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Computer Aided Design of Reshaping Process of Circular Pipes into Square Pipes

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Abstract**—**Square pipes (pipes with square cross sections) are being used for various industrial objectives, such as machine structure components and housing/building elements. The utilization of them is extending rapidly and widely. Hence, the out-put of those pipes is increasing and new application fields are continually developing.

Due to various demands in recent time, the products have to satisfy difficult specifications with high accuracy in dimensions. The reshaping process design of pipes with square cross sections; however, is performed by trial and error and based on expert's experience.

In this paper, a computer-aided simulation is developed based on the 2-D elastic-plastic method with consideration of the shear deformation to analyze the reshaping process. Effect of various parameters such as diameter of the circular pipe and mechanical properties of metal on product dimension and quality can be evaluated by using this simulation. Moreover, design of reshaping process include determination of shrinkage of cross section, necessary number of stands, radius of rolls and height of pipe at each stand, are investigated. Further, it is shown that there are good agreements between the results of the design method and the experimental results.

Keywords—Circular Pipes, Square Pipes, Shear Deformation, Reshaping Process, Numerical Simulation.

I. Introduction

SQUARE pipes (pipes with square cross sections) made by reshaping processes are widely used as structural elements in almost all industries. Despite a long history of the process, because of the complicated deformation behavior of pipes during reshaping, the design procedures for forming rolls and pass-schedules mainly rely on experience-based knowledge. Thus, the fundamental and systematic approaches to the reshaping technology and the guidance for the design of rolls and processes have been required. In order to solve these serious problems, a design method has been developed to determine ideal roll profiles and roll arrangement for the process. It is based on the simulation technique to analyze two-dimensional elasto-plastic deformations of the cross sections of pipes.

Kiuchi [1] conducted a series of experimental investigations for the reshaping processes of the square and rectangular pipes from the circular pipe. Effects of process variables and pass-schedule were investigated on the deformation of formed product, limit conditions for the occurrence of defects and reshaping loads. Moreover, the optimal conditions were investigated to attain the required accuracy of products and the required productivity.

In order to investigate the deformation features of the circular welded steel pipes into the square sectional pipes reshaped, using an extroll-forming mill, Onoda, et al. [2] developed the conventional rigid-plastic finite element method. The calculated cross-sectional geometry of the formed pipe is in good agreement with the experimental result.

Kiuchi, et al. [3] have also developed the 3-D elasto-plastic finite element method by which various deformation features and mechanical characteristics of pipes with square and rectangular cross sections can be simulated. It is also useful for process control, quality control and production management.

Most theoretical studies have been developed based on the membrane theory and subsequently the effect of bending is ignored. However, bending under the peripheral tension or compression causes the thinning pipe; thus, the bending effect may not be neglected and the membrane theory cannot be applied. On the other hand, if the bending is taken into account in the finite element method, a large number of elements and also much calculation time are needed.

For these reasons, this study aims to develop a two-dimensional elasto-plastic theoretical method to analyze and optimize reshaping processes. The developed method introduces a new type of contact model, considered a method to deal with wall-thickness change and is able to handle various roll profiles. Through the analysis, geometrical characteristics and deformation behavior of cross sections of pipes are investigated under required conditions to satisfy the equilibrium equations of peripheral and radial forces and peripheral bending moments [4].

Moreover; the numerical analyses of forward and backward deformations of the pipe are performed by the above-mentioned analysis method and a design method has also been developed to determine the number of rolls, ideal roll profiles and an appropriate arrangement of rolls at each stand [5]. However, the shear deformation between two nearby elements was not considered.

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II. Method of Analysis

In this analysis, the cross-section of pipe is divided into the appropriate number of elements in the peripheral direction. In this method, the cross section of the pipe is divided into an appropriate number of elements named 1, 2... i... nd from the mid-part of the cross section in the peripheral direction as shown in Fig. 1.

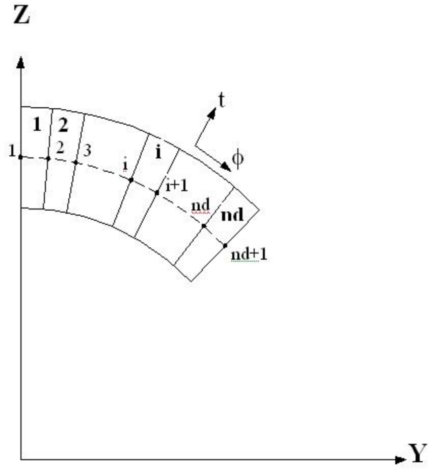

Fig. 1 The cross section of the pipe and the divided elements in the peripheral direction

Each element is also divided into ne small elements in the thickness direction called "sub-element" and named 1, 2...j... ne from the inside of the pipe as shown in Fig. 2. The thickness of sub-elements are hi1 ‘ ... ‘hij ‘ ... ‘hine. The position of the border (nodal point) i is expressed by the components (yi, zi).

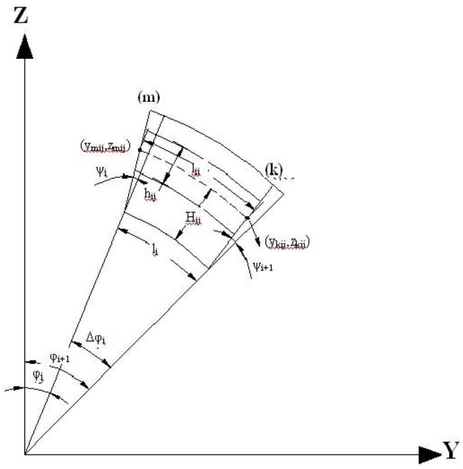

Fig. 2 The divided sub-elements of each element of cross section in the radial direction

In order to consider the shear deformation between two nearby elements in analysis, the extended Kirchhoff-Love assumption [6], i.e. the border planes of elements are not reminded perpendicular to the peripheral surface of pipe during deformation, is used.

To simplify the analysis, the longitudinal strain is neglected, so that the deformation will be the plane strain deformation. The curvature of each element is fixed in the peripheral direction.

The peripheral lengths of the element i and the sub-elements i,j are

$$l_i = \sqrt{(y_{i+1}-y_i)^2+(z_{i+1}-z_i)^2} \tag{1}$$

$$l_{ij} = l_i + (\varphi_{i+1}-\varphi_i-\psi_{i+1}+\psi_i)H_{ij} \tag{2}$$

where Hi,j is the distance from the mid-surface of the element i to the sub-element i,j expressed by

$$H_{ij} = \frac{1}{2}(h_{i1}+h_{i2}+\ldots+h_{ij-1}-h_{ij+1}-\ldots-h_{ine}) \tag{3}$$

The strain increments in the longitudinal direction x, the peripheral direction ϕ, the thickness direction t and the shear strain of the sub-element i,j are defined as:

$$(d\varepsilon_x)_{i,j} = 0 \tag{4}$$

$$d(\varepsilon_\phi)_{ij} = \frac{dl_{ij}}{l_{ij}} \tag{5}$$

$$d(\varepsilon_t)_{ij} = \frac{dh_{ij}}{h_{ij}} \tag{6}$$

$$d\gamma_{ij} = d\psi_i \tag{7}$$

The equilibrium equations of forces in the radial and peripheral directions and the peripheral bending moment about x-axis are as follows (Fig. 3)

$$\begin{aligned}&-N_{i+1}\sin(\varphi_{i+1}-\psi_{i+1})-N_i\sin(\varphi_i+\psi_i)-\\&Q_{i+1}\cos(\varphi_{i+1}-\psi_{i+1})+Q_i\cos(\varphi_i+\psi_i)-P_i=0\end{aligned} \tag{8}$$

$$\begin{aligned}&N_{i+1}\cos(\varphi_{i+1}-\psi_{i+1})-N_i\cos(\varphi_i\\&+\psi_i)-Q_{i+1}\sin(\varphi_{i+1}-\psi_{i+1})-Q_i\sin(\varphi_i+\psi_i)=0\end{aligned} \tag{9}$$

$$\begin{aligned}&(M_{i+1}-M_i)+N_{i+1}\sin(\varphi_{i+1}-\psi_{i+1})\frac{l_i}{2}-N_i\sin(\varphi_i+\psi_i)\frac{l_i}{2}\\&+Q_{i+1}\cos(\varphi_{i+1}-\psi_{i+1})\frac{l_i}{2}+Q_i\cos(\varphi_i+\psi_i)\frac{l_i}{2}=0\end{aligned} \tag{10}$$

In Fig. 3 P_i is a contact force between roll and pipe on the element *i*. N_i, Q_i and M_i are the peripheral, radial (shear) forces and peripheral bending moment; respectively, acting on the nodal point *i*.

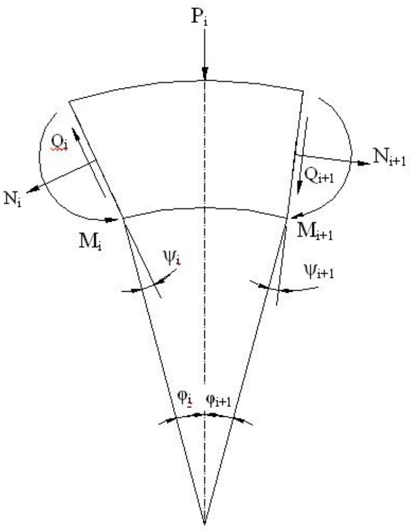

Fig. 3 Forces and moments on the element *i*

According with Fig. 4 stresses in a sub-element can be calculated. In this element stress in direction of thickness can be defined as following equation:

$$(\sigma_t)_{ij} = \frac{1}{2}(\sigma^n_{ij+1} + \sigma^n_{ij}) \quad (11)$$

With noticing Fig. 4 the $\delta(\sigma_{\square})_{ij}$ increment is considered for peripheral stress $(\sigma_{\square})_{ij}$ between two main-elements. The increment has effected in longitudinal direction is $(\sigma_x)_{ij}$ that has not shown in this figure.

With considering Fig. 4 the equilibrium equation for a sub-element is written as following:

$$(\sigma^n_{ij+1} - \sigma^n_{ij}) l_{ij} = \tau_{i+1j} h_{ij} - \tau_{ij} h_{ij} + (\sigma_\phi)_{ij} h_{ij} (\varphi_{i+1} - \psi_{i+1} + \varphi_i + \psi_i) \quad (12)$$

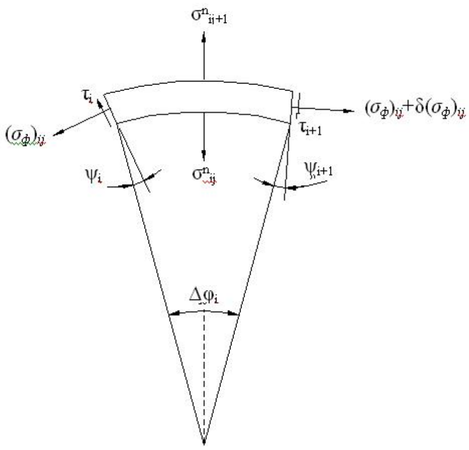

Fig. 4 Peripheral and radial forces and peripheral moments acting on the element *i*

Then, the differential forms of the compatibility equations of displacements of the divided elements, the above equilibrium equations of the peripheral and radial forces and peripheral bending moments acting on every elements, the boundary conditions and the roll positions are transformed to the linear simultaneous equations. In the equations, the variables are the increments of displacements, peripheral and radial forces, and peripheral bending moments of nodal point. By solving these equations, the increments of strains, stresses and others occurring in every element are calculated. The detail procedure is explained in Ref. [4].

III. Design Method

In the design method, the ideal roll profiles, amount of deformation and the peripheral shrinkage of cross section at each stand are determined. The cross-sectional profiles of pipes are considered to be similar to roll profiles at intermediate reshaping steps between the circular pipes and non-circular pipes. In order to obtain cross-sectional profiles of pipes, the numerical analyses of forward and backward deformations of the pipes are performed on the basis of the above mentioned analysis method. The forward deformation corresponds to the process in which the circular pipe is reshaped into non-circular pipe. The backward deformation corresponds to the process in which non-circular pipe is virtually reshaped into the circular pipe.

IV. Discussion of Results

In the following sections, the reshaping process from a circular pipe into a square pipe by the 4-roll-stand is investigated.

The reshaping conditions for the reshaping process of the square pipe used in the design method and actual production in Sadid Pipe and Profile Company are given in Table I. Some theoretical results and comparison with experimental data are as follows:

TABLE I
THE RESHAPING CONDITIONS USED IN ROLL DESIGN AND ACTUAL PRODUCTION

Materials of circular pipe	St37 (E=204 Gpa, σ_y=278.6 Mpa, $\overline{\sigma} = 671.4(0.0394 + \overline{\varepsilon}_p)^{0.272}$ ν=0.29,
Dimension of product	140 ×140
Initial wall-thickness *t* /mm	4.0

A. Determination of Diameter of Initial Circular Pipe

Firstly, the peripheral shrinkage Ey of cross-section of pipe is determined by backward deformation analysis, and then the diameter of circular pipe is calculated.

In the backward analysis, the square pipe is virtually reshaped into circular pipe. In this procedure the virtual displacement of each nodal point can be obtained by the similar procedure of reference [7]. Fig. 5 shows the virtual

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displacements of element nodal points in Y and Z directions for backward deformation analysis[8].

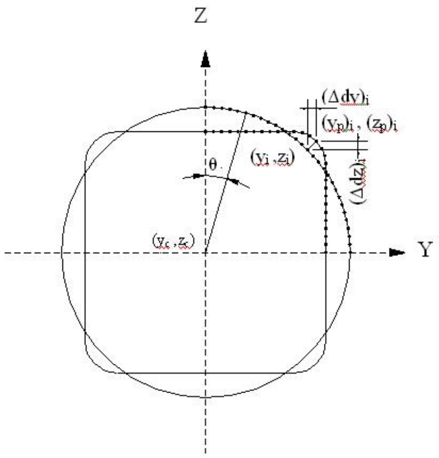

Fig. 5 Virtual displacements for backward deformation analysis

As a result, it is found that the peripheral shrinkage Ey is 2% and the necessary diameter of circular pipe is 177.21 mm. In actual production, the same square pipe is reshaped from the circular pipe with the diameter of 178.9 mm, which is close to the result of the design method.

Fig. 6 shows the square pipe and the obtained circular pipe after performing the backward deformation analysis[8].

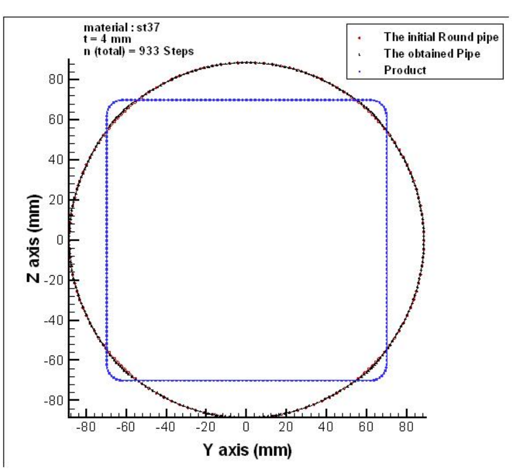

Fig. 6 The square pipe and the obtained circular pipe

B. Necessary number of Stands

In order to determine the necessary stands, the backward deformation analysis from square pipe is carried out until n = 100, 200, 300, 400 steps. Fig. 7 shows the cross-sectional profiles of the pipe at each step in the backward deformation analysis [8].

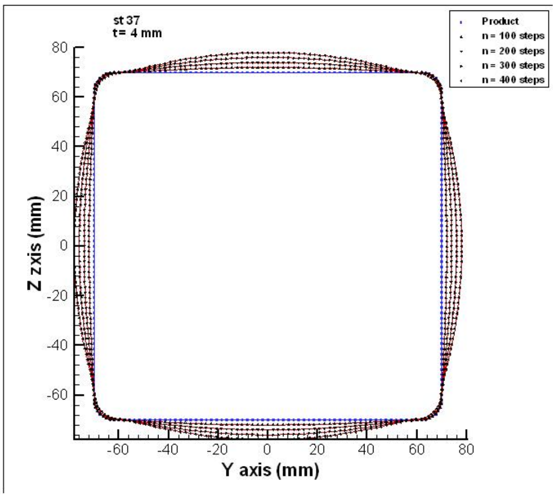

Fig. 7 Cross-sectional profiles at each step in the backward deformation analysis

After the backward deformation analysis is performed to the specific step, the forward deformation analysis is curried out for the same step. Then, the obtained cross-sectional profile after the forward analysis is checked to see if it can coincide with the initial cross-sectional profile. If there is a good coincident between two cross-sections, the number of steps in backward deformation analysis is selected for concerned stand.

In case of n = 400 steps, shape failure is observed, i.e., the sides of square portion of the product can not attain their flatness, which is an important factor of evaluation of quality of the product. This shape failure is shown in Fig. 8[8].

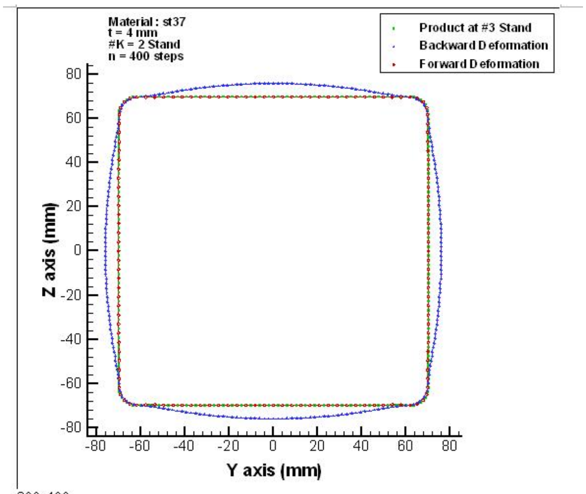

Fig. 8 Cross-sectional profiles at n = 400 in the forward deformation analysis

By comparison between three other cases, n = 100, 200 and 300 steps, it can be seen that all of them are returning back to the initial cross section, well. On the other hand another requirement for the better design of intermediate profiles is that the ideal intermediate cross-sectional profile should be close to that of the circular pipe. Therefore, from these requirements, the cross-sectional profile at n = 300 steps is considered a better intermediate cross-sectional profile of the pipe and the roll profile for the concerned stand.

C. Profiles of Rolls

By the design method, it is possible to design all of the roll profiles, which are suitable for reshaping circular pipes into the square pipes.

The radius of rolls obtained for the first, second, and third stand are 190.96 mm, 484.64 mm, and infinite, respectively, while these values in actual production are 238.5 mm, 552.5 mm, and infinite.

D. Amount of Deformation (Height of Pipe) at Each Stand

Determination of amount of deformation (height of pipe) at each stand is important parameter in reshaping process of circular pipe into square pipe.

The height of pipe in the first, second, and third stand for production the square pipe with specification of Table I, are obtained by using the design method and the formula of the systematic method [8]. The results are shown in Table II. As it can be seen, there is a very good agreement between these values.

TABLE II
COMPARISON BETWEEN THE DESIGN METHOD AND REF.[9] FOR HEIGHT OF PIPE

Stand No.	Height of pipe (mm)	
	Design Method	Ref. [8]
#1	165.21	163.82
#2	151.21	151.45
#3	140.0	140.0

V. CONCLUSION

Through this procedure, the following results were obtained:

1. By considering shear deformation between two nearby elements, a systematically analysis method of reshaping circular pipes into square pipes has been developed.
2. Based on this analysis method, the backward deformation analysis and forward deformation analysis are performed. It can be used for determining all of the roll profiles that are suitable for reshaping circular pipes into square pipes.
3. Based on the proposed design method, peripheral shrinkage and diameter of the circular pipe and the necessary number of stands in the reshaping processes can also be obtained.
4. Results of simulation are compared with the experimental results to verify the design method. It is observed that the results in general show good correlation.

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