dimensions of 4-roll caliber used in experiments

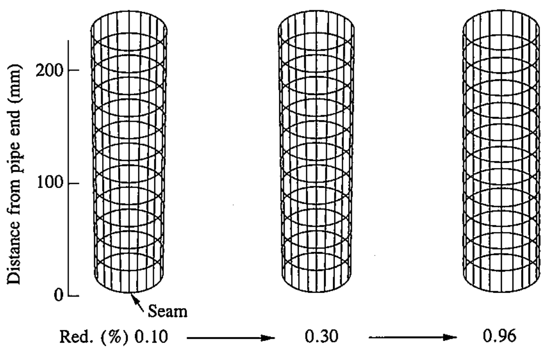

Fig. 12 Configuration of pipe end deformation using 4-rolls of different radii (×20 magnification)

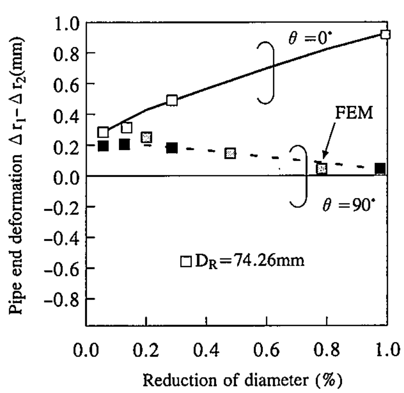

Fig. 13 Relationship between pipe end deformation and contraction percentage using 4-rolls of different radii

5. Technique of Measuring the Configuration of Pipes

5.1 External roundness gauge

For pipe end deformation, it was possible to ensure high dimensional accuracy as described above. Since high dimensional accuracy must be ensured for pipe bodies also, an on-line external roundness gauge capable of accurately measuring the outside diameter and configuration (roundness) of pipes by noncontact was developed to shorten the roll adjustment time and to achieve

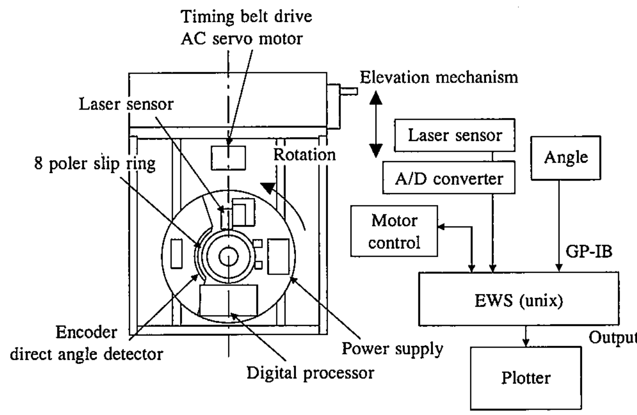

Fig. 14 On-line external roundness measuring system

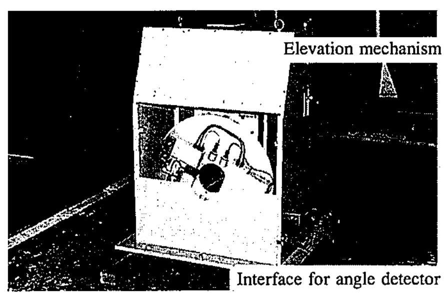

Photo 1 Appearance of on-line external roundness gauge

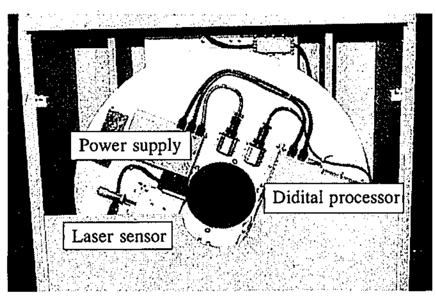

Photo 2 Enlargement of sensor portion

high accuracy. In forming by a 4-roll sizer in particular, it is difficult to adjust roll marks using roll flanges and to make measurements by the conventional method of using the diameter. Therefore, a device capable of measuring roll alignment quantitatively is required.

We therefore developed a measuring device using the radius and installed an actual device. **Fig. 14** shows the outline of the device, which can measure external roundness with a noncontact laser displacement gauge that offers excellent response processing for high precision digital signals (see **Photos 1** and **2**). Measurement is processed in Windows X11 under Unix on an EWS (engineering workstation). Circumferential measurement includes 1,024 points, and the device can measure at a maximum speed of 60 rpm.

Fig. 15 shows an example of the measurement of 4-roll forming, enabling measurement at a level not possible by the conventional measuring method, and the roundness of a pipe body can be made as good as $\Delta r = 35 \mu m$ by adjusting the roll from the configuration of the pipes, thus achieving high dimensional accuracy of pipes.

Application of the external roundness gauge also achieved good roll set accuracy and the rate of mill operation by significant reduction of adjustment time were improved.

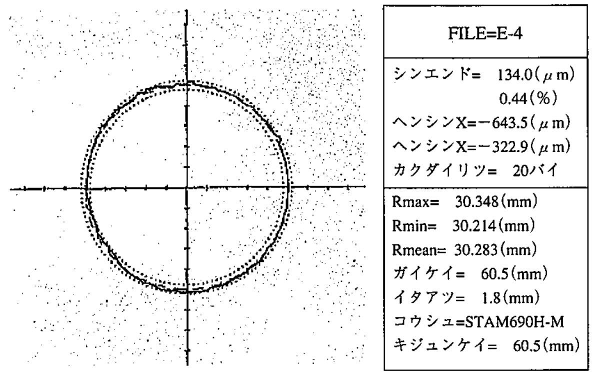

Fig. 15 Example of measurement of 4-roll forming with an external roundness gauge

6. Conclusion

We investigated a method of preventing pipe end deformation in sizers resulting from the difference in strength of the welded seams of thin wall electric resistance welded (ERW) pipes by experiments and with the three-dimensional finite element method. When the strength of welded seams differs from the base metal, pipe end deformation can be minimized by changing the ratio of the radius of rolls depending on the strength. We also developed an external roundness measuring instrument to enhance the dimensional accuracy of pipe bodies and applied it to actual operation. Installation of the instrument reduced the time required for adjusting rolls and thus increased the operation rate.

The above technology achieved high strength and high precision for both pipe ends and pipe bodies with welding, thus reducing manufacturing cost.

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