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ORIGINAL ARTICLE

Effect of internal fluid pressure on quality of aluminum alloy tube in rotary draw bending

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Abstract In the present study, the rotary draw bending of aluminum alloy tubes with internal fluid pressure is investigated by finite element simulation and experiments. The effect of the internal pressure on the cross-section ovality, wall thinning, and wall thickening was studied. The results show that the internal pressure has a significant effect on cross-section quality of aluminum alloy bent tubes. As the internal pressure increases, the cross-section ovality and the wall thickening decrease, and the wall thinning increases. The effect of internal pressure on wall thinning is more significant than its effect on wall thickening.

Keywords Tube bending · Internal pressure · Cross-section ovality · Wall thinning · FE simulation

1 Introduction

Bending is one of the most significant processing methods applicable to the metallic tubes. The tubular products obtained by bending are widely used in the automotive, aerospace, machinery, plant, and equipment production, as well as in the chemical industry. Bent tubes have also acquired a significant importance with the development of the hydroforming processes. In many cases, bent tubes are used as half-finished parts for hydroforming, in which case the pre-bending operation may decisively influence the success of the hydroforming operations [1, 2].

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Due to the process-induced stresses, defects such as excessive wall thinning in extrados, wall thickening in intrados, cross-section ovality, and even wrinkle on intrados may appear. During the bending process, wrinkling can be avoided, but the cross-section ovality and wall thinning are inevitable [3, 4].

During the in-service of the tube, its strength, against internal pressure, is even better as its cross section is closer to the circular shape. On the other hand, the wall thinning at the extrados causes a weakening of the tube strength. This wall thinning has undesirable consequences as the inner surface of the tube wall at the extrados is subjected to wear by friction during in-service, under the action of the fluid flowing through the tube. Given these issues, as a primary criterion for assessing the quality of a bent tube, the cross-section ovality and wall thinning should be considered together. These statements are also supported by the conclusions of other authors such as Veerappan and Shanmugam [5] who investigated the effect of ovality and wall thinning on the ratio of internal fluid pressure, during in-service of the tube, to allowable stress.

Great efforts have been made to study the effect of various parameters on the cross-section distortion and wall thickness change in the tube bending process. Lee et al. [6] conducted parametric studies on the rotary draw bending of oval tubes, using FE simulations, and effects of bending radius and the aspect ratio of the tube ovalness on the deformation characteristics were investigated. They found that bending of oval tubes, rather than circular ones, reduces the wall thinning on the outside of the bend when compared to circular tubes bent with a mandrel. Li et al. [7] investigated the interactive effects of wrinkling, thinning, and cross-section distortion by using a finite element (FE) model of the thin-walled tube numerical control (NC) bending process. The studies performed by Li et al. [8] were focused on the rotary draw bending of tubes under the action of a push assistant force. They found that the push assistant force has more significant effect on extrados than on

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intrados, because more material is pushed into the bending regions, leading to the reduction of ovality and the thinning. Tang et al. [9] studied the effect of the pressure force and booster speed on the wall thinning and cross-section ovality using FE simulation. Naoi et al. [10] studied the evolution of ovality and wall thickness in the case of the intrusion bending method with and without the use of the inner tool. Li et al. [11, 12] investigated the effect of the mandrel and the clearance between tube and dies on wrinkling, wall thinning, and cross-section deformation in NC bending using FE simulation. Lai et al. [13] simulated the effect of the material and process parameters on the quality of tubes subjected to rotary draw bending. Yang et al. [14, 15] studied the effect of the friction between the tools and tube on the cross-section quality in rotary draw bending of tubes using FE simulation. The studies performed by Li et al. [16] were focused on the forming characteristics and the influence of the bending parameters on the cross-section distortion and wall thickness of thin-walled circular tubes subjected to bending.

The influence of the internal pressure on the tube deformation during the push bending process with axial forces and internal pressure was experimentally studied by Zeng et al. [17]. The internal pressure was created using an elastic medium. They concluded that ovality and wrinkles could be eliminated by increasing the internal pressure. Wang et al. [18] studied the tube bending with internal pressure and axial stretching using the FE simulation and an analytical model. They concluded that wrinkles tend to be minimized by applying the axial force. The tendencies for wrinkles and the cross-section distortion were also reduced by applying the axial force.

There are few researches on the bending of tubes with internal fluid pressure. Due to the lack of knowledge on the deformation behavior, the quality of tubes cannot be improved.

Therefore, the aim of this paper is to investigate the quality of aluminum alloy tubes in rotary draw bending with internal pressure. A hand bender device, based on the principle of rotary draw bending, is used to perform this study. A finite element model of the bending process with internal pressure effect has been developed and validated with experiments. The effect of the internal pressure on the cross-section ovality, wall thinning, and wall thickening has been investigated.

2 Experimental research

2.1 Bending of tubes with and without internal pressure

The bending experiments are carried out in order to determine the effect of the internal pressure on the quality of the bent tubes and to verify the results of the FE modeling. In order to perform the bending of tubes without internal pressure, a hand bender device shown in Fig. 1 has been used. This device is based on the principle of rotary draw bending. First, the tube is clamped between the insert die and movable clamp die. Then, the pressure die is moved until its semi-circular groove comes into contact with the tube. The tube is bent by rotating the bending die to the desired bending angle.

The experimental setup for bending with internal pressure is shown in Fig. 2. The main components of the system are the hydraulic pump, the tube bending device, and the sealing system with the flexible hose that connects the tube with the hydraulic pump. During the tube bending with internal pressure, the tube is subjected to an internal pressure in combination with a bending moment.

2.2 Quality characteristics of the bent tubes

A quality factor is defined in order to evaluate the undesirable deformation of the cross section of the bent tubes. This factor, called the cross-section ovality ψ, is defined using the equation

$$\psi = \frac{D_{\max} - D_{\min}}{(D_{\max} + D_{\min})/2}, \quad (1)$$

where $D_{\max}$ is the maximum tube diameter after bending, while D_{min} *is the minimum tube diameter after bending (see Fig. 3 for details).*

In order to evaluate the variation of wall thickness, the thinning degree ξ is used

$$\xi = \frac{t_0 - t_{\min}}{t_0} \times 100\%, \quad (2)$$

where t_0 is the original wall thickness, and $t_{\min}$ is the minimum wall thickness on extrados (see Fig. 3).

Similarly, a thickening degree ζ is defined in order to assess the wall thickening of the bent tubes

$$\zeta = \frac{t_{\max} - t_0}{t_0} \times 100\%, \quad (3)$$

where $t_{\max}$ is the maximum wall thickness on the intrados (see Fig. 3).

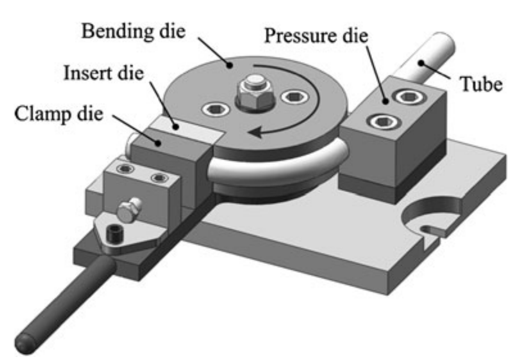

Fig. 1 Rotary draw tube bending device

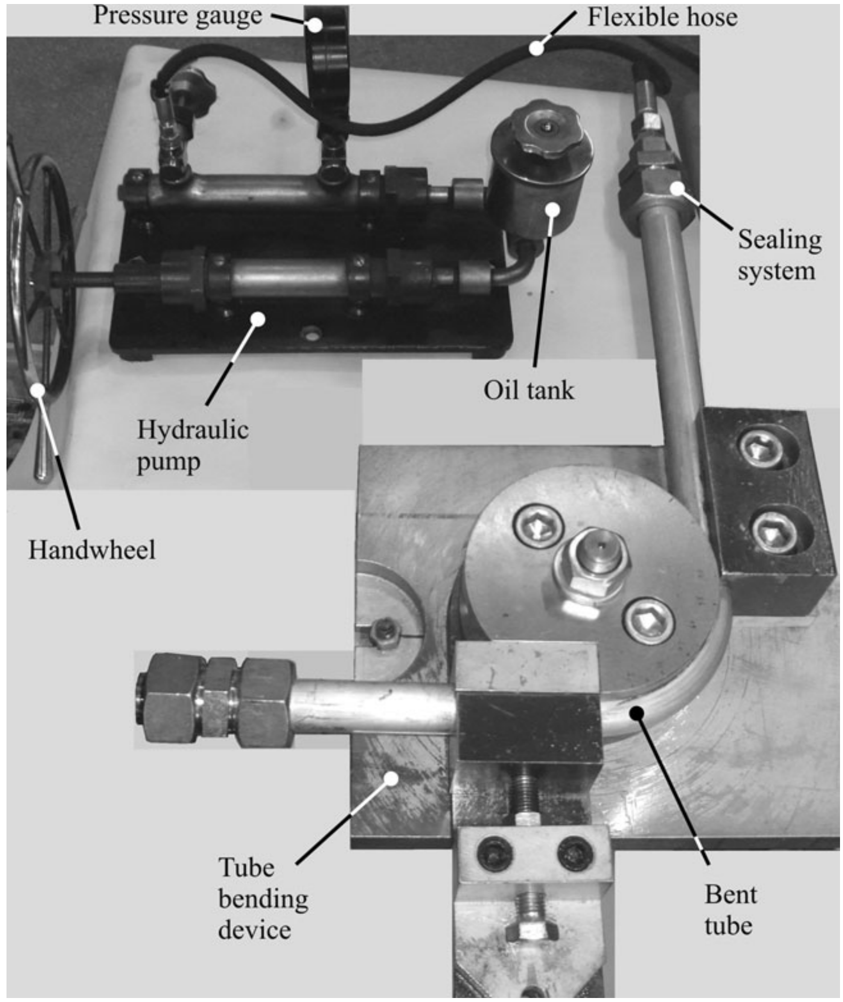

Fig. 2 Experimental setup for bending of tubes with internal pressure

2.3 Material and experimental conditions

Tubes made from an AA 1050-O aluminum alloy have been used in this research. The original outside diameter and wall thickness of the tube have been determined by circumferential measurements in several cross sections along the tube axis. Subsequently, the following values have been obtained: average outside diameter, D_0, is 29.7 mm, and average wall thickness, t_0, is 1.8 mm.

Tube samples taken by means of water jet cutting have been subjected to tensile tests in order to determine the mechanical parameters of the tube material. Figure 4 shows

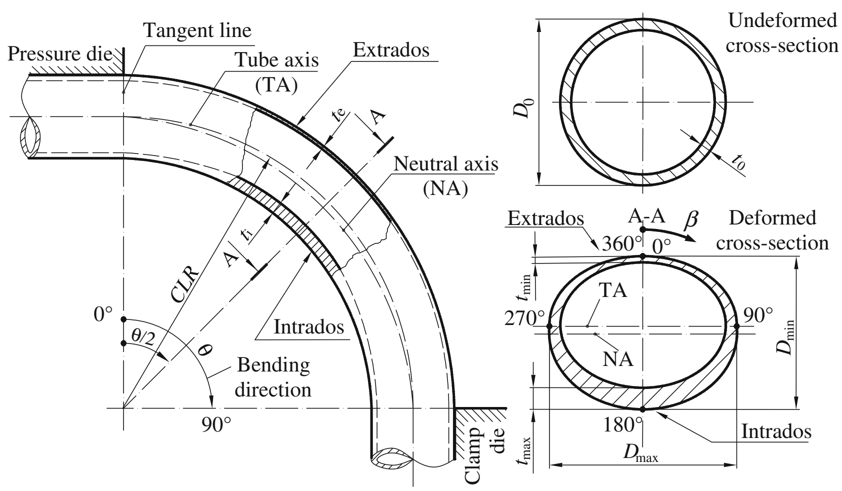

Fig. 3 Geometry of a bent tube

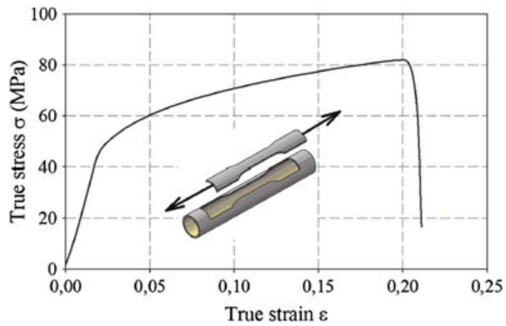

Fig. 4 Stress–strain curve for an AA 1050 O aluminum tube

the stress–strain curve of the tube material, and Table 1 summarizes the mechanical parameters.

The bending condition for FE simulation and experiments are as follows: bending radius along the centerline of the tube CLR is 75 mm, and bending angle θ is 90°. The internal pressure p is set as 0, 0.6, 1, 1.4, and 1.8 MPa.

After bending, the tubes were cut in the cross section located at the middle of the bending angle, and the sections were scanned using a 3D coordinate measuring machine with the purpose of determining the cross-section profile. The drawings of cross-section profiles were saved as DXF file and then imported into AutoCAD, and the tube diameters and the wall thickness were determined.

3 FE simulation of the tube bending process

3.1 Finite element model

In this study, a 3D finite element model of the tube bending process is developed using the commercially available, explicit finite element code eta/DYNAFORM. The finite element model of the rotary draw bending process of a circular tube and meshing are shown in Fig. 5. The model includes the tools: bending die, clamp die, insert die and pressure die and the tube. Shell elements of the type Belytscho-Tsay with five integration points were used for meshing the mid-surface of the tube. The dies are defined as discrete rigid bodies. The contact between various pairs of surfaces (bending die–tube and pressure die–tube) was defined using the Coulomb friction model. The value of the friction coefficient used in the simulation was 0.125.

Table 1 Mechanical properties of the AA 1050 O aluminum tube

Parameter	Value
Ultimate tensile strength, UTS (MPa)	82
Initial yield stress, σ_y (MPa)	45.96
Total elongation, A (%)	39
Initial plastic strain, ε_0 (−)	0.0048
Hardening exponent, n	0.1828
Strength coefficient, K (MPa)	109.62
Young's modulus, E (MPa)	6.9E+004
Poisson's ratio, ν	0.33

3.2 Material behavior

During the FE simulation of the bending process, the tube is assumed to be made of an anisotropic strain hardening elasto-plastic material. The strain hardening is described by Swift's equation

$$\sigma_y = K \cdot \left(\varepsilon_0 + \varepsilon_p\right)^n, \quad (4)$$

where σ_y is the yield stress, while K, ε_0, and n are material parameters. These parameters are listed in Table 1. The material model 36 (Barlat 1989 yield criterion) has been used [19], with the following parameters: the anisotropy coefficients r_0, r_{45}, and r_{90} are 1 and the flow potential exponent M is 6.

3.3 Experimental validation of the FE model

In order to validate the reliability of the finite element model built in this work, the results of the simulation were compared with experimental data. The tubes were bent in the same conditions as in the experiments described in § 2.3. Figures 7, 8, 9, and 10 compare the results of the finite element simulation with experimental data. One may notice from these figures that there are no significant differences between the simulation results and the experimental data. Therefore, the FE model can simulate the tube bending process well and can be used to study the quality of bent tubes.

4 Results

4.1 Effect of internal pressure on cross-section deformation

In order to study of the effect of the internal pressure on the cross-section deformation and wall thickness change, the experiments and FE simulations were performed in the conditions described in § 2.3. The experimental result is shown in Fig. 6.

Due to the boundary constraints shown in Fig. 3, the tube is constrained in the direction of the maximum diameter (D_{max}) by the groove of the bending die and under free deformation in the direction of minimum diameter (D_{min}). Therefore, in the bending without internal pressure, the cross section of the tube will deform more in the direction

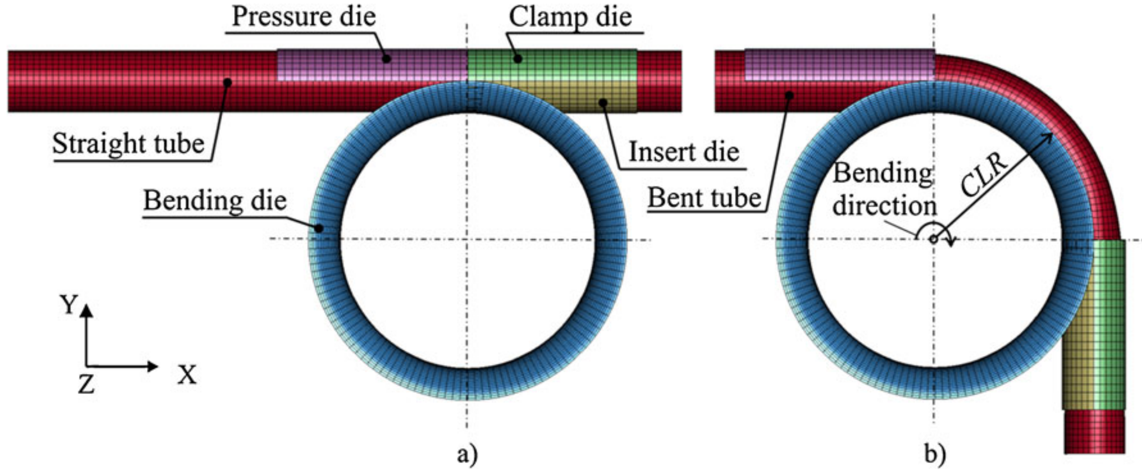

Fig. 5 3D FE model for the rotary draw bending of a tube: **a** initial position, **b** bending at 90°

of the minimum diameter than in the direction of maximum diameter.

Figure 7 shows the effect of the internal pressure on the changes of tube outside diameters ($D_{\min}$ and $D_{\max}$). When the bending is done without internal pressure, the minimum diameter is 26.509 mm, which means a decrease with 3.191 mm of the original tube diameter (D_0). When the internal pressure is 1.8 MPa, the minimum diameter is 29.675 mm, which means only 0.025 mm difference between the actual minimum diameter and the original tube diameter.

The increase of the internal pressure determines a decrease of the maximum diameter ($D_{\max}$) deviation too (Fig. 7). Thus, when the bending is done without internal pressure, the difference between the actual maximum diameter and the original diameter is 0.702 mm. While increasing the internal pressure, this difference decreases, reaching, at the pressure of 1.8 MPa, the value of 0.645 mm.

Figure 8 shows the influence of the internal pressure on the cross-section ovality ψ. One may notice from Fig. 8 that the amount of cross-section ovality presents a sharp quasi-linear decrease from 13.68% to 2.23%, while the increase of internal pressure is from 0 to 1.8 MPa. Therefore, the cross-section ovality was reduced with 11.44% by an increase in the internal pressure from 0 to 1.8 MPa.

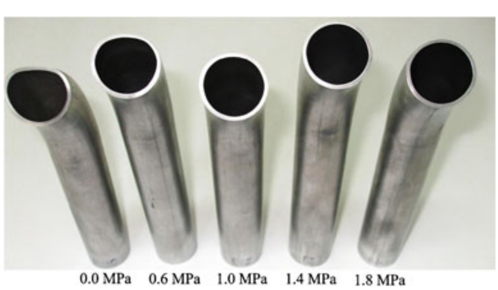

Fig. 6 Cross-section shapes of tubes bent under different pressures

4.2 Effect of the internal pressure on the change of the wall thickness

Figure 9 shows the wall thickness change versus internal pressure. As the internal pressure increase from 0 to 1.8 MPa, the maximum thickness decreases from 1.983 to 1.928 mm. When bending is performed without internal pressure, the deviation from the original thickness is +0.183 mm. When the internal pressure is elevated at 1.8 MPa, the maximum thickness decreases to +0.128 mm. Therefore, the deviation of the maximum thickness was reduced with 0.055 mm by an increase in the internal pressure from 0 to 1.8 MPa.

As shown in Fig. 9, the increase of the internal pressure determines an excessive reduction of the minimum thickness $t_{\min}$ measured at the extrados. When the internal pressure increases from 0 to 1.8 MPa, the minimum thickness linear decreases from 1.661 to 1.558 mm. Therefore, the deviation of the maximum thickness increases with 0.103 mm by applying an internal pressure during the bending.

Figure 10 depicts the effect of the internal pressure on wall thinning and wall thickening. As expected, taking into account the evolution of the wall thickness described above,

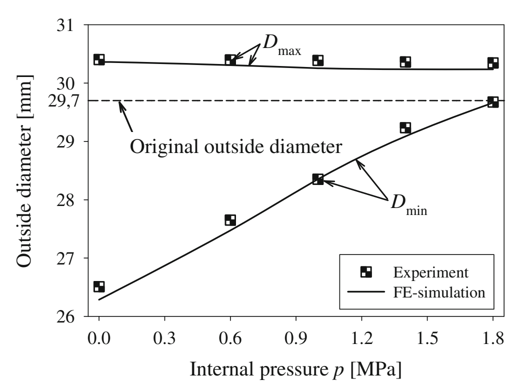

Fig. 7 Effect of the internal pressure on the cross-section deformation

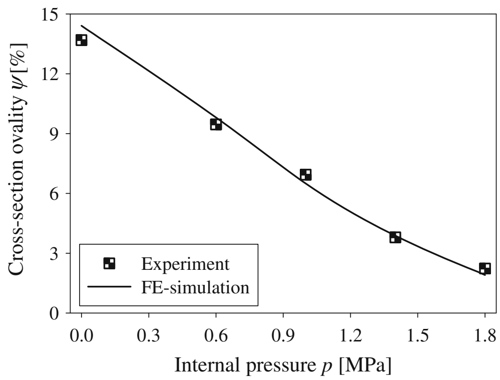

Fig. 8 Effect of the internal pressure on the cross-section ovality

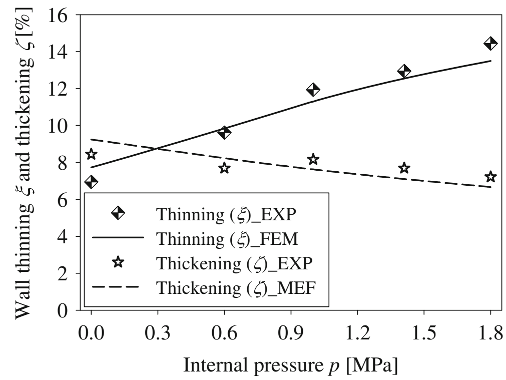

Fig. 10 Effect of the internal pressure on the wall thinning and thickening

while increasing the internal pressure from 0 to 1.8 MPa, the wall thickening degree ζ decreases from 10.16% to 7.11%, whereas the wall thinning degree ξ increases from 7.72% to 13.44%. Therefore, the influence of the internal pressure is greater on thinning than on thickening.

Figure 11 shows the FE simulation results of the wall thickness change in the so-called critical cross section, located at the middle of the bending region, depending on the position on the cross-section β, for different values of the internal pressure. For the values of β-coordinate, between 0° and 90° (at the extrados), the tube wall is stressed by axial tensile stresses and its thickness decreases, and for values of β, between 90°and 270° (at the intrados), the tube wall is stressed by the axial compressive stresses and the wall thickness increases. Next, for values of β, between 270° and 360° (at the extrados), it gets back to the domain of tensile stresses and the wall thickness decreases. At the points where the β-coordinate has the values of 90° and 270°, respectively, the tensile and compressive stresses are theoretically equal to each other. Therefore, the resulting strains are null, which would mean that the wall thickness is equal to the original thickness. But, as it can be seen from Fig. 11, the intersection between the straight line representing the original thickness (t_0) and the actual thickness curves after bending at different values of pressure falls at values of the β-coordinate about 96° and 264°, respectively, which means a shift of the neutral axis to the intrados.

From Fig. 11, it is also found that with the increase of the internal pressure, the curves of the wall thickness, at the intrados, tend to move closer to the straight line representing the original thickness, while at the extrados, tends to move away from the line depicting the original wall thickness.

Figure 12 shows the FE simulation results of wall thickness change in the axial section of the tube versus the angular position from the tangent line to clamp die end, and for different values of the internal pressure. Figure 12 shows that, when the internal pressure increases, the curves of the wall thickness, at the intrados (t_{i}), tend to move closer to the straight line representing the original thickness (t_0), while at the extrados, the wall thickness curves (t_{e}) tend to move away from the line depicting the original wall thickness. This is in agreement with the effect of the internal pressure on the wall thickness change curves in the critical cross section, located at the middle of the bending region, as it has been shown in Fig. 11.

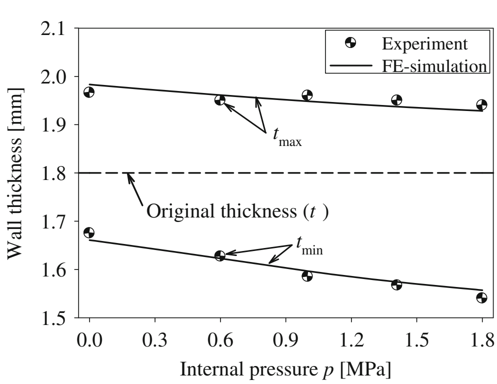

Fig. 9 Effect of the internal pressure on the wall thickness

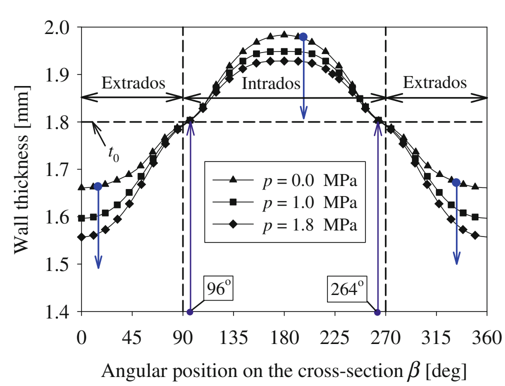

Fig. 11 Effect of the internal pressure on the change of the wall thickness at the level of the cross section located in the middle of bend region (see Fig. 3)

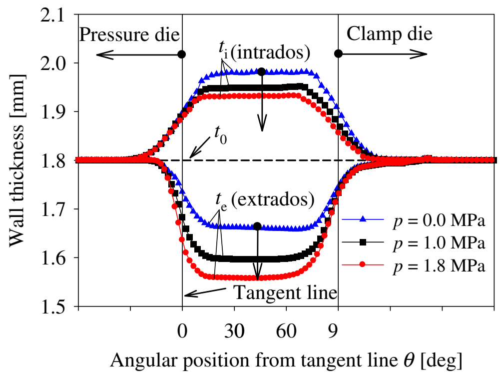

Fig. 12 Effect of internal pressure on the wall thickness t_i and t_e at the level of the axial section shown in Fig. 3

5 Conclusions

In this paper, the effect of the internal fluid pressure on the quality of aluminum alloy tubes has been investigated experimentally in combination with FE simulation in rotary draw bending process. Based on the obtained results, the following conclusions can be drawn:

1. With the increase of internal pressure, the cross-section ovality decreases.
2. As the internal pressure increases, the wall thickening on the intrados decreases and the wall thinning on the extrados increases. The influence of the internal pressure is more significant on thinning than on thickening.
3. At a bending angle of 90°, the aluminum alloy tube is successfully bent when the internal pressure is 1.8 MPa. The cross-section ovality is 2.23%, the wall thinning is 13.44%, and the wall thickening is 7.72%.

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