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# Development of a Cross Roll Edge-bending (CRE) Method for ERW Tube Forming

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**Abstract:**

*The authors have contrived a Cross Roll Edge-bending (CRE) method that can be used for an ERW tube mill, and which produces thin- to thick-walled tubes through adjustment of the roll pass profile according to the bending curvature and required wall thickness. To do so, the upper and lower rolls are permitted to turn and cross one another on their vertical axes in order to provide roll shareability for work involving changing outer diameters and wall thicknesses, as well as to improve edge formability in order to stabilize product quality. A formability test on an experimental test stand and subsequent numerical analysis proved the validity and superiority of the CRE method in several regards, including its ability to deliver roll shareability to meet a desired bending curvature, improved edge formability due to effective action of the bending moment, and high-precision forming performance with few impressions.*

## 1. Introduction

With its excellent features in cold rolling, the ERW tube mill is currently utilized in a variety of areas. In the small-diameter ERW tube mill used at Kimitsu Works, unique high-grade tubes such as boiler tubes and stainless steel tubes have been developed.[1] The high quality of these products has earned them considerable support and confidence among users. However, the recent, rapid changes in the social environment and the serious business slump of the last few years have affected the ERW tube industry as well. The industry must respond with further cutbacks in costs and more stringent quality requirements. As part of this effort, large-capacity, high-grade tube mills (i.e., those capable of producing tubes with a wide range of wall thicknesses, as expressed by a ratio of outer diameter to wall thickness of 2% - 20%) must be modified to employ more productive, reliable technologies allowing higher-grade tubes to be manufactured in a variety of wall thicknesses. Such technologies depend greatly on roll forming technique.

For roll forming in mills that move between making thin- and thick-walled tubes, dedicated rolls are generally used for work of a specific diameter. To enhance the productivity of the tube mill, therefore, rolls are changed using a quick-change method that expedites the process. On the other hand, in mills making only thin-walled tubes (i.e., mills capable of producing tubes with an outer diameter to wall thickness ratio of 10% or less), a new type of flexible forming (FF) technique[2] is available. Mills using this new FF technique can meet requirements for both roll shareability and improved formability. This new technique can be considered revolutionary as it allows any optimized roll pass as well as a constraint mode to be freely selected for the forming process. The bending method it employs, however, is no better than the

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conventional method, and is likely to cause deformation (as described later) due to the roll pass and structure. Hence, this FF technique cannot be applied to mills making both thin- and thick-walled tubes, such as the ERW tube mill at Kimitsu Works.

The CRE method introduced in this paper was developed as a novel edge-bending technique which permits both roll shareability and quality stabilization in mills making both types of tubes. It replaces conventional concepts of bending techniques.

## 2. Principle and Features of the CRE Method

As shown in **Fig. 1**, edge-bend rolls consist of a pair of the upper and lower grooved rolls. The work is formed on the basis of the four-point bending principle.

A set of rolls is usually changed as the outer diameter of the work is changed. For a change in the wall thickness of the work, however, the current rolls remain in place, and only the gap between the upper and lower rolls is adjusted to improve the productivity. As a result, inadequate edge bending has occurred during thin-walled work, while thick-walled work displayed an impression in the bent part, as shown in **Fig. 1**.

To solve these problems, the CRE allows the upper and lower rolls to cross each other so that the resulting roll pass profile can be adjusted to fit itself to the bending curvature and wall thickness required.

**Fig. 2** shows this principle of the CRE method. Sketch (a) illustrates what happens when a hardboard paper edge is bent by hand. It is possible to bend the paper to a smoother curvature by rubbing the inside of the bent section towards the center of the paper with a forefinger, while rubbing the outside of the paper towards the edge with the thumb. In the CRE method, this same principle is applied to the roll forming process. As shown in sketch (b), by allowing the upper and lower rolls to cross each other, the upper roll directs the roll surface track inward, while the lower roll directs it outward. This effective action of the bending moment improves edge formability.

**Fig. 3** shows an outline of the CRE method. The upper and lower rolls at the edge bend are split into a right and left side and are allowed to cross each other to improve edge formability. And, concurrently, by adjusting each turning angle of the upper and lower rolls, roll shareability is achieved for a wide range of wall thicknesses and outer diameters.

**Fig. 4** (b) - (f) shows wire frame models that depict the path of contact of the rolls when the upper and lower rolls — with the pass profile shown in (a) — are allowed to turn to their respective angles. As described above, by adjusting the turning angle of the upper roll and the roll gap, roll shareability can be provided for changes in wall thickness. Likewise, by adjusting the turning angle of the lower roll, roll shareability can also be maintained for changes in the outer diameter. And since the point of contact between the upper roll and the inner surface of the work is constantly moving, the impression on the work caused by local contact with the upper roll should be reduced.

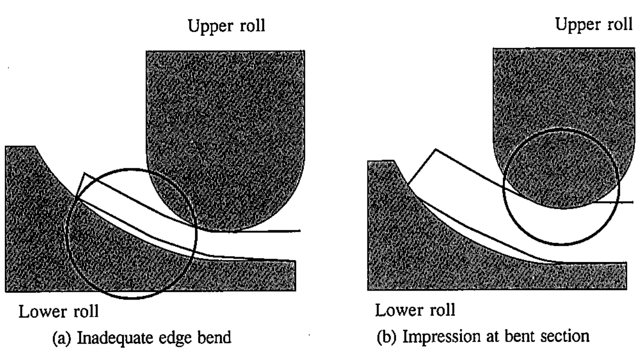



**Fig. 1** Problems of conventional edge bend methods

## 3. Test Results with a CRE Test Stand

### 3.1 Method of testing

A CRE test stand as shown in **Photo 1** was manufactured for trial, and used to conduct the test. Major specifications of the test stand and the tested materials are tabulated in **Tables 1** and **2**. The test stand was so structured as to permit the adjustment of the upper and lower roll positions in both the cross and vertical directions, and adjustment of the turning angles of the upper and lower rolls on their vertical axes. A load cell built into the stand was used to measure roll pressure and cross-directional thrust load.

**Fig. 5** shows the roll pass profile used in the test. These rolls were designed to form tubes with an outer diameter of 50.8 - 76.2 mm and maximum wall thickness of 10.5 mm, and, through the use of the CRE method to realize edge bending to 100% of the intended final curvature. For bending length, the roll position in the cross direction was adjusted so as to bend up to 20% of the plate width (10% on each side). The rolls were designed so as to locate their center of rotation on the base diametral planes.

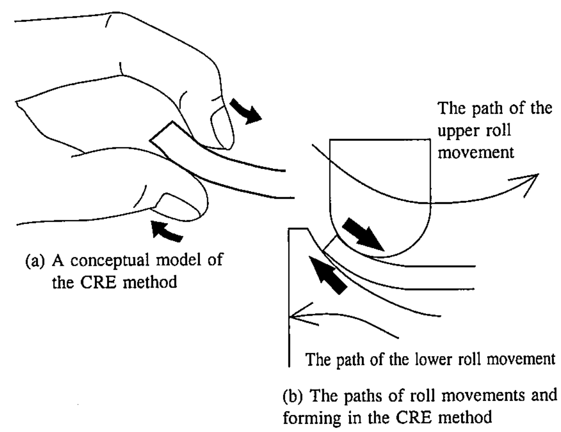



**Fig. 2** Principle of the CRE method

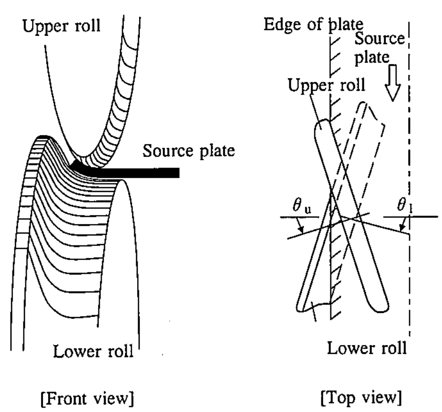


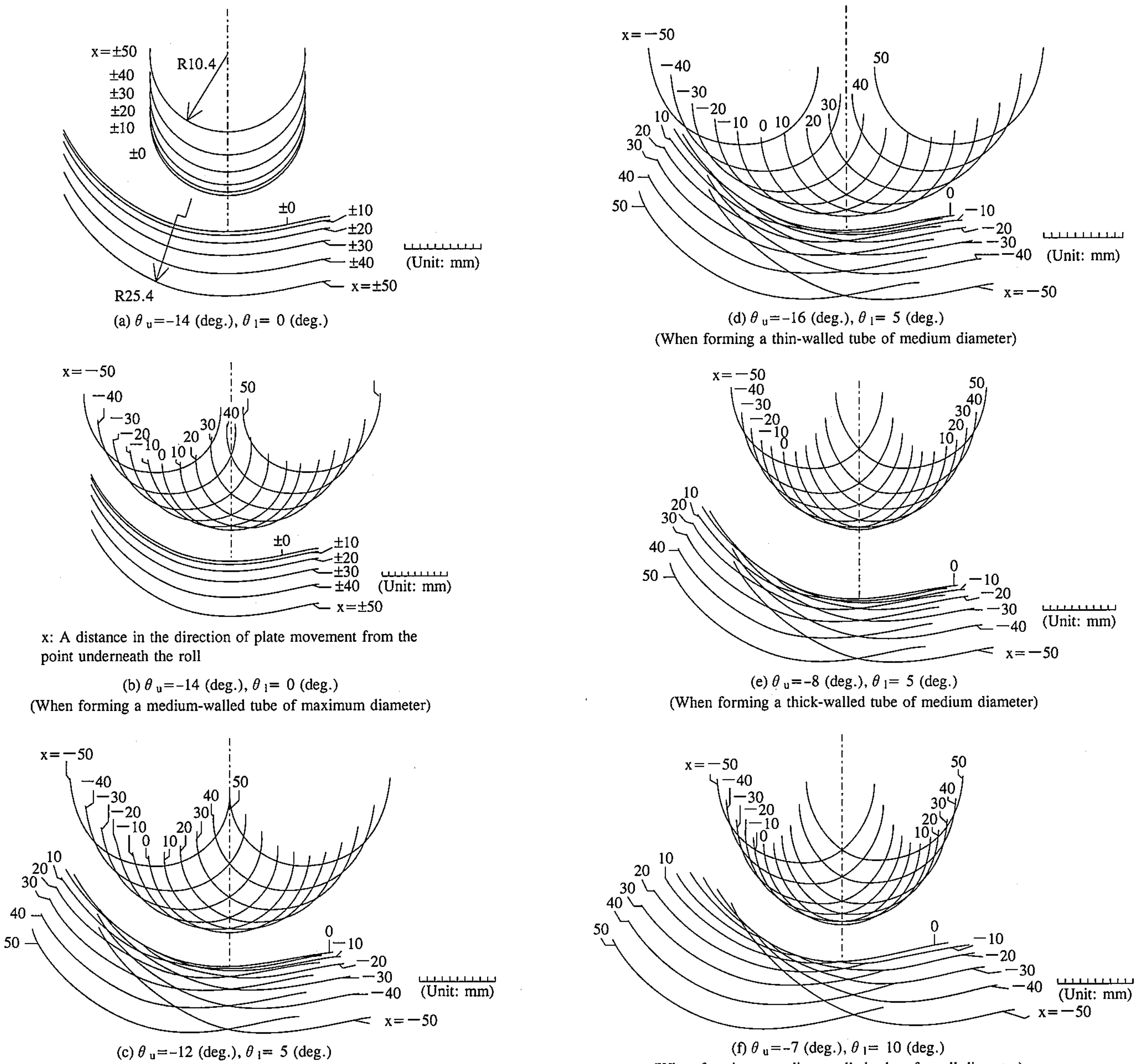

**Fig. 3** An outline of the CRE method

The wall thickness distribution of the formed material was measured using a micrometer, and curvature distribution using a three-point curvature gage (i.e., the relationships of the positions of three marked points, with a distance of 10 mm between each are converted into a curvature).

As for the crossing of the upper and lower rolls, as **Fig. 6** shows, two types of forming can be considered: an inward forming type, in which the point of contact between the upper roll and the work moves from the work's edge to its center; and an outward forming type, in which the point of contact moves from the work's center to its edge. For the two types, the same wire frame model should be established if the absolute values of the turning angle in both types are identical. (Note that the directions of movement of the wire frame are opposite in the two cases.) Differences in formability between the two types were also examined.

### 3.2 Test results

**Fig. 7** shows the cross sections of materials formed by the conventional method (turning angle = 0), the inward forming method, and the outward forming method. As noted, the best edge formability was achieved by the inward forming method. This result is in agreement with the basic principle behind the CRE method, i.e., the movements of the fingers when bending a thick paper by hand. Under this method, the lower roll (in contact with the outer surface of the bend section) was moved towards the edge of the material, while the upper roll (in contact with the inner surface of bend section) was moved towards the center of the material. Overall bending performance was thus




(a) $\theta_u$=-14 (deg.), $\theta_l$= 0 (deg.)

x: A distance in the direction of plate movement from the point underneath the roll

(b) $\theta_u$=-14 (deg.), $\theta_l$= 0 (deg.)
(When forming a medium-walled tube of maximum diameter)

(c) $\theta_u$=-12 (deg.), $\theta_l$= 5 (deg.)
(When forming a medium-walled tube of medium diameter)

(d) $\theta_u$=-16 (deg.), $\theta_l$= 5 (deg.)
(When forming a thin-walled tube of medium diameter)

(e) $\theta_u$=-8 (deg.), $\theta_l$= 5 (deg.)
(When forming a thick-walled tube of medium diameter)

(f) $\theta_u$=-7 (deg.), $\theta_l$= 10 (deg.)
(When forming a medium-walled tube of small diameter)

**Fig. 4** Wire frame model of the CRE method

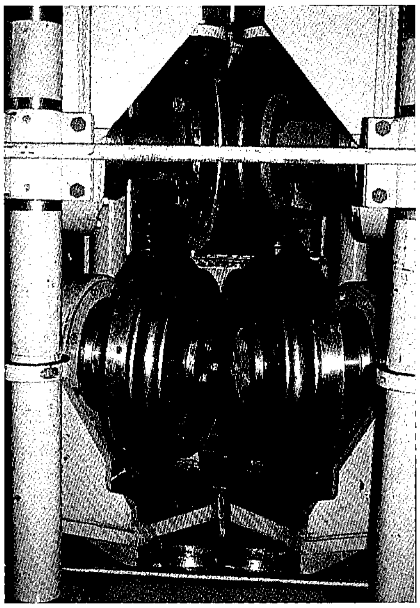


**Photo 1** CRE test stand

**Table 1** Major specifications of the CRE test stand

| | |
|---|---|
| Type | The width-variable horizontal roll stand with upper and lower rollers, which are made to rotate on their vertical axes and split into a right and left side |
| Roll size | Upper roll diameter: 260 -350 mm, Lower roll diameter: 350 mm |
| Load resistance | Screw down direction : 20 t max.<br>Longitudinal direction : 10 t max.<br>Cross direction : 3 t max. |
| Rigidity of mill | ≧15 t/mm |
| Turning angle | Upper and lower rolls: ±30 deg. |
| Size | Plate width : 150 - 360mm; for 50.8 - 101.6mm dia. |

**Table 2** Formed materials

| | |
|---|---|
| Class of steel | SS410 class steel |
| Plate thickness | 2.2, 4.4, and 8.6 (mm) |

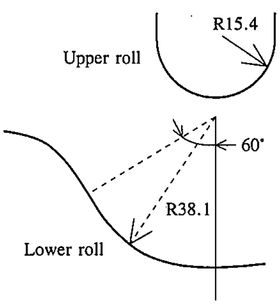



**Fig. 5** Roll pass profile

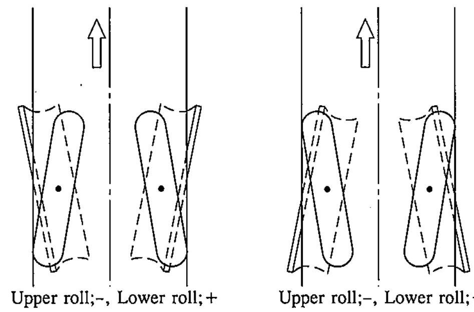



**Fig. 6** Definition of roll pass profile and the turning direction

improved. This mechanism will be discussed subsequently in the section on numerical analysis. The inward forming method produced the following test results.

**Fig. 8** shows the curvature distribution and wall thickness distribution when turning angle was provided for the upper and lower rolls. In the conventional method, where no turning angle is provided, a larger curvature is seen only at the point of contact with the upper roll; there is no curvature in the vicinity of the edge, thereby causing large impressions to form in the local contact zone. This local contact of the material with the upper roll was attributable to the fact that the upper roll curvature had been designed on the basis of the maximum wall thickness of the work. Such contact was a common phenomenon which would occur when the rolls were in shared use for a wide range of wall thicknesses. When a turning angle was provided for the upper and lower rolls, however, dramatic improvement was seen both in edge formability and in wall thickness distribution. By turning the upper roll, forming occurred up to the vicinity of the edge; further, the continuously moving point of contact between the upper roll and the material worked to eliminate local contact and reduce impressions made. In addition, the turning of the lower roll caused greater curvature in the material than that of the lower roll and shareability of approximately 1.5 times for the outer diameter was verified.

**Fig. 9** shows the effects of the upper and lower roll rotation angles, and of the upper roll diameter, on edge curvature and on reductions in wall thickness caused by impression. Edge curvature is expressed as an average curvature of a section of a possible bending length. As shown in **Fig. 9**(a), the rotation of the upper roll improves edge formability and reduces impressions, while the rotation of the lower roll enables control of edge curvature, thus ensuring that the shareability effect is present when outer diameter is changed. An increase in the roll diameter will reduce the optimum turning angle and the size of impressions, as


(a) $\theta_u$=0 (deg.), $\theta_l$= 0 (deg.)

(b) $\theta_u$=-14 (deg.), $\theta_l$= 15 (deg.) (Inward forming type)

(c) $\theta_u$=14 (deg.), $\theta_l$= -15 (deg.) (Outward forming type)

**Fig. 7** Cross sections of formed materials shown in **Fig.** 9 (b). Under both conditions, no phenomena such as roll seizure were observed.

We now turn to the load characteristics of the CRE method. Assuming that an edge bend is modeled and that rigid and plastic materials are evenly bent to an angle of $\theta$ within a zone of bending length L, the bending load P can be obtained by the energy method, and is expressed by the following equation:

$$P=1/4\cdot L\cdot l_d\cdot(1/R(1-\cos\theta))\cdot(1/R)\cdot\sigma_y\cdot t^2 \quad \cdots\cdots(1)$$

where $l_d$ is the length of a longitudinal contact, R is the radius of curvature, $\sigma_y$ is yield stress, and t is the thickness of a plate.

Assuming that $P=\alpha\cdot(1/R)^a\cdot\sigma_y^b\cdot t^c$, a multiple regression analysis of the test results reduces to

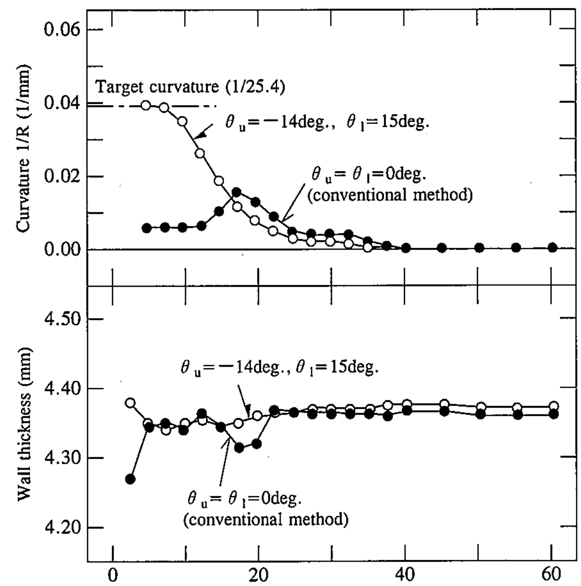



**Fig.** 8 An example of curvature and wall thickness distribution — Plate thickness = 4.4mm

$$P=59\,(1/R)^{0.92}\cdot\sigma_y^{1.14}\cdot t^{2.23} \quad \cdots\cdots(2)$$

(n=49, correlation coeffcient; 0.95)

From equation (2), the roll pressure load can be estimated. A comparison between the estimated pressure load obtained from equation (2) and the actual pressure load is shown in **Fig.** 10.

## 4. Deformation Analysis for the CRE Method

### 4.1 Analytical method

The analysis was conducted using two-dimensional plane strain 4-contact point isoparametric elements according to the general-purpose finite element code MARC. A computation model is shown in **Fig.** 11. A two-dimensional model was devised on the assumption that the roll gap profile, which is determined by the position of a plate material in the direction of forming (X), is moved on the same plane (Y-Z) at velocities (Vy, Vz), and that the cross section of the roll pass will remain unchanged in the direction of forming (X). Computational conditions are tabulated in **Table** 3. To simplify the model, it was assumed that the upper roll alone would rotate. The computation was conducted for both the inward forming and outward forming cases; for the former case, the edge formability improvement mechanism was examined.

### 4.2 Results of the analysis

**Fig.** 12 shows the deformation profile and **Fig.** 13 the curvature distribution compared to the respective results obtained through the experiment. The computational results of the ultimate profile nearly agreed with the experimental results, suggesting that this computation may yield an approximate estimation of edge curvature. The computation also indicated an edge forming improvement effect from the inward forming method.

**Fig.** 14 shows changes in the cross direction stress in the inner and outer surfaces of the plate in the vicinity of the edge (i.e., within 5 mm of the edge). In the case of the inward forming method, cross directional stress was imposed on both sides of the surface up to the vicinity of the edge; this took the form of compressive stress on the inner surface and tensile stress on the outer surface. In the case of the outward forming method, how-

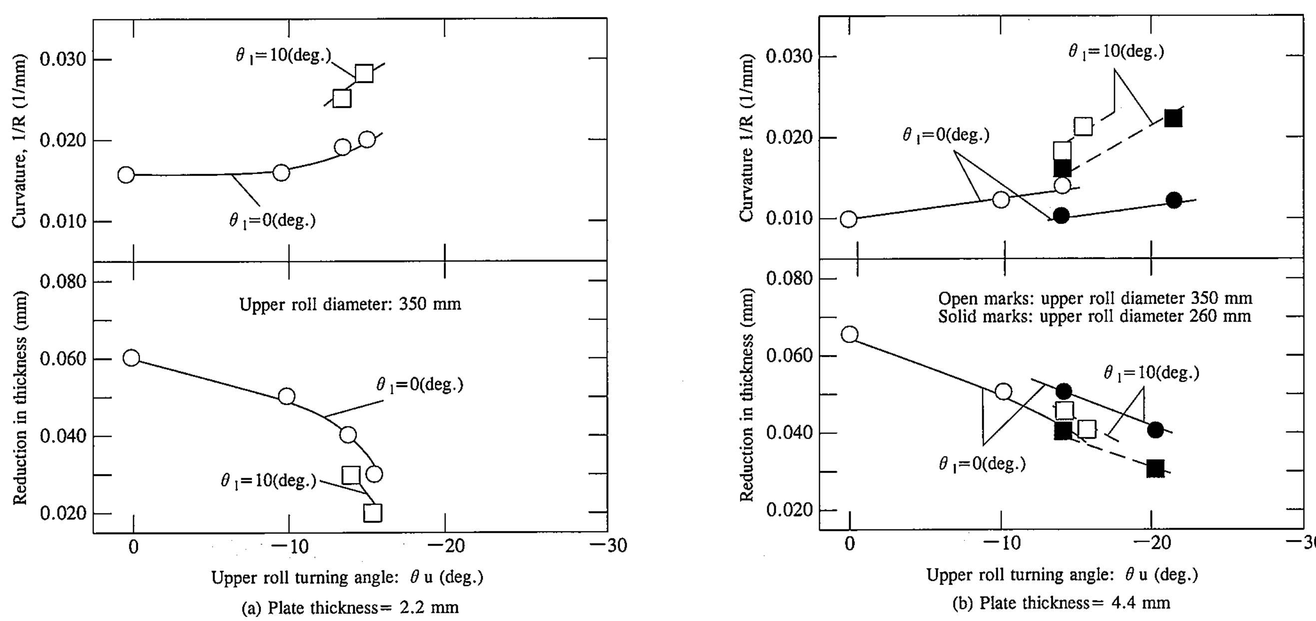



**Fig.** 9 Impacts of turning angle on curvature and reduction in thickness due to impression

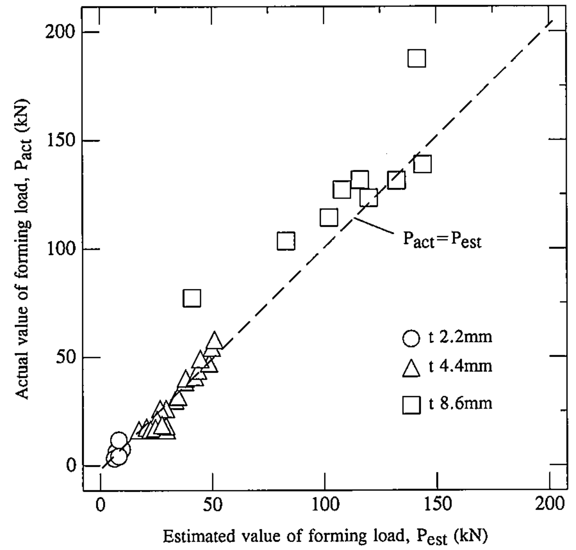



Fig. 10 Comparison between estimated pressure load and actual pressure load

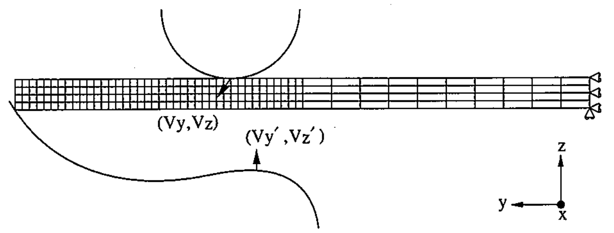



Fig. 11 Computational model

Table 3 Computational conditions

| | Item | Condition |
|---|---|---|
| Roll | Radius of curvature of roll pass | Upper roll :10.4, Lower roll: 25.4 (mm) |
| | Roll diameter | Upper roll : 300 $\phi$ , Lower roll : 300 $\phi$ (mm) |
| | Turning angle | Upper roll : $\theta_u$: ±18, Lower roll : $\theta_l$ : 0 (deg.) |
| Plate to be formed | Elastic modulus E | 206 (kN/mm²) |
| | Yield stress $\sigma_y$ | 350 (N/mm²) |
| | Working effect modulus H' | 980 (N/mm²) |
| | Size | plate width 170 x plate thickness 5.0 (mm) |
| | Number of split elements | For plate thickness: 4, For bent length (cross direction): 20 |
| Coefficient of friction μ | | 0.2 |

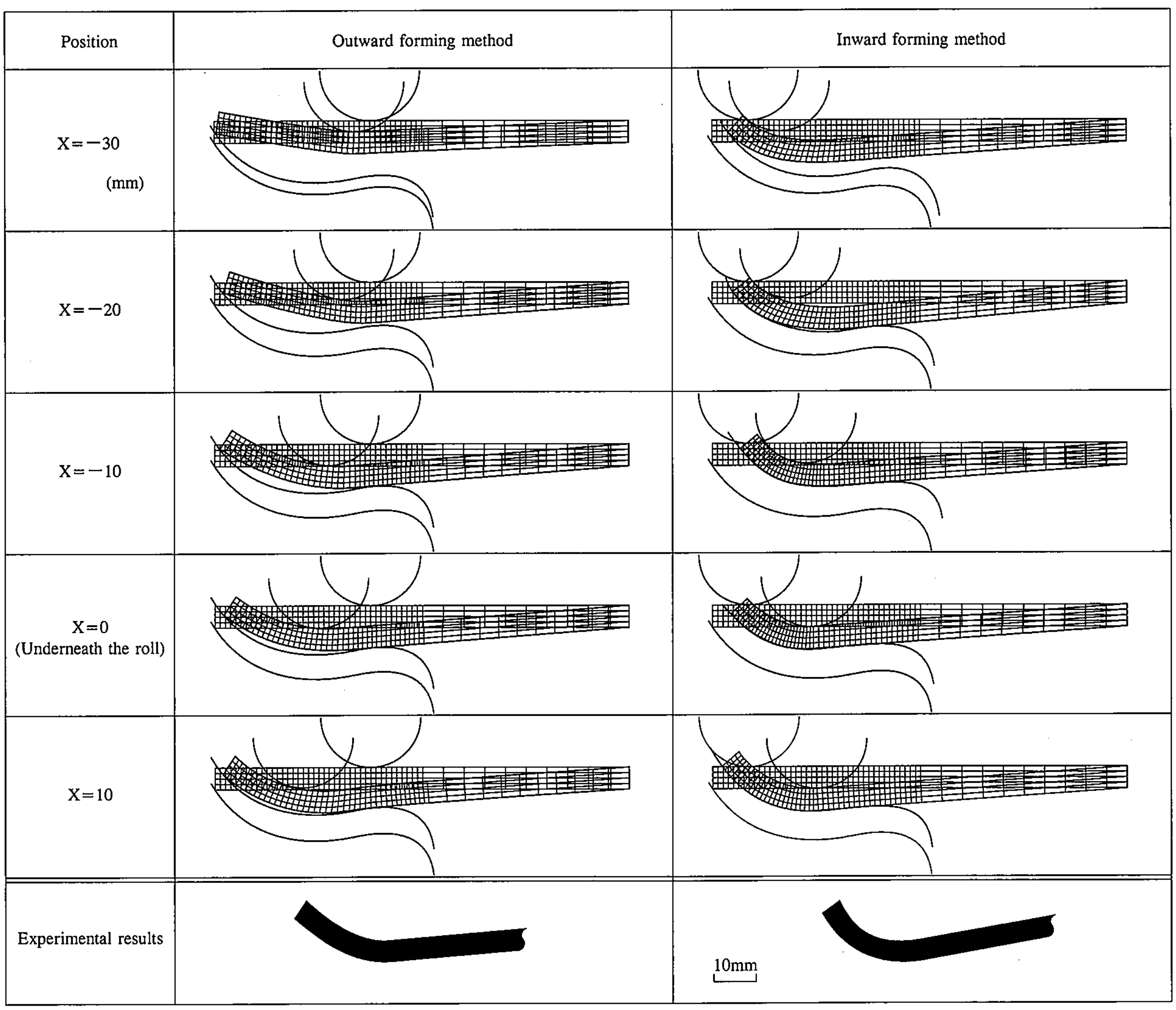
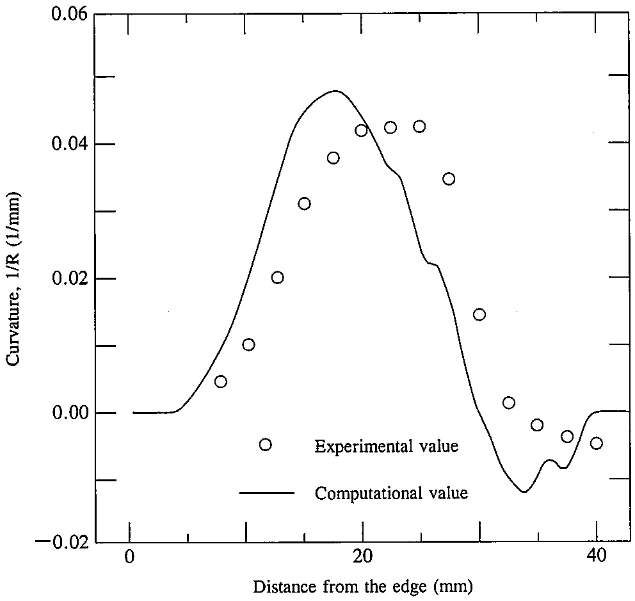
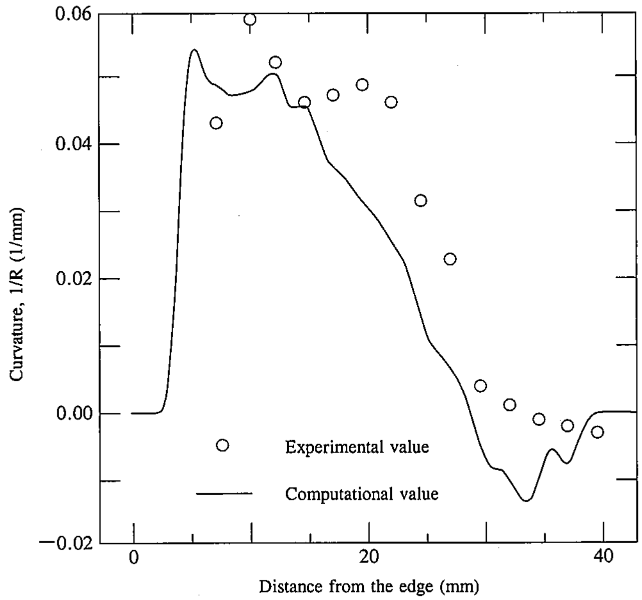



Fig. 12 Deformation profile



(a) Inward forming method



(b) Outward forming method

**Fig. 13** Curvature distribution

ever, almost no cross directional stress was imposed.

**Fig. 15** shows the changes of bending moment in the direction of forming (X) which acted on the bending zone. In the case of the inward forming method, a large bending moment was initiated immediately after the start of forming. This suggests that in this method, edge formability can be improved in the initial forming process once the upper roll has come into contact with the work's edge zone. On the other hand, in the case of the outward forming method, as shown in **Fig. 12**, the roll is not in contact with the edge of the work in the position X=10 or thereafter, suggesting that inadequate forming takes place at the edge. This indicates that the roll gap produced by the rotation of the upper roll is not appropriate, relative to the thickness of the work, in the vicinity of the edge. During actual forming, however, this degree of inappropriateness can be estimated from the error in the roll setting, the rigidity of the stand, and the deviation of plate thickness. In other words, the inward forming method thus seems less susceptible to these factors. Or to put it slightly differently, the inward forming method seems to feature a geometric relationship between the roll and the work that helps increase the effectiveness of the bending moment, which in turn improves edge formability.

## 5. Conclusion

Large-scale ERW tube mills capable of producing tubes having a wide range of wall thicknesses currently confront two significant issues: the shareability of forming rolls for a change in the tube's outer diameter or wall thickness; and the need to improve edge formability in order to stabilize product quality. To

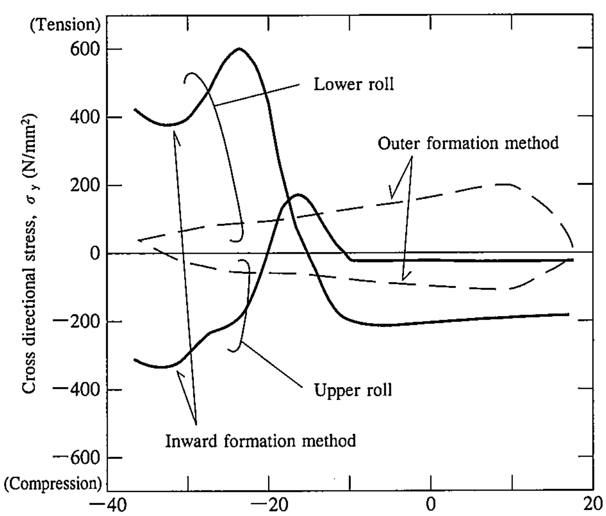


**Fig. 14** Changes of cross directional stress (at a location 5 mm from the edge)

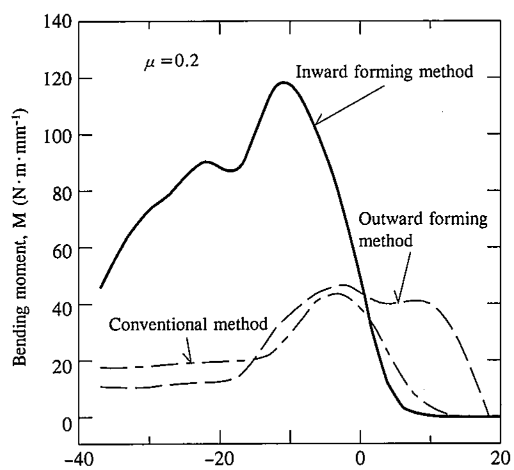


**Fig. 15** Changes in the bending moment

address both these issues, the Cross Roll Edge-bending (CRE) method has been devised. Under this method, the roll gap profile can be properly adjusted according to the required bending curvature and wall thickness by allowing the upper and lower edge bend rolls to turn and cross each other. A formability test on an experimental test stand and a numerical analysis have proved the following effects:

(1) By rotating the rolls, roll shareability can be maintained up to about 1.5 times the bending curvature.

(2) By allowing the upper and lower rolls to cross each other in such a direction that the upper roll surface track will move from the work's edge towards its center, the bending moment will effectively work to improve edge formability.

(3) By using a rotation angle for the upper roll appropriate to the thickness of the work, high-precision forming can be accomplished with few impressions made.

The CRE method was introduced in the small-diameter ERW tube mill at Kimitsu Works in August 1995. The mill is operating successfully at present, and this method is contributing significantly to providing stabilized weld performance for thin-walled high tensile steel materials, particularly in terms of optimizing the forming while simultaneously preventing irregular product thickness.

## References

1) Sumimoto, D. et al.: Shinnittetsu Giho. 362, 54 (1997)
2) For example, Li, G. F.: TUBETEC 95. Shanghai, 1995-3