Effects of Reinforcing Rib on Draw Bending of Pipes Examined by Finite Element Method*¹

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In recent years, thin aluminum alloy extruded pipes have been applied to structural parts, such as automobile space frames, to save energy. If the aluminum pipes could be processed in a greater variety of ways, such as bending, their range of applications would expand. In our previous study, we evaluated the bending of thin extruded square pipes. In the current study, we examined the bending formability of aluminum alloy pipes with reinforcing ribs using the finite element method (FEM). The influence of the reinforcing ribs on the form accuracy of the aluminum pipes in draw bending was investigated. The effective arrangement and thickness of a reinforcing rib was also investigated. As a result, it was clarified that two types of buckling arise for the reinforcing rib. Furthermore, a critical ratio $T = t_2/t_1$ (t_1 : the circular portion thickness of pipe; t_2 : the thickness of rib) for controlling buckling and flattening was proposed. [doi:10.2320/matertrans.P-MRA2008815]

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1. Introduction

In recent years, aluminum alloy extruded sections have been used in various structural parts, such as the space frames of automobiles, to reduce weight.¹⁾ When lightweight sections are used, a secondary forming, such as bending, is generally required. However, during the bending of thin-walled light materials, undesirable deformations tend to occur, it is therefore necessary to establish countermeasures for these deformations and to improve the bending limit. During the bending of aluminum alloy extruded sections, undesirable deformations, such as flattening, wrinkling, and folding, as well as undesirable phenomena, such as necking and splitting, easily occur. The working limits of bending of various aluminum alloy extruded sections have been examined by many researchers, and the results have been applied to practical work.²⁾

We examined in detail the forming properties of the draw bending of aluminum alloy extruded square pipes. The results clarified that the use of a mandrel, such as a laminated mandrel, is indispensable in suppressing flattening and folding. Furthermore, the loading of axial tension is effective to prevent wrinkling and folding.³⁾ In addition, it was clarified that a reinforcing rib placed in the bending radial direction of the cross section is effective in improving the working limit of bending.⁴⁾ These results have helped in widening the application range of aluminum alloy extruded sections. To produce lightweight products, the reinforcing rib should be as thin as possible; furthermore, the shape of the cross section of the extruded section should be selected so that it increases the working limit of bending.

In this study, we examined the draw bending formability of aluminum alloy extruded circular pipes with a reinforcing rib

by the finite element method (FEM). First, the effects of the reinforcing rib on the form accuracy of the pipe cross section were examined by simulating draw bending. Next, the effects of the position of the rib on the flattening and skew deformation of the pipe cross section were examined considering the buckling of the rib. Finally, the effective location and thickness of the reinforcing rib⁵⁾ were studied.

2. Simulation of Draw Bending

2.1 Rotary draw bending model

To simulate draw bending, FEM software (LS-DYNA3D) was used. The rotary draw bending equipment designed and fabricated by the authors is schematically shown in Fig. 1. The main parts of the equipment are a drum around which a workpiece is wound, a unit of the bending and a system for applying additional axial tension. The simplified model for FEM composed of the workpiece and tools shown in Fig. 2. The workpiece is gripped by chuck integrated with the drum, and is bended along the drum groove with rotation of the drum under a constraint by the bending bar and guide bar. In

Fig. 1 General assembly of draw bending equipment.

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Fig. 2 Model of FEM.

Fig. 3 Shape and dimensions of pipe model with rib.

this simulation, rotational angle increment of drum was given as parameter of displacement.

The rotation rate of the drum was set at approximately 180° per second. When the pipe diameter D was 50 mm, axial tension was distributed to 495 nodes of which distance from the back end of pipe was within D to avoid a concentration to partial nodes. In the simulation, the drum, chuck, bending bar and guide bar were all defined as rigid body elements. Shell elements were used throughout the model. The contact conditions between various jigs and the pipe were taken into account using Coulomb's friction, and the coefficients of static and dynamic frictions between the jigs and the pipe were set at $\mu_s = \mu_k = 0.10$. Details of the draw bending simulation can be found in the authors' previous papers.⁶⁻⁸⁾

2.2 Cross-sectional shape and constitutive equations of pipe

An aluminum alloy extruded pipe, A6063S-O, was assumed in the pipe used for bending. As shown in the cross section of the pipe in Fig. 3, the pipe has one reinforcing rib at the center of the cross section. To verify the geometric similarity rule of the FEM analysis, the diameter D was set at 25, 50 or 100 mm. As shown in Fig. 4, the groove radius of the drum, r_d , was made equal to $D/2$ and the groove depth was made equal to $D/5$ so as not to constrain the movement of the rib.

Table 1 shows a summary of the mechanical properties of the pipe used in the FEM analysis. The material of the pipe in the model is assumed to be an isotropic elastoplastic body with the power law hardening rule. The constitutive equation is given as

$$\bar{\sigma} = C(\varepsilon_e + \bar{\varepsilon}_p)^n, \quad (1)$$

where $\varepsilon_e = 0.0013$.

Fig. 4 Arrangement of rib on winding drum.

Table 1 Mechanical properties of pipe used in FEM analysis.⁸⁾

Model of material		A6063S-O
Tensile strength	σ_B /MPa	97
Proof stress	$\sigma_{0.2}$ /MPa	30
Elongation	$\delta(\%)$	39
Work-hardening exponent	n	0.27
Plastic modulus	C /MPa	181

Table 2 Model conditions used in FEM analysis.

Bending radius R (mm)	R/D^*	Circular portion thickness t_1 (mm)	Rib thickness ratio $T(t_2/t_1)$
50	2.0	1.5	0.67–0.90
100	2.0	3.0	0, 0.33–1.00
200	2.0	6.0	0.67–0.90

* D : Outer diameter of pipe

2.2.1 Effect of rib thickness

To examine the effect of rib thickness, a simulation was carried out using a pipe ($D = 50$ mm, circular portion thickness $t_1 = 3.0$ mm) for a bending radius (= drum radius) $R = 100$ mm and a rib thickness $t_2 = 1.00$ – 3.00 mm.

2.2.2 Effect of rib angle

The effect of the position of the rib on form accuracy during bending was examined assuming three-dimensional bending. A simulation was carried out under four conditions for pipes with a reinforcing rib; that is, the angle between the rib and a straight line from the drum center to the center of the pipe cross section, i , was either 0, 30, 60 or 90° (cf. Fig. 4).

2.2.3 Buckling of rib

The buckling of the rib was examined under a geometrically similar condition except for a rib thickness t_2 (R/D and t_1/D were constant) as shown in Table 2, where t_2/t_1 is called "rib thickness ratio" in hereafter. Note that the axial tensile force is set to 0 when the effect of the rib thickness is considered.

3. Flattening of Pipes

The flattening⁹⁾ generated by the bending of pipes can be suppressed by restricting the deformation from inside each

Fig. 5 Mechanism of partial force causing flattening.

pipe. Figure 5 shows the mechanism underlying the generation of the flattening component of force^{10,11)} and its magnitude. Let the radius of curvature of the pipe be ρ , and the distance from the neutral axis N.A. be y . Note that the distortion of the pipe cross section due to bending and the change in the pipe thickness are not considered.

The axial force applied to back end of pipe, P_a , is given as an area integration of stress distributed in the cross-section by $P_a = \int_A \sigma dA = P_T + P_C$ ($P_C < 0$), where P_T and P_C are the resultant forces of tension side and compression side, respectively. When P_a is 0, P_T becomes equal to P_C . Assigning the arbitrary distance from the N.A. for the tension side and the compression side to be y_T and y_C , respectively, the bending strains at the corresponding positions (ε_T , ε_C) are expressed as

$$\varepsilon_T = y_T/\rho, \quad \varepsilon_C = y_C/\rho. \quad (2)$$

So, the stresses in the plastic region are approximated from eq. (1), assuming uniaxial stress state.

As shown in Fig. 5(b), when the pipe with a radius of curvature, ρ , is cut by the two planes AB and CD with a small angle $d\theta$, the small distances between the two planes are denoted by dx on the neutral axis, dx_T on the tension side and dx_C on the compression side. The circumferential component of the force dP_T , which is applied to A and C on the tension side, has an angle of $d\theta$. In addition, $dP_T = \sigma_T dA$, $dP_C = \sigma_C dA$ (A : total cross-sectional area of the pipe) can be expressed. The components of forces are expressed as

$$dP_{TN} = 2dP_T \sin(d\theta/2) \cong dP_T d\theta, \quad dP_{CN} \cong dP_C d\theta, \quad (3)$$

where dP_{TN} and dP_{CN} represent the small flattening components of force, with respect to dA , on the tension and compression sides, respectively. The axial tensile force applied to the pipe is effective in suppressing wrinkling and folding; however, flattening is enhanced with an increase in the flattening component of force on the tension side. The insertion of a rib in the pipe is effective in suppressing flattening.

Figure 5(c) shows the distribution of the flattening components of force, dP_{TN} and dP_{CN} , applied to the pipe. When the rib is inserted asymmetrically with respect to the bending plane, a torsional moment is generated around the center of the pipe cross section.

4. Analysis Results and Discussion

4.1 Effect of thickness of reinforcing rib

A simulation was carried out using 6 types of pipe, i.e., a pipe without a rib and pipes with a rib (rib thickness ratios $T = t_2/t_1$: 0.33, 0.50, 0.67, 0.83 and 1.00) for $t_1 = 3.0$ mm. Figure 6 shows the cross section of each pipe after bending. The flattening component of force discussed in section 3 acts on the rib in the bending radius direction as a compressive load, and become buckling factor. Therefore, at a bending radius $R = 100$, buckling in the rib radius direction is

Fig. 6 Effect of thickness of rib on flattening in pipe bending ($i = 0^\circ$, $R = 100$ mm, $D = 50$ mm, without axial tension, $T = t_2/t_1$, t_1 : periphery part thickness, t_2 : rib thickness).

Fig. 7 Effect of reinforcing rib on flattening in pipe bending ($i = 0^\circ$, $R = 100$ mm, $D = 50$ mm, without axial tension).

suppressed when the rib thickness is relatively large ($T = 0.83$ or more); the deformation of the cross section is suppressed. When $T = 1.00$, the bending was successful, generating no undesirable deformations or phenomena.

To examine the effect of the rib ($T = 0.83$) against flattening, the result was compared with that obtained using a pipe without a rib but having the same cross-sectional area with $t_1 = 3.81$ mm. Figure 7 shows the results and exterior view of the pipe. As is obvious from Fig. 7(b), although no undesirable deformations, such as wrinkling and buckling, are observed, flattening proceeds and no round cross section can be maintained. The total amounts of the individual cross section shown in Figs. 7(a) and 7(b) are the same. In the original cross-sectional shape, the geometrical moment of inertia of (a) with a rib is 17% less than that of (b) without a rib. And, in the condition of (a) with a rib, flattening is sufficiently suppressed as shown in Fig. 7(a). On the basis of the discussions above, the rib in the pipe for bending plays a very important role in suppressing the flattening of the pipe.

4.2 Effect of rib angle

The deformation of the cross section of the pipe was compared for four rib angles, $i = 0, 30, 60$ and 90° . As shown in Fig. 8, flattening with skew is notable for both $i = 30^\circ$ and 60° . Because the flattening component on the inclined rib serves as a couple of forces, as explained in Fig. 5(c), a torsional moment is generated, causing deformation with significant skew. For $i = 0$ (Fig. 7(a)) and 90° (cross section in Fig. 9(a)), flattening is suppressed to a certain degree; however, folding (Fig. 9(a)) is generated on only the compression side for $i = 90^\circ$. To suppress folding during the bending of the pipe with $i = 90^\circ$, a tensile force was applied to the pipe in the longitudinal direction. The results of the bending simulation for load factors K (when the product of the tensile strength, σ_B , and the cross-sectional area of the pipe, A_0 , was set to $F_{\max}$, and the axial tensile force was set to P_a , $K = P_a/F_{\max}$ holds) = 0.10, 0.15, 0.20 and 0.25 indicate that $K = 0.25$ or more is required to eliminate folding and wrinkling.

Figure 9 shows a comparison of the deformation of the entire pipe and the cross-sectional deformation between $K =$

Fig. 8 Buckling behavior of cross section and bending moment (A6061S-O, Type A, $t_0 = 2.0$ mm, $H_0 = W_0 = 40$ mm).

Fig. 9 Effect of axial tension in bending ($i = 90^\circ$, $R = 100$ mm, $D = 50$ mm, $t_1 = 3.0$ mm, $t_2 = 2.5$ mm).

0 and $K = 0.25$. When the position of the N.A. moves to the compression side with respect to that of the central axis (C.A.), this is equivalent to the rib being placed on the tension side. As a result, the rib is subjected to the flattening component of force, which is directed toward the N.A. (Fig. 5(c)), in addition to the tensile force due to bending deformation, which leads to the deformation of the pipe, as shown in Fig. 9(b). However, the peripheral dimensions of the pipe $H_1/D = 0.92$ and $W_1/D = 0.98$ are respectively equivalent to $H_1/D = 0.91$ and $W_1/D = 0.99$, which are obtained without the loading of axial tension (for H_1 and W_1 , refer to Fig. 9). On the basis of this result, $i = 0$ and 90° are effective rib angles for suppressing the flattening of the pipe.

4.3 Buckling limit of rib

A simulation was carried out for three bending radii ($R = 50, 100$ and 200 mm) for a rib thickness ratio $T = 0.67$ – 0.90 . The results indicate that there are two mode bucklings of the rib, i.e., circumferential and radial mode bucklings. Figure 10 shows typical examples of these bucklings ((a) circumferential and (b) radial mode bucklings). Both bucklings are caused by a compressive load; however, the compressive loads causing the circumferential

Fig. 10 Typical buckling on rib ($i = 0^\circ$, $R/D = 2.0$).

and radial mode bucklings are caused by completely different mechanisms.

Circumferential mode buckling is caused by the compressive load dP_C due to bending stress on the compression side expressed by eq. (3). Circumferential mode buckling (Fig. 10(a)) is caused by the bending stress of the rib. The bending stress is determined by the distance from the N.A. on the tension (y_T) and compression (y_C) sides. Therefore, the bending stress is determined by the circumference of the pipe and bending radius. When the bending stress exceeds the buckling limit of the material property and rib thickness, wrinkling occurs on the compression side of the rib.

On the other hand, radial mode buckling (Fig. 10(b)) is generated by the flattening component of force generated during the bending of the pipe; thus, buckling develops when a rib is subjected to a compressive force in the radial direction. Here, the radial compressive load applied to the rib is the sum of the flattening component of force generated in the rib itself and part of the flattening component of force applied to the circumference of the pipe.

Figure 11 shows the buckling limit and deformation modes on the rib for 24 combinations of conditions (three bending radii and eight rib thickness ratios). The marks ($\times \triangle$) in the figure indicate the conditions under which both radial and circumferential mode bucklings are generated. Under the conditions examined in this study, circumferential mode buckling is first generated at a bending angle α of approximately 50° (Fig. 10(b)). With further bending, radial mode buckling is also generated. The conditions under which only circumferential mode buckling is generated are denoted by $\triangle$. The presence of buckling is determined when the height of wrinkles satisfies $h_w/D \geq 0.0024$.¹²⁾

When the degree of processing, R/D , is set to be constant, it is confirmed that the bending radius and pipe dimensions are geometrically similar with respect to the buckling limit of the rib used in the bending analysis. On the basis of the results in Fig. 11, both radial and circumferential mode bucklings are judged to be generated at an approximately

Fig. 11 Buckling limit and deformation modes on rib ($i = 0^\circ$, $R/D = 2.0$, without axial tension).

constant rib thickness ratio. In other words, when T is approximately 0.72, radial mode buckling disappears; when T is approximately 0.88, circumferential mode buckling disappears. Thus, we can obtain a rib without buckling.

An example of the extruded square pipe A6063S-T5 obtained by draw bending is shown in Fig. 12. We can confirm that two types of buckling are generated in the reinforcing rib, as shown in Fig. 10. We also confirm that the deformation modes and buckling limit, as shown in Fig. 11, obtained by FEM are in good agreement with those obtained by experiment.¹³⁾

5. Conclusions

The effect of a reinforcing rib on the draw bending of aluminum alloy pipes were examined by FEM and the following conclusions were drawn.

- (1) By increasing the rib thickness ratio T (rib thickness/pipe thickness), flattening during the bending of pipes can be suppressed. For example, for $i = 0^\circ$, $R = 100$ mm and $D = 50$ mm, radial mode buckling disappears for $T = 0.83$ or higher, and flattening is limited. When $T = 1.0$, at which the rib thickness is equal to the pipe thickness, neither radial nor circumferential mode buckling occurs, and flattening becomes limited.
- (2) When two pipes having the same cross-sectional area are compared, the use of a rib is more effective in suppressing deformation than having a large pipe thickness. Therefore, the effectiveness of the rib is confirmed for bent products for which appearance is particularly important.
- (3) For rib angles $i = 0$ and 90° , flattening is suppressed. Three-dimensional products with accurate dimensions can be obtained by bending with rib angles $i = 0$ and 90° .
- (4) Two types of buckling, i.e., circumferential mode

Fig. 12 Buckling on reinforcing rib in draw bending process of square tube (without mandrel and axial tension).¹³⁾

buckling due to bending stress and radial mode buckling due to the flattening component of force, are generated in the reinforcing rib in the radial direction. When $R/D = 2.0$, both circumferential and radial mode bucklings are generated for pipes with a T of 0.72 or less, and only circumferential mode buckling is generated in the pipes with T in the range of 0.72–0.88.

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