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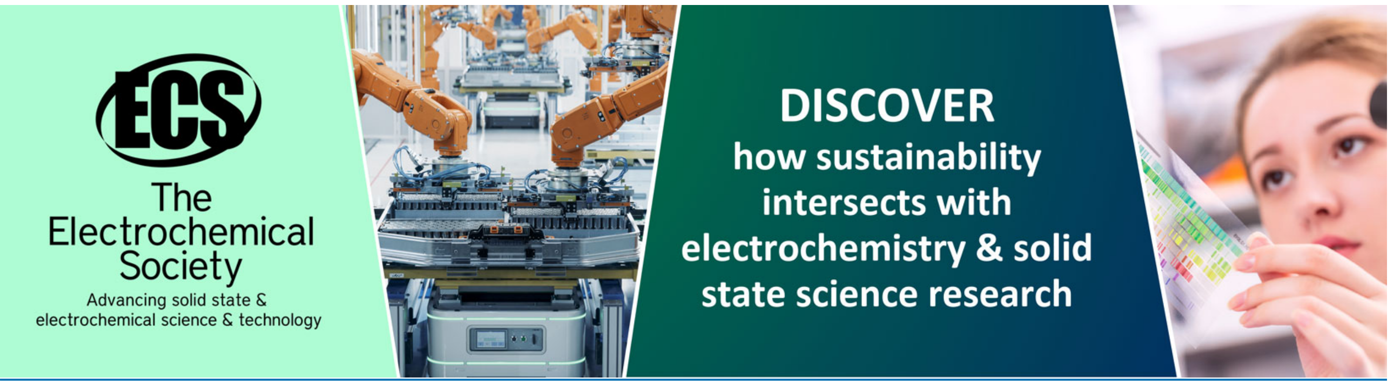

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Experimental study on rotary draw bending of magnesium alloy extruded tubes

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Abstract. In this research, the rotary draw bending of magnesium alloy extruded tubes was experimentally investigated. At room temperature, circular magnesium alloy tubes were bent without cracking and wrinkling, but with defective shape. The mandrel effect on the cross-sectional distortion, wall-thickness variation, and spring-back of the bent tube were analyzed and discussed. Results indicated that the rotary draw bending with the mandrel decreased the cross-sectional distortion and spring-back angle of the bent tube, slightly exacerbating the thinning rate of the tube wall thickness. The largest distortion of the cross-section of circular bent tubes with a 90° bending angle occurred in the position about 30° from the clamp die.

1. Introduction

As one of green engineering materials used in the 21st century, magnesium alloys have received increasing attention [1]. Magnesium alloys are widely used in the automotive, aerospace, machinery, and other industries due to their significant role in achieving lightweight, reducing energy consumption and reducing environmental pollution [2]. However, the cold workability of magnesium is poor because of its close-packed hexagonal (HCP) crystal structure [3]. In bending, magnesium alloys are more prone to produce quality defects than steels and aluminum alloys. These shortcomings hinder the application of magnesium alloys as structural components [4]. The material design, fabrication, and processing of magnesium alloy should be improved to accelerate the application of magnesium alloy. With the mature of material design and fabrication, the magnesium alloy forming process becomes a research hotspot.

Rotary draw bending (RDB) is a forming process in which the metallic tube is drawn and rotated around the bending die. It is widely applied in the processing of a variety of thin-walled tubes because of its high forming precision, high efficiency, good bending quality, and easy automation. Compared with other bending processes, there are additional longitudinal stresses along the axial direction of the tube during the draw bending, which benefits the reduction of the spring-back of the bent tube. It is important for magnesium alloy with a relatively low Young modules. For the rotary draw bending, the overall structure of bending tooling is simple and compact, and the produced parts own good surface quality. During the RDB, forming defects such as cross-sectional distortion, wrinkling, wall-thickness thinning (even cracking,) and spring-back may appear due to inhomogeneous tensile and compressive deformations at the extrados and the intrados of the bent tube [5].

In this paper, the RDB process of circular extruded tubes of magnesium alloy Mg-8Al-0.5Zn-0.5RE was investigated. The mandrel effect on the cross-sectional distortion, wall-thickness variation, and spring-back of magnesium alloy tube are analyzed and discussed.

2. Experimental

2.1. Material

The material under investigation was magnesium alloy Mg-8Al-0.5Zn-0.5RE, containing La and Gd rare earth elements. The magnesium alloy was hot-extruded into circular tubes at the initial billet temperature 250 °C, extrusion ratio 68 and extrusion speed approximate 20mm/s. Figure 1a shows the cross-section dimensions of the extruded circular tube, where the outer diameter was 20 mm and the wall-thickness was 1.25 mm. The bent profile is schematically shown in figure 1b, in which the bending radius is 100 mm and the bending angle is 90°. Uniaxial tensile test of specimens taken from tube was conducted to obtain the mechanical properties of the studied magnesium alloy. The strain hardening was fitted according to the Swift model. Mechanical parameters are summarized in table 1.

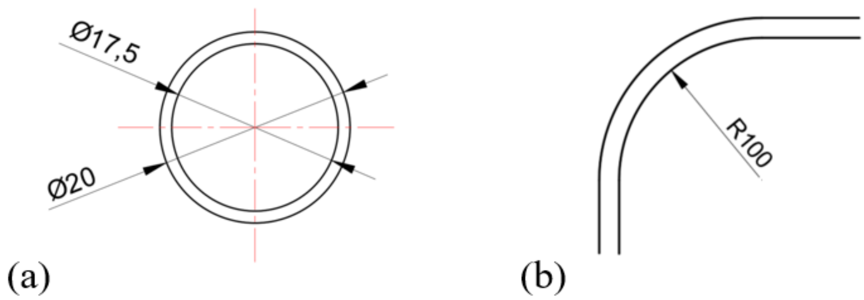

Figure 1. Dimensions of (a) cross-section and (b) bent outline of magnesium alloy extruded tube.

Table 1. Mechanical parameters of the studied magnesium alloy.

Parameter	Value
Young's modulus E (GPa)	43
Poisson's ratio v	0.35
Yield strength σ_Y (MPa)	178.6
Fracture Elongation δ (%)	18
Ultimate tensile strength σ_B (MPa)	396
Strength coefficient K (MPa)	599.1
Strain hardening exponent n	0.27
Initial strain parameter ε_0	0.0125

2.2. Bending experiment

Figure 2 shows the RDB tooling of circular magnesium alloy tube, including bending die, insert die, clamp die, pressure die, wiper die and mandrel. During the RDB, bending die is driven by the spindle to rotate at a given angular velocity. One end of the extruded tube is mounted on bending die by clamp die and insert die. The rest of the tube is constrained by pressure die, wiper die, and mandrel. When bending die rotates, the clamped tube co-rotates to the predetermined angle. During the tube bending, the pressure die moves forward with the tube feeding at a certain speed to reduce the friction force and wiper die remains stationary.

Rotary draw bending experiments were carried out on a numerical control tube bender (W27YPC-63, Guoqing, Shanghai) at room temperature. In order to analyze the influence of the mandrel on the forming quality of magnesium alloy, the tube bending experiments with and without mandrel were tried out. The process parameters of the RDB of the magnesium alloy tube are listed in table 2.

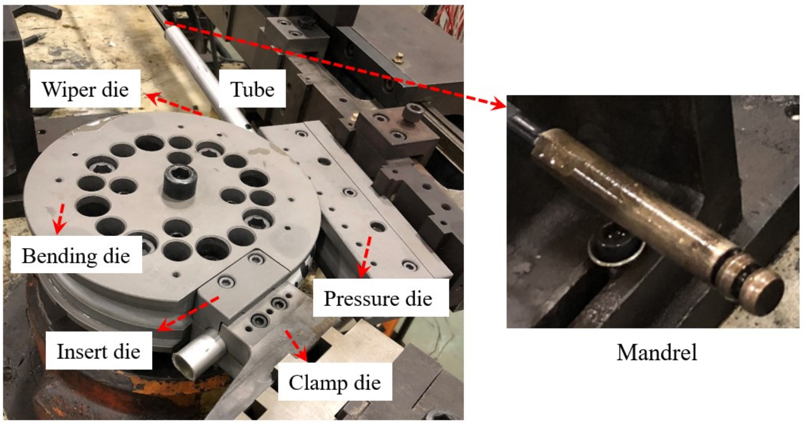

Figure 2. Tooling of the RDB of magnesium alloy tube.

2.3. *Shape distortion*

The main indicators used to characterize the precision of the bent tube is the diameter change rate, the tube wall thickening and thinning rates and the spring-back angle.

The diameter change rate L_d is defined as

$$L_d = \frac{|D' - D|}{D} \times 100\% \tag{1}$$

where, D and D' are the initial diameter of tube and vertical length after bending measured from the cross-section of the bent tube, respectively.

The thinning of tube wall at the extrados leads to a strength weakening of circular tube during the bending process. Tube wall thickness variation rate is usually adopted to measure the tube wall thinning and thickening degree and is defined quantitatively by

$$L_W = \frac{T - T_{min}}{T} \times 100\% \tag{2}$$

where T and T_{min} are the tube wall thickness before bending and the minimum one after bending, respectively.

Due to the effect of the spring-back of metallic materials, the actual bending angle of the bent tube is less than the predetermined one. The spring-back angle is expressed as

$$\Delta\theta = \theta - \theta' \tag{3}$$

where θ and θ' are bending angles predetermined and after spring-back, respectively.

Table 2. Process parameters of the RDB of magnesium alloy tube.

Process parameter	Value
Bending velocity, (rad·s^{-1})	0.5
Bending angle, (°)	90
Pressure die speed, (mm/s)	50
Speed of mandrel retracted, (mm/s)	100
Clearances between tube and tools, (mm)	0.1
Length of pressure die, (mm)	200

3. Results and discussion

Compared with other magnesium alloys, the magnesium alloy under investigation possesses larger elongation and high ultimate tensile strength [6]. The cracking and wrinkling were not found in the bent

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tubes, indicating the good cold workability of the investigated magnesium alloy. During the magnesium alloy tube bending, it is prone to result in forming defects such as outer wall thinning, inner wall thickening, cross-section distortion, and spring-back, degrading the performance of the bent tubular parts. The application of mandrel in tube bending can partly eliminate or weaken these forming defects. The mandrel effect on the forming quality of the bent tube of magnesium alloy was analyzed.

3.1. Cross-sectional distortion

Figure 3 shows the half split tubes that were bent with a bending angle of 90°, where the deformed cross-sections can be found. The largest distortion occurred in the position approximate 30° far from clamp die. Figure 4 demonstrates that the distribution of the diameter change rate along the tubing elbow, where ten positions were selected every an angle of 10°. The maximum value of outer diameter change rate of circular tube bent without mandrel was approximatively 7.5%, while the corresponding value of the tube bent with mandrel was less than 5.0%. It indicated that the mandrel played an important role in weakening cross-section distortion of magnesium alloy tube. It shows that the diameter change rate decreased with increasing distance (angle) from the clamping end of the bent tube. This was because the mandrel length was limit and has little supporting effect at the clamped end of the tube.

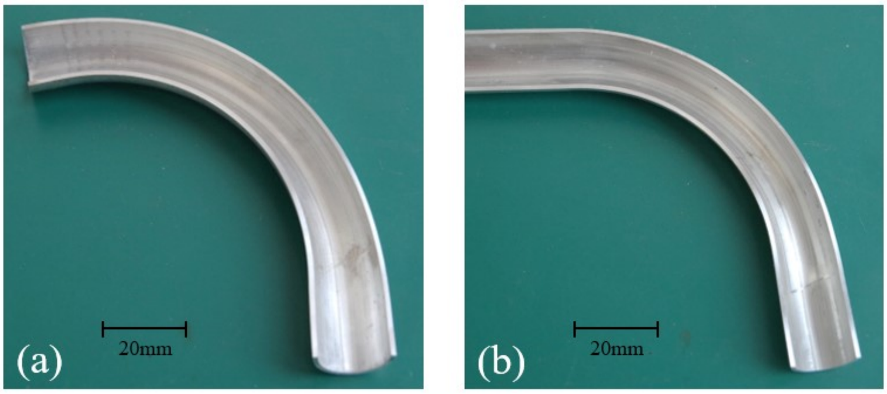

Figure 3. Split magnesium alloy tubes bent (a) with mandrel and (b) without mandrel.

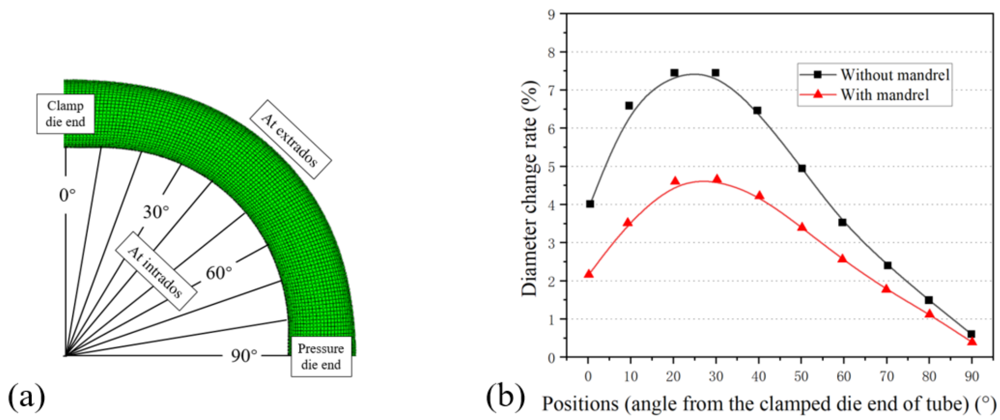

Figure 4. (a) Measured positions, (b) diameter change rate varying with positions.

3.2. Tube wall thinning

Figure 5 shows the tube wall thinning rate distribution at the extrados along the angle from the clamped end of the tube to the position close to wiper die. With increasing distance (angle) from the clamped end of the tube, the wall thinning rate without mandrel first rose from 3% at 0° to 12.4% at 45° (the middle of the bent tube elbow). After that, the tube wall thinning rate fell to 2.5% at 90° (another end of the tube elbow). It indicated that the middle of the tubing elbow was more thinned than both ends, which was consistent with other research [7] on the variation trend of the wall thinning rate.

It can be found that the wall thinning rate of the tube bent without mandrel was lower than that bent with the mandrel. The maximum wall thinning rate of the tube bent with mandrel was 14.0% compared with that of 12.1% without the mandrel. Bending without mandrel reduced the tube wall thinning rate at the extrados, but also exacerbated the thickening of the tube wall at the intrados and even contributed to the occurrence of wrinkles. The tube wall thickness deformation began to decrease gradually at a distance close to both ends of the tubing elbow. While the straight section of tube that did not participate in the bending deformation also underwent a certain wall thickness deformation, which indicated the straight tube section absorbed and alleviated local deformation in the bending area.

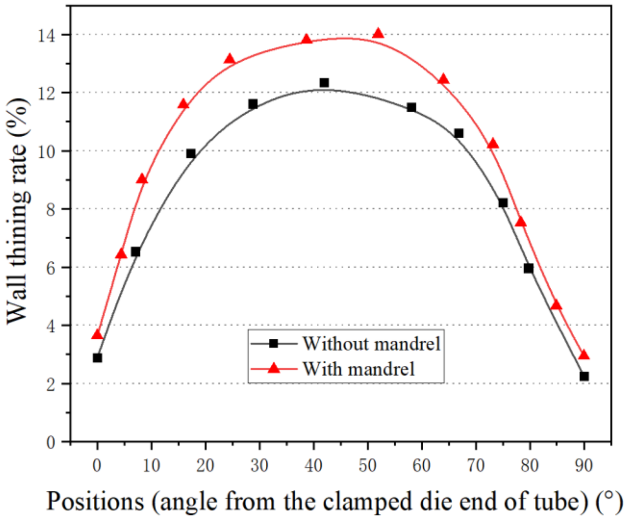

Figure 5. Wall thinning rate distribution of the tube.

In order to analyze the variation of the tube wall thickness at the cross-section, it was measured at sampling positions every 30 degrees along the circumference. Measurement results are shown in figure 6, the staring measured point is at the top of the extrados. It indicated that the tube wall-thickness varied with the position along the cross-section circumference of the circular tube. At the top of the extrados, the maximum thickening rate appeared, and the maximum thinning rate at the middle of the intrados.

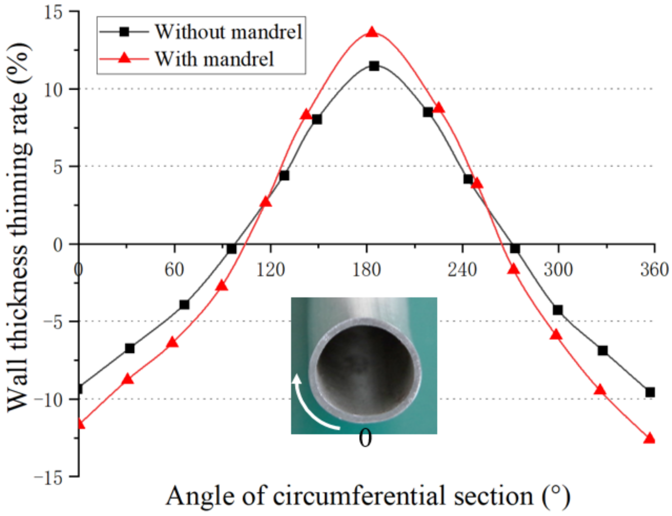

Figure 6. Distribution of wall thickness along the circumferential section of bent tube at the 45°section of the extrados.

3.3. *Spring-back*

Figure 7 shows curves of the spring-back angle versus the bending angle of the magnesium alloy tube. RDB experimental results showed that the spring-back angle increased approximately linearly as the bending angle increased, which was in good agreement with the previously reported research [8] on the springback trend of metallic alloy tubes. The spring-back angle in the mandrel bending was smaller than that in the mandrel-free bending. The magnitude of the spring-back angle depended mainly on the elastic strain energy stored inside the bent tube wall during the deformation process. The greater the elastic strain energy stored in the tube wall, the larger the spring-back angle after the tube bending. Bending with mandrel weakened the elastic strain energy, resulting in a smaller spring-back angle.

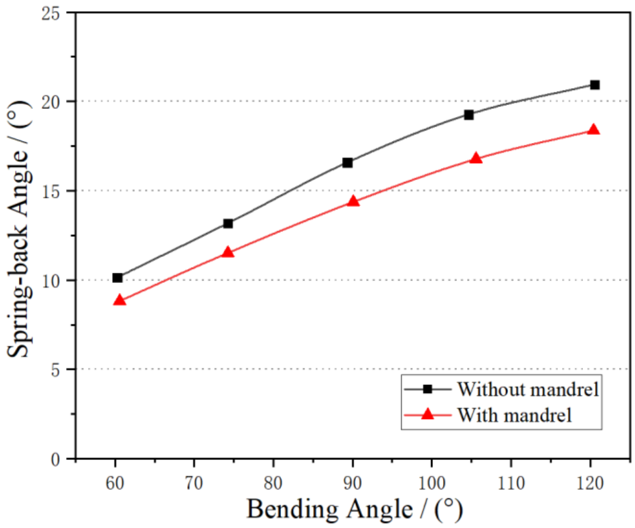

Figure 7. Spring-back angle versus bending angle curve of magnesium alloy tube.

4. Conclusion

The rotary draw bending of the extruded tube of magnesium alloy was presented. At room temperature, the tubes were bent without cracking and wrinkling, but the shape distortions were inevitable. The shape and dimension precisions of bent tubes were analyzed, including the diameter change rate, the tube wall thinning and thickening rate and the spring-back angle. The influences of the mandrel on the shape distortion were analyzed. The main conclusions drawn were as follows.

(1) The extruded magnesium alloy tubes were bent at room temperature, and the favorable surface and geometrical quality were obtained. The present bending experiment further validates the good workability of the newly developed magnesium alloy with rare earth addition.

(2) The largest distortion occurred in the position approximate 30° far from clamp die. The mandrel played an important role in weakening cross-sectional distortion of the bent tube. The diameter change rate decreased with increasing distance (angle) from the clamping tube end.

(3) The middle section of the tube elbow was more thinned than both ends of the tube. The maximum thickening appeared at the extrados and the maximum thinning at the intrados. The bending without mandrel reduced the tube wall thinning at the extrados.

(4) The spring-back angle increased approximately linearly as the bending angle increased. Bending with mandrel weakened the elastic strain energy, resulting in a smaller spring-back angle.

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