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On a new concept of rotary draw bend-die adaptable for bending tubes with multiple outer diameters under non-mandrel condition

T. Wen*

College of Materials Science and Engineering, Chongqing University, Chongqing 400044, China

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ABSTRACT

A traditional rotary draw bending die on the numerically controlled (NC) tube benders or other benders can bend tubes with only one kind of outer diameter. It is difficult for such a situation to meet the requirement of modern manufacturing with characters of much varieties and small batch. The present study proposed a new concept of rotary draw bending die called MDB-Die (Multiple-diameter Bending Die), on which tubes with different outer diameters within a definite range can be bent using the same die by only adjusting the pads inside the die set. Numerical and experimental approaches were employed to investigate the forming process of tubes with different outer diameters when bent on the MDB-Die, especially on the characters of force and elastic-plastic deformation of tube wall, and the effects of groove shapes and bending parameters on the cross-section distortion and wall thinning in the process. Analytical expressions in simple tube bending based on plastic theories given by Tang (2000) for calculating the magnitude of stresses, together with the wall thickness change, deviation of the neutral axis, and section flattening, were also used for comparison. The result proved that tubes with different outer diameters (from 18 to 25 mm in the study) can be bent successfully on MDB-Die without degrading the bending quality, i.e., the aspect ratios of section distortion of less than 5% and wall thinning of less than 7.8%.

1. Introduction

As important lightweight structures and liquid conveying or heat exchanging components, metallic tubular parts are widely used in the fields of aeronautics and aerospace, automobile, oil and chemical industries, etc. It has great advantages of efficiency, cost, and quality when tubular productions are made by plastic forming technologies. Among them, bending is most commonly used, and till date, numerous tube bending approaches, such as rotary draw bending, press bending, drawing bending, and pushing bending have been developed in response to the diverse demands of tube specification, shapes, materials and forming tolerance. Due to the characters of high efficiency, stable quality, and ability to form tubular parts with complex shapes, rotary draw bending is the dominant approach and is used on most of the tube benders, especially the numerically controlled (NC) tube benders.

During the rotary draw bending process, complex uneven tension and compression stress distributions are induced in extrados and intrados of the bent tube, which may cause multiple defects or instabilities such as cross-section distortion, wall thinning (even cracking), wrinkling, and springback. Till date, as Yang et al. (2012) summarized, many studies have been conducted on tube bending, and most of them are concentrated on the analysis of multiple defects/failures, selection/optimization of the forming parameters, and tooling to promote the development of tube bending science and technology by using experimental, analytical, and numerical methods. Al-Qureshi (1999) employed plastic-deformation theory to calculate stress distribution and bending moment, which are needed for springback analysis. Orynyak and Radchenko (2007) proposed an analytical method for the investigation of the end effect in a pipe bend loaded by a bending moment with consideration for the action of internal pressure. Megharbel et al. (2008) introduced a theoretical analysis of the elastic–plastic bending of tube and section made of strain-hardening materials, while Li et al. (2007) discussed the role of mandrel in NC precision bending process of thin-walled tube.

Due to the complex physical and geometrical nonlinear characters of the plastic deformation in most tube bending processes, it is difficult to obtain comprehensive results by just using the analytic approaches; thus, numerical methods like FEM have been frequently used in the studies of tube bending in recent years, for example, Li et al. (2009) studied the deformation behaviors of thin-walled tube NC bending with large diameter and small bending radius via a series of 3D-FE models under ABAQUS platform. Meanwhile, attempts on the renovation of tube bending techniques have never ceased; e.g., the proposals of Free-Bending given by Gantner

* Tel.: +86 13018363383; fax: +86 23 65112879.
E-mail addresses: wentong@cqu.edu.cn, tonywen68@hotmail.com

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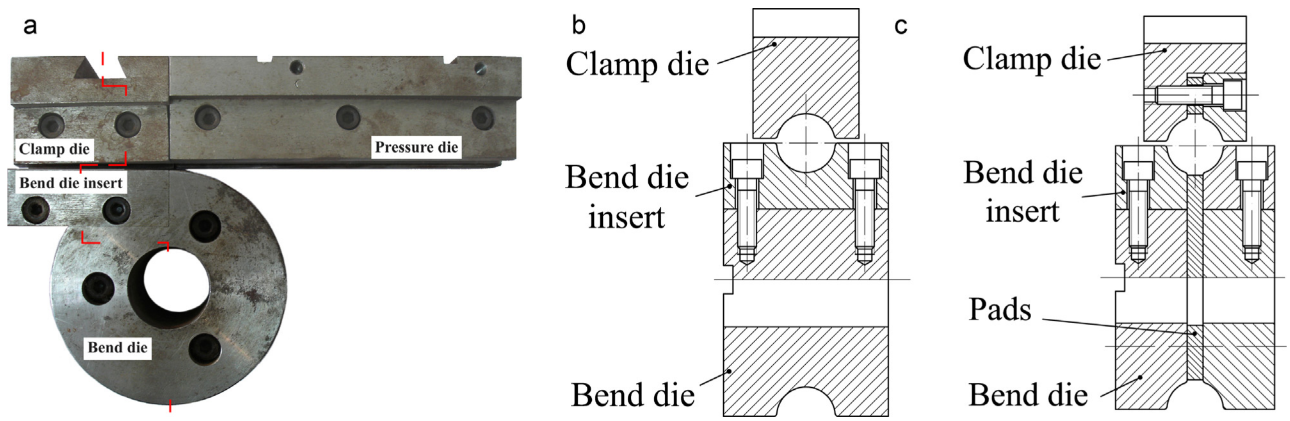

Fig. 1. Structure of the rotary draw bending die assemblage. (a) A set of rotary draw bending die (b) Section of traditional die (c) Section of MDB-Die.

et al. (2005) and Shear Bending given by Goodarzi et al. (2005), and the introduction of local induction heating in the bending of a large-scale pipe (Hu, 2000). Recently, with the increasing demand of light metal in some high-technological industries such as aeronautics and aerospace, bending of non-ferrous metal tubes have attracted more and more attention. For example, Wu et al. (2008) studied the bendability of the wrought magnesium alloy AM30 tubes using a rotary draw bender; Li et al. (2012) studied the springback characterization and behaviors of high-strength Ti—3Al—2.5V tube in cold rotary draw bending, while Lăzărescu (2013) investigated the effect of internal fluid pressure on quality of aluminum alloy tube in rotary draw bending.

However, in the existing techniques of tube rotary draw bending, a die set can bend tubes with only one kind of outer diameter. The whole die set must be replaced if the outer diameter of the tube is changed; thus, beyond all doubt, this would increase the cost and lower the efficiency. The current study put forward a novel concept of rotary draw bending die called Multiple-diameter Bending Die or MDB-Die based on one of the author's (Wen and Chen, 2009) former work, on which tubes with different outer diameters within a relative wide range can be bent on the same die by simply adjusting the shape of the die groove. Numerical and experimental methods were employed to study the elastic-plastic deformation of the tubes with different outer diameters when bent on MDB-Die without the use of a mandrel. The main purpose of the study was to obtain the fundamental understanding of the effect of groove shapes on the section deformation and wall thickness of the bent tube, and then prove the practical validation of such a concept.

2. Principle of the MDB-Die

Traditionally, a rotary draw bending die is an assemblage composed of a bend die and die insert, a clamp die and a pressure die, as shown in Fig. 1. Sometimes, a so-called wiper die and a mandrel are also used to improve the bending quality. During the operation, after each part of the die set is settled on the corresponding position of the bender, the tube is held tightly between the bend die insert and the clamp die; then, the bend die, die insert, and clamp die rotate together around the axis of the bend die, forming a bent shape. To clamp the tube and accomplish the processing successfully, the outer diameter of the tube should fit the die groove, which is usually a whole circle in section and comprises two semicircles of cavities of the clamp die and bend die insert.

Fig. 1(b) and (c) gives a comparison of the section of a traditional die and an MDB-Die. When compared with the traditional one, both the semicircles on the clamp die and the bend die insert of the MDB-Die are cut into two, between which pads with different thicknesses are inserted and the corresponding parts of the die are fixed together with bolts. As shown in Fig. 2, the groove shape of MDB-Die can be modified by adjusting the thickness of pads, and then tubes with different outer diameters can be held and bent on the same MDB-Die. Certainly, bending process with a MDB-Die is still the same as that with a traditional die.

Let us assume that the initial diameter of the die groove is D. As shown in Fig. 2(a), then D represents the maximum outer diameter of the tubes that can be bent on the die, and the initial thickness of pads is maximum of $h_{\max}$. If the outer diameter d of the tube is less than D, namely, $d < D$, the pads thickness must be decreased to h, and there is

$$h = h_{\max} - \Delta h = h_{\max} - (D - d) \quad (1)$$

The pads consist of slices with thickness from 0.2 to 2 mm; thus, the whole pads thickness could be adjusted conveniently.

From Fig. 2, it is clear that the groove shape matches the tube outline completely only when the tube has maximum outer diameter, namely $d = D$. The smaller the d is, the larger the groove shape deviates from an ideal circle. Therefore, it is essential to know the deformation of the tubes with different diameters when bent on the MDB-Die.

3. Experimental and theoretical model

The experiment was conducted on an NC tube bender on which the processing parameters such as bending angle and bending velocity can be procedurally settled in advance. Welded tubes of AISI 1020 with a length longer than 300 mm were used; the outer diameter d was 18 mm with 2.5 and 2 mm of wall thickness t, $d = 20$ mm with $t = 2$ mm, and $d = 25$ mm with $t = 2$ mm, respectively. The diameter D of the die groove was 25 mm, bending radius r was 58 mm, and bending angles θ were 30°, 90°, 120°, and 150°, $h_{\max}$ was 7 mm, respectively. Under each condition, three tubes were

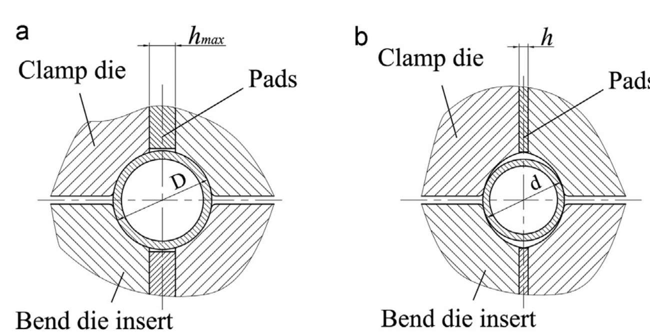

Fig. 2. Groove shape of MDB-Die when bending tubes with different outer diameters. (a) $d = D$, (b) $d < D$.

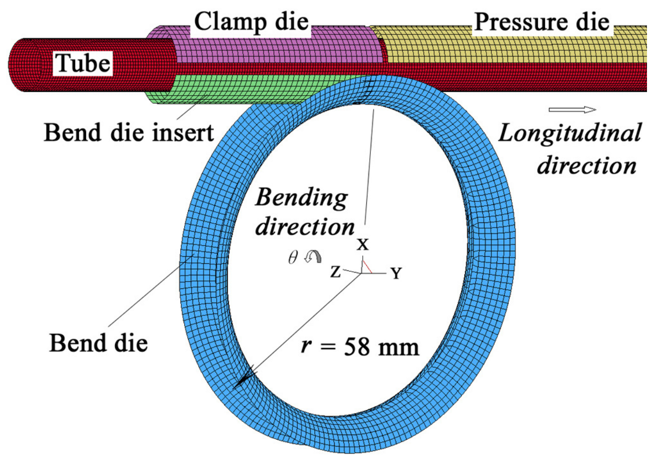

Fig. 3. The 3D FEM model for rotary draw bending.

Table 1
Mechanical properties of AISI 1020.

Young's modulus, E (GPa)	207
Poisson's ratio, υ	0.28
Elongation percentage, δ (%)	25
Yield strength, σ_s (MPa)	252
Strain hardening index, n	0.22

bent and the average values of the measured data were considered in the experiment. To determine the cross-section profile, the tubes were cut in the cross-section located at the middle of the bending angle after bending, and the sections were measured using a 3D coordinate measuring machine.

Dynamic explicit formulation FEM code, LS-Dyna, was used to simulate the elastic–plastic deformation of the tube rotary draw bending process under various forming conditions. Fig. 3 shows the 3D FEM model of the rotary draw bending, which includes the tools: bend die, die insert, clamp die, pressure die and the tube. The mechanic parameters of AISI 1020 are listed in Table 1. Coulomb friction law was employed with the friction factor of 0.15. Three-parameter Barlat–Lian model for anisotropy elastic-plastic material and BELYTSCHKO–TSAY (BT) shell element were used in the calculation. Fig. 4 shows the bent tube samples with different diameters, thickness and bending angle in the experiment.

4. Results and discussion

During the bending process, besides section distortion such as flattening of the circular section, tube wall thickness at the extrados frequently decreases due to the longitude tensile stress, while wall thickness at the intrados increases and even wrinkling occurs due to the longitude compressive stress. Springback is another inevitable defect in bending; nevertheless, it can be compensated by adjusting the bending angle on the bender. Therefore, section distortion, wall thinning and wrinkling are the major concerns in the latter discussion.

Fig. 4. Bent tube samples.

4.1. Strain and stress distribution

Fig. 5 shows the FEM results of the longitude stress distribution within the bending region. Fig. 5(a) represents bending with a traditional die and Fig. 5(b) shows the result of bending with a MDB-Die when $d < D$. It can be found that under these two conditions, the location and area of maximum longitude compressive and tensile stress are different, i.e., the maximum stress of tube bent on the traditional die is located near the clamp die and is distributed more widely. On the other hand, on an MDB-Die, when $d < D$, the maximum stress is located near the pressure die with a relative smaller area. The possible reason is that the constraint conditions of the tubes are different, resulting in different stress distributions during the bending process.

According to expressions given by Tang (2000), in the outer semi-circle of the bent tube, the longitudinal stress in a simple tube bending is expressed as

$$\sigma_y = \sigma_s \frac{2k+1}{2k+2-\cos\alpha} \tag{2}$$

where σ_s is the yield strength, k is the relative bending radius r/d, α is the departure angle from x-axial in x–z plane, and $\alpha = 0$ at the outermost point of the outer semi-circle. In Fig. 5, $k = 3.2$ and then σ_y is about 252 MPa at the outermost point, which is smaller than the FEM result due to the assumption of ideal plastic.

Fig. 6 shows the strain distribution within the bending region. The length of the element edge is from about 0.8 to 0.9 mm for each tube dimensions used in the simulations. For both the cases, the maximum strain in extrados is distributed between the pressure die and clamp die; however, within the bent region, the strain distribution of the tube bent on traditional die is more uniform.

4.2. Section distortion

Without any special control, flattening should occur when (Tang, 2000)

$$r \le \frac{3.43d^2}{4t_0} \tag{3}$$

where t_0 is the original thickness of the tube wall and d is the original outer diameter of tube. In the current study, according to the range of d and t_0, the smallest r was 93 mm when $d = 18$ mm and $t_0 = 3$ mm, and was still larger than the actual $r = 58$ mm; thus, flattening was inevitable when tubes were bent on a traditional die.

The section distortion of a bent round tube is usually described by the aspect ratio of the ovality, which is defined quantitatively by

$$\phi = \frac{d_{max} - d_{min}}{d} \times 100\% \tag{4}$$

where d_{max} and d_{min} are the major and minor axes of the section after bending, respectively.

The concept of ovality relies on the assumption that the deformed tube section is an oval shape. In fact, as shown in Fig. 7, the cross-section of the bent round tube is usually not oval. In each plot of Fig. 7, the left side shows the experimental result and the right side shows the FEM result. To provide a common description,

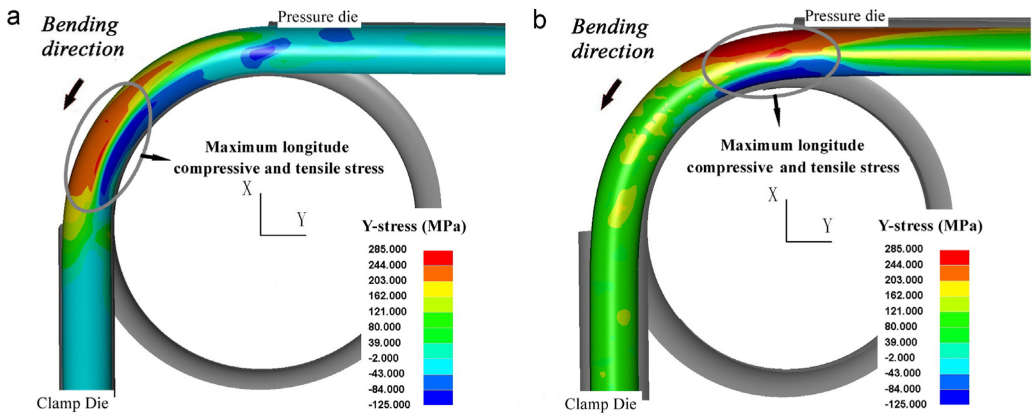

Fig. 5. Longitude stress distribution, $d = 18$ mm, $t = 2$ mm, $\theta = 90^{\circ}$. (a) $D = 18$ mm, (b) $D = 25$ mm.

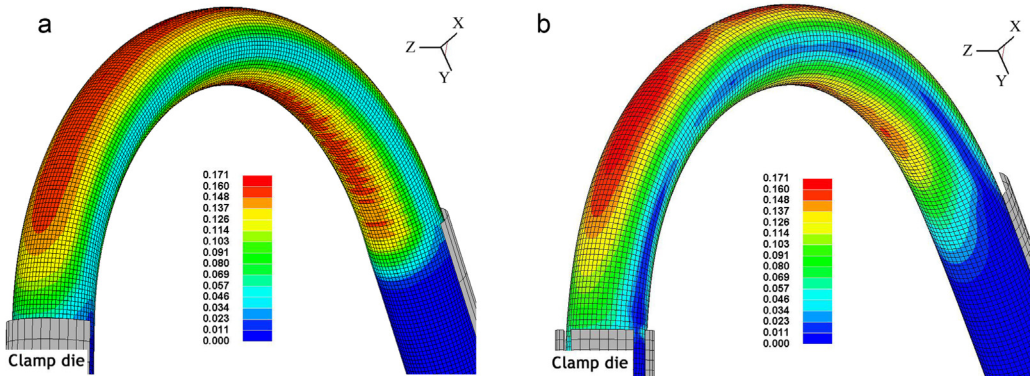

Fig. 6. Effective plastic strain, $d = 18$ mm, $t = 2$ mm, $\theta = 150^{\circ}$. (a) $D = 18$ mm, (b) $D = 25$ mm.

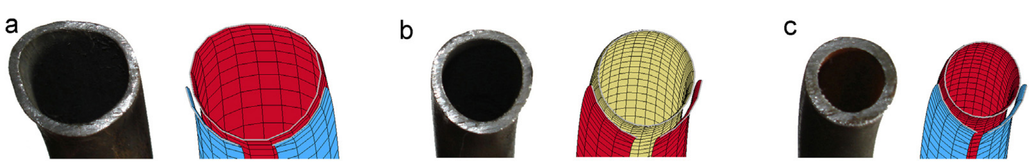

Fig. 7. Cross-section of tubes bent on a MDB-Die, $\theta = 150^{\circ}$, $D = 25$ mm. (a) $d = 25$, $t = 2$, (b) $d = 20$, $t = 2$, (c) $d = 18$, $t = 2.5$.

the current study defines the aspect ratio φ of the section distortion of a bent round tube as

$$\varphi = \frac{d'_{\max} - d'_{\min}}{d} \times 100\% \quad (5)$$

where $d'_{\max}$ is the diameter of the minimum envelope circle of the cross-section and $d'_{\min}$ is the diameter of maximum inscribed circle at the same section, as shown in Fig. 8. This definition adopted a concept commonly used in the evaluation of circularity error. In this study, a program wrote in C-language was also developed to calculate the aspect ratio based on the measured data in the experiment.

Figs. 9 and 10 present the experimental and numerical results of section distortion of tubes with different outer diameters. The unit of d, D, and t in the figure is mm.

As mentioned earlier, when $d = D$, the deformation of tube bent with a MDB-Die is similar to that bent with a traditional die, and the aspect ratio φ increases slightly with θ, as shown in Fig. 9. When d is smaller than D, the groove shape of MDB-Die is not a circle, as shown in Fig. 2(b), and under such a situation, there are clearances between the tubes and die groove, indicating that the outer and inner side of the tube wall are not constrained completely. The more smaller the d is than D, the greater is the difference between the tube section and die groove; however, this does not mean that larger section distortion of bent tube would occur. In fact, as shown in Figs. 9 and 10, unlike the process on a traditional die, the aspect ratios φ is less than 5% throughout the process and even exhibits a little decrease with the increase

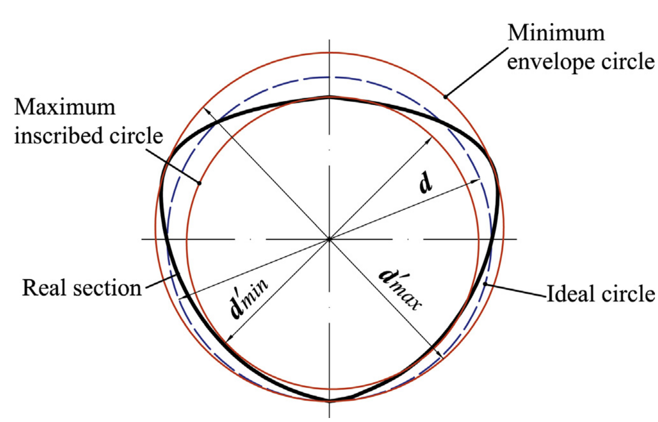

Fig. 8. Definition of the section distortion.

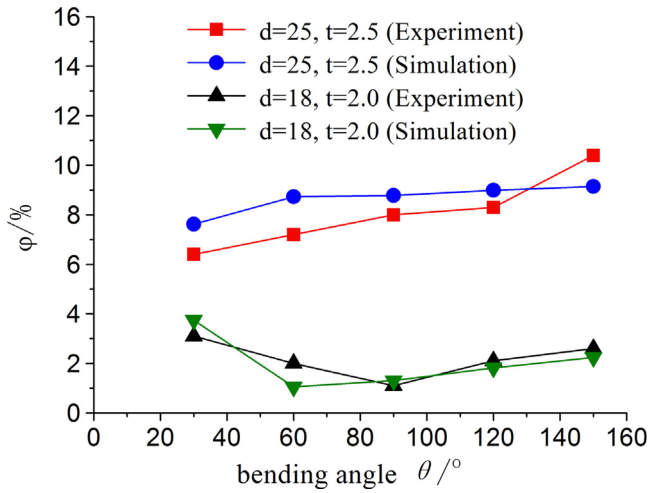

Fig. 9. Section distortion bent on MDB-Die, $D = 25$ mm.

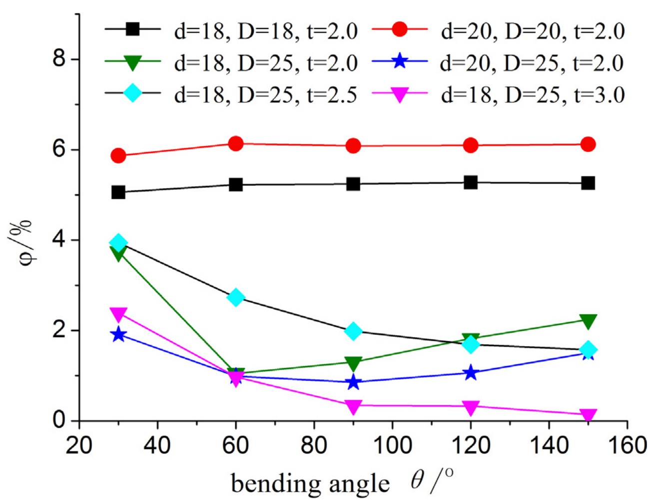

Fig. 10. FEM result of section distortion vs. bending angle.

in θ when bent on MDB-Die, indicating that higher quality of the tubular parts can be obtained by using MDB-Die.

Such a phenomenon can be interpreted on the aspect of different contact force and constraint status of tubes when bent on MDB-Die and traditional die. As shown in Fig. 11, when $d < D$, there are similar characters of contact force of tubes bent on a MDB-Die and on a die with a so-called Multiple-radius Groove (also Anti-deforming Groove) as described by Miller (2003). For these dies, both the grooves are sharpened in the outside region of the tube wall, i.e., the side close to the clamp die, which is benefited to compensate the flattening of the tube section.

Larger t/d means better stiffness of the tube wall, which will lead to a smaller section distortion, as shown in Figs. 7 and 10. Nevertheless, it should be noted that though the overall trend of section distortion of the tubes bent with MDB-Die is obvious, there is a local deviation in the curve progression in Fig. 10. Factors such as loading condition, deformation mode and deformation degree together with their complex interaction, etc., may have influence on the outcome.

The current experiment was conducted without mandrel. Theoretically, the quality of bent tube with respect to section distortion would be improved if the mandrel is employed.

4.3. Wall thickness variation

The wall thinning at the extrados causes a weakening of the strength during the in-service of the tube. The aspect ratio usually employed to measure the degree of wall thinning is defined as

$$\Delta t = \frac{t - t_{\min}}{t} \times 100\% \tag{6}$$

where t is the wall thickness before bending and $t_{\min}$ is the minimal wall thickness after bending.

Fig. 12(a) shows the relationship of Δt and θ from experiment and numerical simulation, and Fig. 12(b) presents the theoretical wall thinning under various conditions. When the bending angle θ is small, i.e., θ is less than 60°, Δt increases rapidly with θ; when θ is greater than 60°, Δt changes slowly with θ. It can be found that the wall thinning of tube bent on MDB-Die is less than that bent on traditional die when $d < D$. The major reason is that in the earlier stage of bending, the tube wall is forced to flow toward outside of the section by the sharpened die groove; meanwhile, there exists a smaller friction between tube and pressure die due to the less contact area, which would lead to a decrease in the thinning trend of the outside wall.

Fig. 13 shows the principal strain at the extrados and intrados of the tube, while $d = 18$ mm, $\theta = 150°$, $t = 2$ mm, and $D = 18$ or 25 mm. $D = 18$ mm indicates that the groove is the same as that of the traditional die, and the strain is listed in parentheses. When $d < D$, the longitude strain is greater, but the latitude compressive deformation increases more at the extrados, and in accordance with the law of volume constancy in plastic deformation, this would lead to a smaller thinning of the wall.

From the expression for calculating the wall thickness at the outermost point of the outer semi-circle (Tang, 2000)

$$t_{om} = \left(1 - \frac{2k+1}{2k(4k+2)}\right) t_0 \tag{7}$$

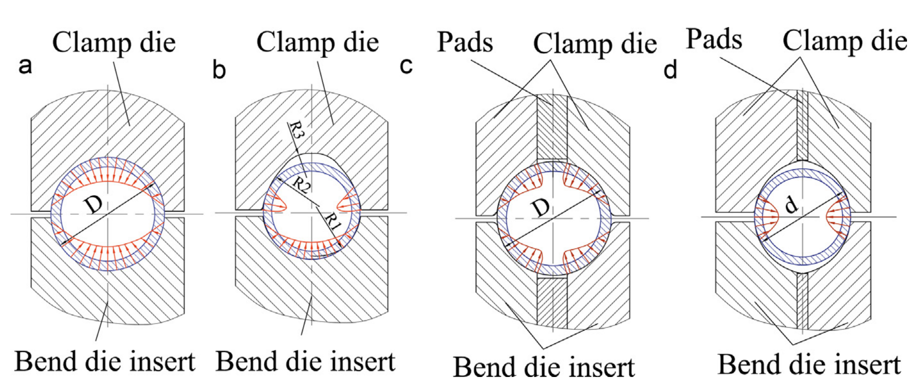

Fig. 11. Contact force on traditional die, Multiple-radius die, and MDB-Die when $d = D$ and $d < D$. (a) Traditional die, (b) Multiple-radius die, (c) MDB-Die when $d = D$, (d) MDB-Die when $d < D$.

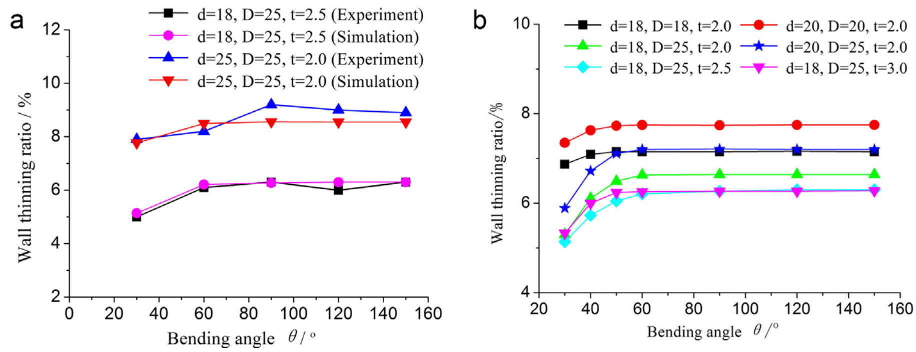

Fig. 12. Wall thinning with the bending angle. (a) Experimental and theoretical results, (b) Wall thinning vs. bending angle, FEM results.

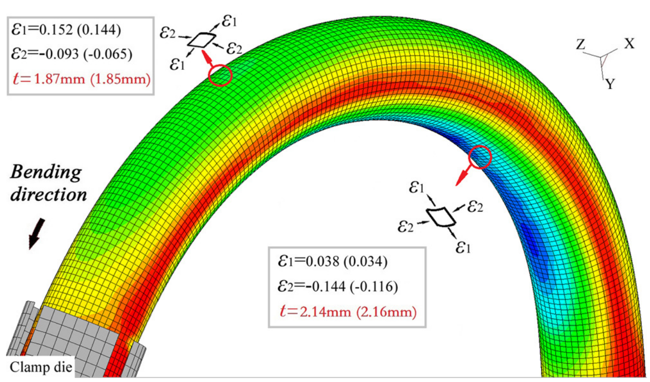

Fig. 13. Principal strain and wall thickness at extrados and intrados.

it can be computed that in the current study, t_{om} = 1.844 mm, which is very close to the FEM result.

During the tube bending process, the outer wall becomes thinner and its stiffness decreases, while the inner wall becomes thicker and the stiffness increases. For the balance of the moment of the internal force, the neutral axis should move to its inner side, which is called neutral axis deviation (Tang, 2000). Fig. 14 presents a sectional view of wall thinning ratio from FEM result when bent on MDB-Die with D = 25 mm, θ = 150°, d = 18 mm, and t = 2 mm. It can be observed from the figure that the neutral layer of wall thinning deviates inwards from the centroid.

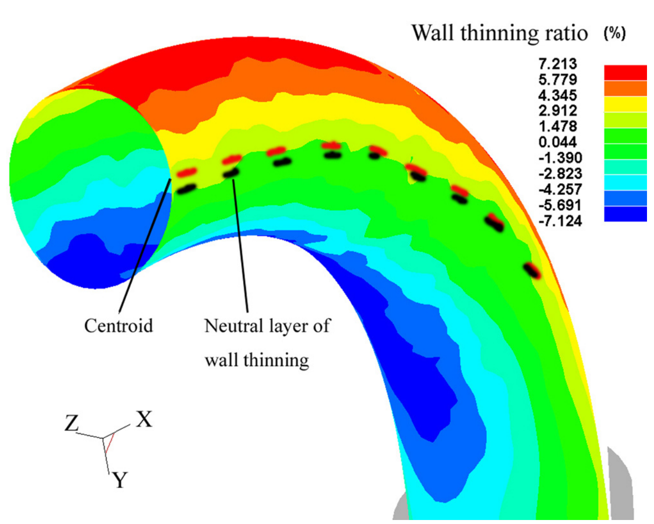

Fig. 14. FEM result of the wall thinning ratio, when D = 25 mm, d = 18 mm, t = 2 mm.

4.4. Wrinkling at the intrados

The inner wall of tube thickens with in-plane double compressive stresses in the bending process, and to some critical extent, wrinkling instability may occur, as described by Yang et al. (2012). The relative bending radius r/d has remarkable impact on the deformation degree within the bending region; the smaller the r/d is, the larger is the deformation, and hence, the defects/failures such as wrinkling are prone to occur. In general, for most of the thin-walled tubes the critical wrinkling value of r/d is around 2, according to the conclusion drawn by Goodarzi et al. (2005). In the current study, r/d was between 2.32 and 3.2, which is higher than the critical value. Thus, it can be concluded that wrinkling within the inner sidewall of the bent tubes is rare from the experimental (see Fig. 4) and numerical (see Fig. 13) result.

From the different distributions of maximum longitude compressive stress, as shown in Fig. 5, it can be derived that the possible wrinkling location at the intrados of tubes bent on MDB-Die when $d < D$ is close to the pressure die, while that of tubes bent on traditional die is near the clamp die and distributes wider simultaneously.

With a definite D, the smaller the minimum diameter d_{min} bent on the MDB-Die, the larger is the range of the tube diameters, which can be bent on the die. The influence of die structure and tube deformation must be taken into account when deciding d_{min}. Based on a comprehensive view of the above-mentioned analysis, the minimum diameter d_{min} is recommended to be about half of D, i.e., tubes with outer diameters from 0.5 D to D can be bent on the same MDB-Die.

5. Conclusions

The current work proposed a new concept of rotary draw bend-die called MDB-Die, on which tubes with different outer diameters can be bent by simply adjusting the thickness of pads and then changing the shape of the die groove. Experimental and numerical methods were employed to study the deformation of tubes with different outer diameters, wall thickness, and bending angles when bent on the MDB-Die. The following are the main conclusions drawn:

(1) When compared with the tubes bent on traditional die, tubes bent on a MDB-Die presented different contact forces and constraint status with the die groove, which resulted in a different stress, strain distribution, and deformation behavior.
(2) Deformation of tubes bent on MDB-Die was affected by forming parameters such as relative wall thickness t/d, bending radius r/d, bending angle θ, as well as the groove shape and their

complex interaction with each other. When the outer diameter d of the tube was equal to the initial diameter D of the die groove, there were few differences between the tubes bent on MDB-Die and traditional die, and the aspect ratio of section distortion φ increased with the bending angle θ. If $d < D$, φ did not increase more or even decreased a little with the increase in θ when bent on MDB-Die due to the so-called correction effect of anti-deforming, indicating that the quality of tubular parts in terms of section distortion is better although the groove shape is not a perfect circle. Meanwhile, the thinning of the wall at the extrados was smaller if $d < D$.

(3) Wrinkling at the intrados of tube bent on MDB-Die did not occur as long as the critical value of the relative bending radius r/d did not exceed.

(4) On the whole, the bending quality in terms of section distortion and wall thinning of tubes bent on MDB-Die did not decrease irrespective of whether d is less than D or not. With the utilization of MDB-Die in tube bending process, higher efficiency and even higher quality can be obtained, and the cost can be cut down.

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