研 究 速 報

Numerical Analysis of Round to Oval Reshaping Process of Pipes

円管の楕円管への再成形過程に関する数値解析

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1. INTRODUCTION

This paper deals with a process in which sheet metals are once formed into round pipes and then reshaped into non-circular pipes having various profiles of cross-sections by the roll-forming technology using grooved rolls.

Pipes with non-circular cross-sections are used for diversified industrial applications, such as machine structure components, machine components and housing/building components. The utilization of them is extending rapidly and widely. Hence, the output of those pipes is increasing and new application fields are continually developing. In addition, the demand for dimensional accuracy of products and variety of cross-sections becomes more and more serious.

The purpose of this research is to develop a convenient and extensive three dimensional theoretical method which makes it possible to anticipate deformation characteristics of the pipes in reshaping processes and predict geometrical features of products.

In this paper, the effects of reshaping conditions on the cross-sectional profile and dimension, corner radius, peripheral shrinkage, longitudinal elongation and increase of wall thickness of the pipes are investigated by using the developed theoretical method.

2. METHOD OF ANALYSIS

2.1 Mathematical model for simulation

Fig. 1 shows the representative three dimensional curved surface of a deformed pipe during reshaping process. It corresponds to a curved surface locating at the middle of the pipe's wall thickness. This curved surface is considered to represent the

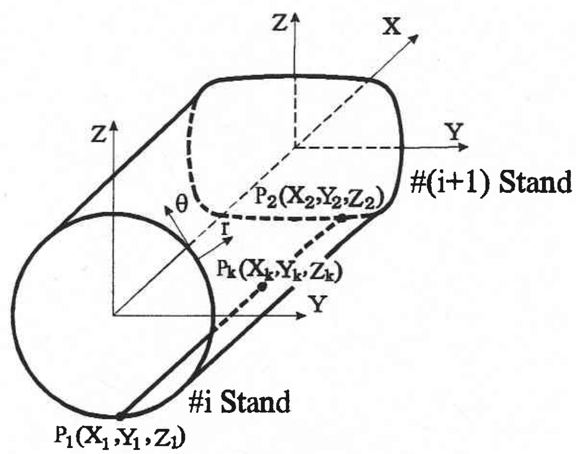

Fig. 1　Schematic illustration of a deformed pipe.

deformation of the pipe concerned between two neighbouring #i and # (i + 1) stand. In order to describe the shape of the deformed curved surface mathematically, two suitable shape functions $S_Y(X)$ and $S_Z(X)$ which developed by Kiuchi *et al.*[1] are used as follows,

$$S_Y(X) = \sin\left\{(\pi/2)\left(\tilde{X}/L\right)^{n_Y}\right\} \quad \cdots\cdots (1)$$

$$S_Z(X) = \sin\left\{(\pi/2)\left(\tilde{X}/L\right)^{n_Z}\right\} \quad \cdots\cdots (2)$$

Here,

$\tilde{X} = X - X_1$

$L = X_2 - X_1$: Distance between two stands

$n_Y\ n_Z$: Parameters of shape functions

By using the above shape functions, the curved surface of the pipe between #i and # (i + 1) stands is expressed as follows,

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$$\left.\begin{aligned} X_k &= X_k \\ Y_k &= Y_1 + (Y_2 - Y_1) S_Y(X_k) \\ Z_k &= Z_1 + (Z_2 - Z_1) S_Z(X_k) \end{aligned}\right\} \quad \cdots\cdots (3)$$

Here, Y_1, Z_1 are Y and Z coordinates of the point P_1 and Y_2, Z_2 are Y, Z coordinates of the point P_2 on the cross-sections of the curved surface.

2.2 Geometrical model of cross-section of pipe

Fig. 2 shows the representative cross-section of the pipe during reshaping process. Due to symmetry only one quadrant of the cross-section need to be considered. Here, the profile of pipe's cross-section is expressed by three kinds of arcs. L is length of the contact part, x_c is length of the corner part, l is length of the non-contact part of cross-section, and R_1 is the radius of the roll's profile.

As a parameter of the rate of deformation of the pipe, the roll gap reduction r is used. r is the ratio of decrease of vertical roll gap d to outer diameter of round pipe D as expressed by Eq. 4.

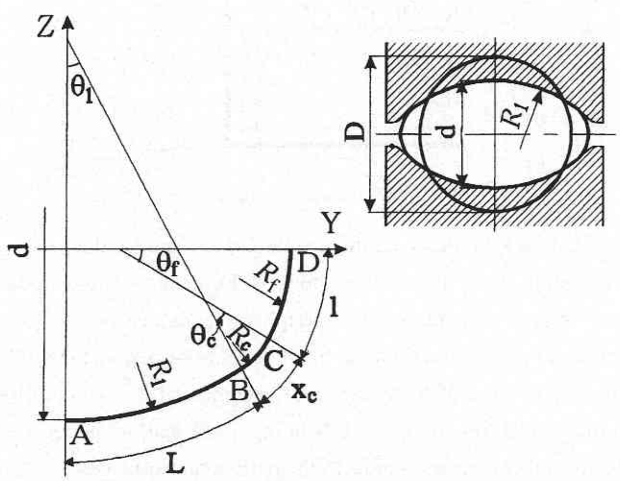

Fig. 2 Geometrical model of cross-section of pipe.

$$r(\%) = \frac{D - d}{D} \times 100 \quad \cdots\cdots (4)$$

In the present simulation, the following assumptions are introduced:

(1) The contact part of the cross-section at the roll gap is completely restricted by the roll's surface and its curvature is identical with that of the roll's profile ($1/R_1$).

(2) The corner part of the cross-section at the roll gap can be expressed by an arc with single curvature ($1/R_c$).

(3) The non-contact part of the cross-section at the roll gap can be expressed by an arc with single curvature ($1/R_f$).

R_1 is known, and θ_1, θ_c and R_c are variables. By introducing the above geometrical model and taking the boundary condition into consideration at the symmetrical plane of the cross-section, R_f, and θ_f can be calculated by Eqs. (5) and (6), and then peripheral shrinkage E_y can also be calculated.

$$\theta_1 + \theta_c + \theta_f = \frac{\pi}{2} \quad \cdots\cdots (5)$$

$$R_f = \frac{d/2 - R_1(1 - \cos\theta_1) - R_c\cos\theta_1 + R_c\cos(\theta_1 + \theta_c)}{\cos(\theta_1 + \theta_c)} \quad \cdots (6)$$

2.3 Equilibrium of force

The equilibrium of the transversal force and the equilibrium of the force in the longitudinal direction are considered in the same manner as Kiuchi *et al.*[1, 2]. As the boundary conditions, the restrictions at the symmetrical plane are introduced.

2.4 Optimization of variables

When the analysis is performed, each forming process is divided into appropriate number of deformation steps. At each deformation step, in the beginning, all of five variables including θ_1, θ_c, R_c and parameters n_Y, n_Z of shape functions are assumed. Then the strain and stress increments are calculated, and also the total power of deformation is calculated. The revision of values of the above mentioned variables is done by using Simplex Method until the minimum total power of deformation is obtained. Thus, the analysis of one deformation step is completed. The analysis is repeated until the required reduction in the concerned forming process is attained. Reshaping conditions of each forming process employed in this analysis are shown in **table 1**.

Table 1 The reshaping conditions employed in this analysis.

Thickness t/mm	Roll gap reduction r(%)	Roll bending radius R_1/mm	Material
1.0	10	100	STK41
2.0	20	200	
4.5	30	400	
6.0			
9.0			
Roll distance : 200 mm　Speed : 40 m/min Diameter of round pipe : 114.3 mm			

3. RESULTS AND DISCUSSION

In the following sections, the effects of reshaping conditions on the cross-sectional shape and dimension, corner radius, peripheral shrinkage, longitudinal elongation and increase of wall thickness of the reshaped non-circular pipes will be explained.

3.1 Contact surface angle θ_1

From **Fig. 3**, it can be found that following to the increase of the roll gap reduction r, the contact part will grow from the middle of cross-section to both sides, in other words, the contact surface angle θ_1 becomes large. In general, with the increase of the bending radius of roll R_1, the contact surface angle θ_1 decreases even though the roll gap reduction r is same.

3.2 Corner radius R_c

The corner radius of cross-section R_c is a very important factor to evaluate quality of sguare/rectangular pipes. **Fig. 4** shows the change of R_c according to the increase of r. From these results, it is known that R_c decreases by a large amount at the initial and mid stages of reshaping process, but it does not decrease so much in the last stage. This means that R_c is converged to a fixed value following to the reshaping rate of the pipes.

In order to get the sharp corner, that is the small value of R_c, r should be made as large as possible.

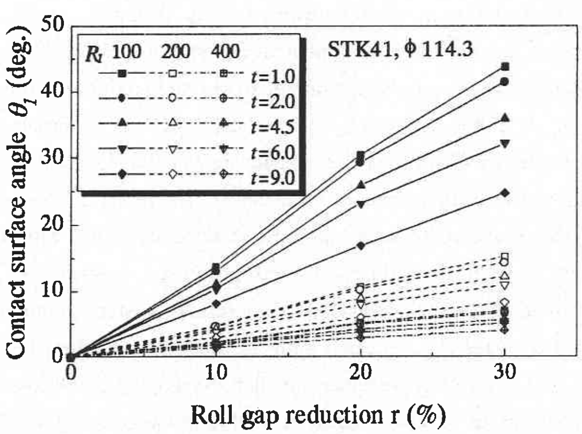

Fig. 3 Effects of r, t and R_1 on R_c.

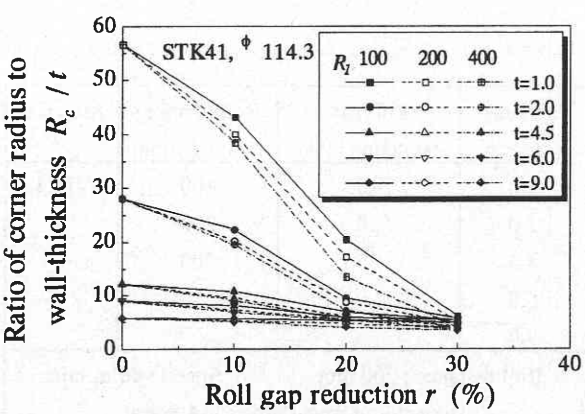

Fig. 4 Effects of r, t and R_1 on R_c.

3.3 Peripheral shrinkage E_y

Usually the pipe is compressed in the peripheral direction at the roll gap. Due to this, from the first step of deformation, the peripheral shrinkage occurs. It is enhanced by not only peripheral compression but also peripheral and longitudinal bending and bending back deformations.

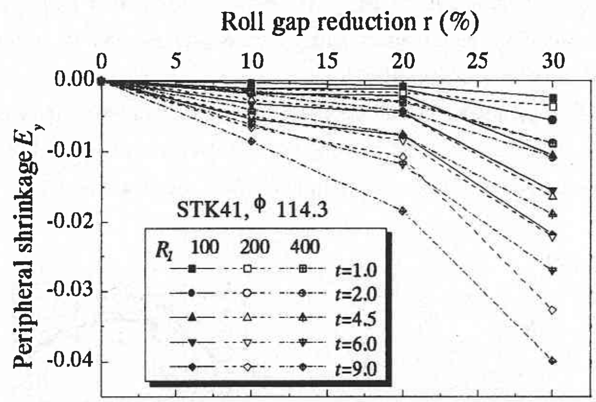

Fig. 5 Effects of r, t and R_1 on E_y.

It can be seen that with the increase of r, t and R_1, the peripheral shrinkage E_y increases as shown in **Fig. 5**. This is due to the fact that as r increases, the peripheral compression by rolls increases, and at the same time, the amount of peripheral bending deformation of the corner part becomes large. It should be noticed that the peripheral bending deformation under the peripheral compression induces the peripheral shrinkage.

3.4 Longitudinal elongation E_x

In general, pipes are elongated in the longitudinal direction by rolls in reshaping processes. The longitudinal elongation occurs with corresponding to the above-mentioned peripheral shrinkage deformation. **Fig. 6** shows the increase of longitudinal elongation E_x against the change of the roll gap reduction r. It can be said that the behavior of E_x is completely similar with that of E_y.

3.5 Relationship between peripheral shrinkage E_y and longitudinal elongation E_x

The relationship between E_y and E_x is important and it is one of the fundamental characteristics of deformation of the pipe. **Fig. 7** shows the relationship between E_y and E_x. It is seen that

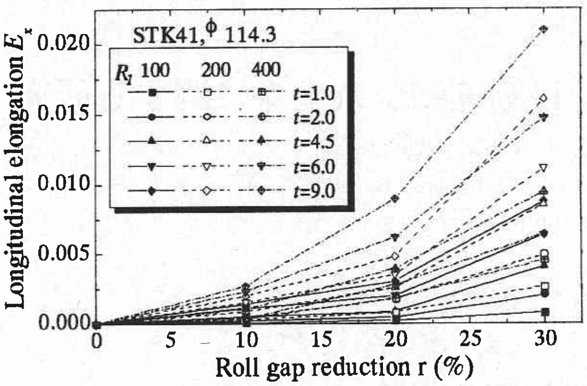

Fig. 6 Effects of r, t and R_1 on E_x.

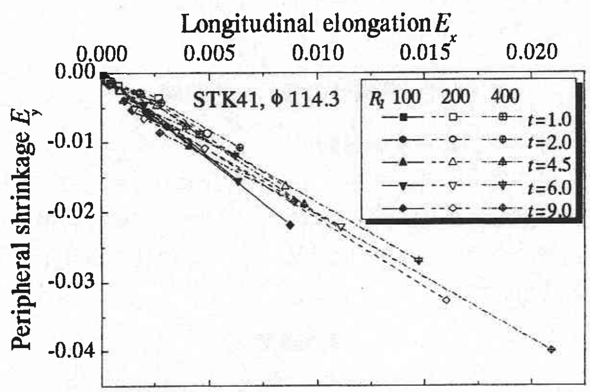

Fig. 7 Relationship between E_y and E_x.

apart from reshaping conditions, there is a clear relation between E_y and E_x. For a fixed value of r, the ratio of E_y to E_x is about 2 to 1, that is, from the peripheral direction view, the deformation of the pipe is so-called simple compression.

In the initial forming process, that corresponds to the initial deformation steps, the contact surface is small, therefore, the plastic deformation zone is relatively small comparing with the pipe's whole cross-section. However, when r increases and the reshaping proceeds, the whole cross-section becomes plastic, then longitudinal elongation tends to occur easily as shown in **Fig. 8**.

3.6 Increase of wall thickness E_t

The difference between E_y and E_x corresponds to the increase of wall thickness E_t. This means that, the condition of volume constancy is satisfied. **Fig. 9** shows increase of wall thickness E_t. Corresponding to the changes of E_y and E_x, as r, t, and R_1 increase, E_t becomes large.

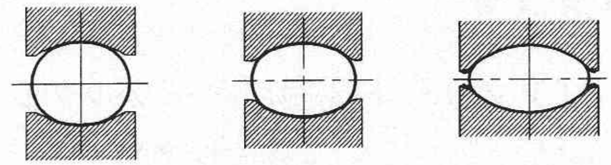

Fig. 8 Cross-sectional diagram of deformed pipe at each step.

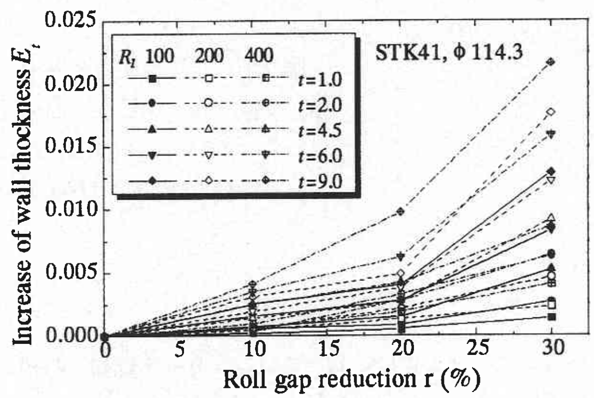

Fig. 9 Effect of r, t and R_1 on E_t.

4. CONCLUSION

In this paper, a theoretical method for analysis of reshaping of the pipes was proposed. It was used for a series of simulations of reshaping processes from round pipes to oval/square/rectangular pipes. The results of analysis were discussed from various view points. Through the study, some fundamental characteristics of deformation of the pipes were found.

The theoretical method will be extended and refined. In the extended method, the profiles of cross-sections of the pipes will be expressed by using an enough number of circular arcs. Then, the analysis of reshaping of the non-circular pipes with more complicated cross-sections will become possible.

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