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Springback characteristics of AZ31 magnesium alloy as-extruded profile in warm tension-rotation bending process

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Abstract: The warm tension-rotation bending process of AZ31 magnesium alloy as-extruded profile with thin-walled and multi-rib was researched by numerical and experimental methods. The effects of process parameters on springback characteristics of AZ31 bent profile were investigated. The results indicate that when the forming temperature increases from 100 °C to 200 °C, the numerical and experimental springback angles of AZ31 bent profile all decrease, the experimental springback angle decreases from 11.6° to 10.7°, and the springback ratio reduces from 11.26% to 10.39%. The relationship between the forming temperature and the springback angle seems to be linear. When the bending angle increases from 100° to 110°, the numerical and experimental springback angles of AZ31 bent profile all increase, the experimental springback angle increases from 10.8° to 11.5°, and the springback ratio increases from 10.48% to 11.16%. When the pre-tension amount increases from 0.2% to 1.1%, the numerical and experimental springback angles of AZ31 bent profile all decrease, the experimental springback angle decreases from 12.5° to 9.8°, and the springback ratio decreases from 12.14% to 9.51%.

Key words: AZ31 magnesium alloy; as-extruded profile; tension-rotation bending; numerical simulation; springback

1 Introduction

Magnesium alloys have been widely used in automobile and aerospace industries due to their low density, superior specific stiffness and strength, and recycleability. They are often bent to appearance with certain curvature in order to improve the aerodynamic performance. There are many research works about the bending of the Mg alloy sheet and tube. KUO and LIN [1] investigated the effect of process parameters on the springback of L-bending through simulation and experiments for AZ31 sheets at various temperatures by using the Taguchi method. KIM et al [2] experimentally investigated the effect of annealing treatment on the springback and microstructure evolution for AZ31 sheets by using the V-shaped air bending tests. QUAN et al [3] investigated the formability of AZ31B sheets in multi-point bending process. HAMA et al [4] investigated the springback characteristics and microstructure evolution of the AZ31B sheets at various temperatures and blank holding forces by two-dimensional draw-bending test. GAO et al [5] examined the bending property of the AZ31B sheets by V-bend test and investigated the springback and microstructure at various temperatures. LEE et al [6] investigated the springback prediction of AZ31B sheets by the developed constitutive model and verified the developed model by using the unconstrained cylindrical bending test and 2D draw bend test. PALUMBO et al [7, 8] investigated the process parameters on the springback of AZ31 sheets in stretch-bending test by experimental and numerical methods. KIM et al [9] investigated the forming limit curve and springback characteristics of AZ31B sheets under various forming conditions. LEE et al [10] investigated the process conditions on the springback of AZ31B sheets in the draw bend test. BRUNI et al [11] investigated the process parameters on the springback of AZ31 sheets in the air bending tests under various forming conditions. CHEN and CHANG [12] investigated the formability of stamping AZ31 sheets and springback in V-bend test. ZHANG et al [13] developed

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the bidirectional cyclic in-plane bending process of AZ31 sheets and investigated the deformed and subsequent annealed microstructures. HUANG et al [14−16] developed the repeated unidirectional bending process of AZ31B sheets and studied the effects of process parameters on the tensile properties, formability of stamping, microstructure and texture of AZ31B sheets. LUO et al [17] investigated the bendability and microstructure of AZ31 tubes at various temperatures. WU et al [18−20] studied the influences of formation conditions on the ovality, wall-thinning and springback of AM30 tubes. They also investigated the bending mechanisms and microstructure evolution of AZ31 tubes in the rotary draw bending process.

However, up to now, rare study can be found on the Mg alloy profiles in bending process. In this work, the springback characteristics of AZ31 profile in warm tension-rotation bending process were investigated. The bending experiments of AZ31 profile were carried out under various forming conditions. And a 3D thermo-mechanically coupled finite element model was established to simulate the bending process. The effects of the forming temperature, bending angle and pre-tension amount on the springback angle of the profile were studied.

2 Experimental

2.1 Experimental principle

Figure 1 shows the principle of the tension-rotation bending process. As shown in Fig. 1, firstly, one end of the profile is fixed on the clamp die, while the other end is clamped on stretching die. Secondly, the profile is heated and held. Thirdly, the axial stretching force F is applied by stretching die to change the stress of the profile. Fourthly, side pressure p is exerted by movable die to make the profile lean on the bending die. Fifthly, the movable die is rotated to make the profile bent, while the bending die is fixed. Finally, while the profile is bent to the desired angle, the dies are removed, and the bent profile is acquired. The advantages of this process are the stretching force, the side pressure and the rotary movable die. The stretching force can reduce the springback of the profile and residual stress after bending. The side pressure can increase the hydrostatic pressure to enhance the plasticity of the profile. The rotary movable die can restrict the cross-section distortion of the profile.

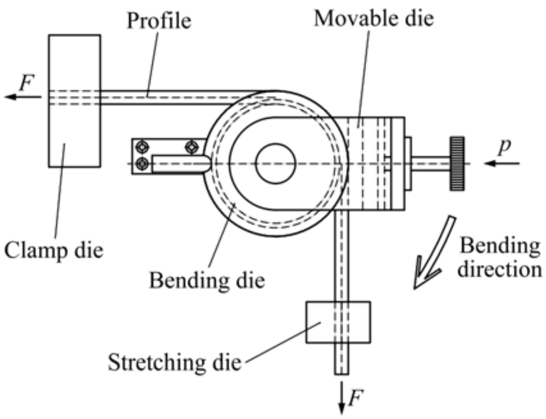

Fig. 1 Scheme of tension-rotation bending process

2.2 Experimental material

The material used in this work was AZ31 magnesium alloy as-extruded profile. The extrusion conditions were set as follows: billets and dies were heated up to 400 °C and 360 °C, respectively, and the extrusion velocity was 60 mm/s. The chemical composition of AZ31 magnesium alloy as-extruded profile is listed in Table 1. The cross-section and geometric dimensions of the profile are shown in Fig. 2.

Table 1 Chemical composition of AZ31 magnesium alloy (mass fraction, %)

Al	Zn	Mn	Si	Fe	Mg
3.07	0.80	0.36	0.01	<0.002	Bal.

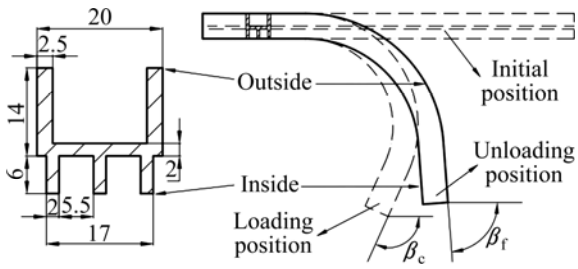

Fig. 2 Cross-section and geometric dimensions of springback (Unit: mm)

2.3 Experimental method

The bending conditions were set as follows: firstly, the profiles were heated up to different temperatures t ranging from 100 °C to 200 °C. Then, they were stretched to different pre-tension amounts δ (It was defined by the ratio of the tensile amount Δl to the initial length of the profile l_0, δ=100$\Delta l/l_0$) from 0.2% to 1.1%. Thirdly, they were bent to different angles β_c from 100° to 110°, while inner bent radius was 84 mm and the rotary speed of the movable die was 0.3 rad/s. Finally, the bent profiles were obtained. Table 2 lists the bending process parameters.

In order to examine the effect of process parameters on the springback of the profile, the springback angle $\Delta\beta$ is defined by the difference between the loading bending angle β_c and final bending angle β_f($\Delta\beta=\beta_c-\beta_f$), which can be seen from Fig. 2. The springback ratio is defined by the ratio of springback angle to the loading bending angle.

Table 2 Process parameters during bending process

Parameter	Value
Forming temperature, t/°C	100, 120, 140, 160, 180, 200
Bending angle, δ/°	100, 103, 105, 107, 110
Pre-tension amount, β_c/%	0.2, 0.4, 0.7, 0.9, 1.1

3 Finite element modeling

The finite element modeling of the profile in bending process includes the following contents: material properties, tool and die geometries, and boundary conditions. In this work, a commercially available implicit finite element code, MSC.Marc, was used to predict the bending behaviour of the profile.

3.1 Material properties

To obtain the mechanical properties of the profile, a uniaxial tensile material test was performed at various temperatures (ranging from room temperature to 220 °C) and a strain rate of 0.001 s^{-1}. Figure 3 shows the true stress—true strain curves of AZ31 magnesium alloy as-extruded profile at various temperatures. It can be seen that with increasing temperature, the curves go down and the elongation increases.

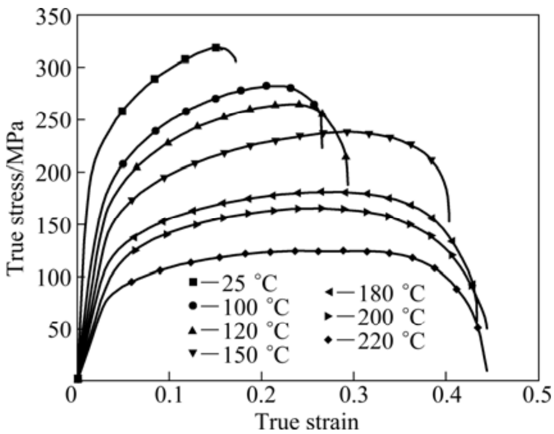

Fig. 3 True stress—true strain curves at strain rate of 0.001 s^{-1} and different temperatures

3.2 Finite element model

A 3D thermo-mechanically coupled finite element model of the bending is shown in Fig. 4. The profile was modelled with the half geometry due to the symmetry. All dies were represented as rigid bodies. An isotropic, homogeneous, thermo-mechanically coupled elastic-plastic material following the von Mises yield criterion was the material model. The large strain and updated Lagrange procedure was adopted due to the large deformation of the bending process. The Full Newton-Raphson iterative procedure was chosen to solve the iteration process and non-linear equations of motion. The other simulation parameters are listed in Table 3.

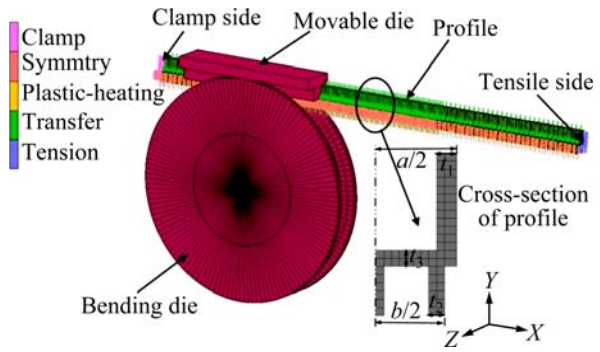

Fig. 4 3D thermo-mechanically coupled finite element model of bending process

Table 3 Simulation parameters used in finite element model

Density/ $(g \cdot cm^{-3})$	Elastic modulus/GPa	Poisson ratio	Interface heat transfer coefficient/ $(N \cdot s^{-1} \cdot K^{-1} \cdot mm^{-1})$
1.77	44.8	0.35	4.5

3.3 Boundary conditions

The boundary conditions include initial condition and boundary condition. The initial condition is the forming temperature of the profile. Four kinds of boundary conditions are clamp constrain, symmetry constrain, thermal constrain, and tension constrain, which are shown in Fig. 4.

4 Results and discussion

4.1 Surface quality of AZ31 bent profile

The AZ31 as-extruded profiles after bending are shown in Fig. 5. It can be seen that no obvious forming defects including crack or wrinkling occur during the bending process. The surface quality of the bent profile is good. This indicates that the AZ31 profile with high surface quality can be obtained by using the warm tension-rotation bending process.

Fig. 5 AZ31 as-extruded profiles after bending

4.2 Effect of forming temperature on springback angle

For a given bending angle of 103° and pre-tension amount of 0.7%, the effect of the forming temperature on the springback angle is shown in Fig. 6. It can be seen from Fig. 6 that, with the forming temperature increasing, the springback angle decreases. The finite element simulation results have the same tendency with the experiment results, while the former is a little smaller than the latter. When the forming temperature increases from 100 °C to 200 °C the experimental springback angle decreases from 11.6° to 10.7°. The relationship between the forming temperature and the springback angle seems to be linear and the following equation is obtained by using least square method:

$$\Delta\beta=12.6-0.01t \quad (1)$$

where $\Delta\beta$ is the springback angle, and t is the forming temperature.

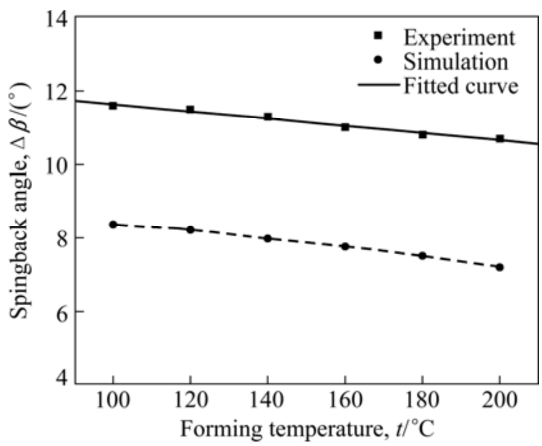

Fig. 6 Effect of forming temperature on springback angle

Figure 7 shows the relationship between the forming temperature and the springback ratio. With the forming temperature increasing from 100 °C to 200 °C, the springback ratio reduces from 11.26% to 10.39%.

With the forming temperature increasing, the flow stress and yield stress of the profile decrease, so the elastic energy decreases with temperature increasing at the same bending angle, which causes the decrease of the springback angle and springback ratio.

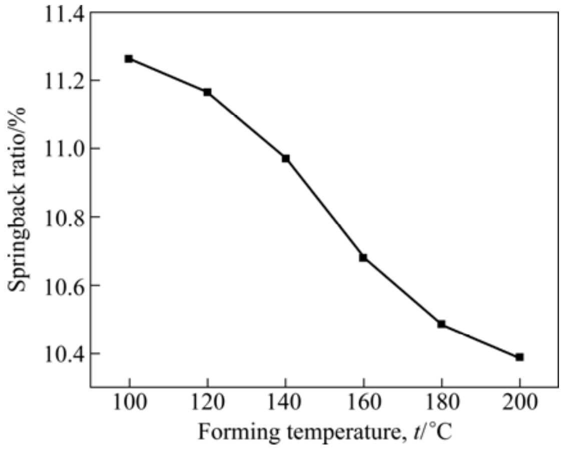

Fig. 7 Effect of forming temperature on springback ratio

4.3 Effect of bending angle on springback angle

Figure 8 shows the curves of bending angle and springback angle of the profile at forming temperature 160 °C and pre-tension amount 0.7%. With the bending angle increasing, the springback angle increases. Finite element simulation results have the same tendency with the experiment results, while the former is a little smaller than the latter.

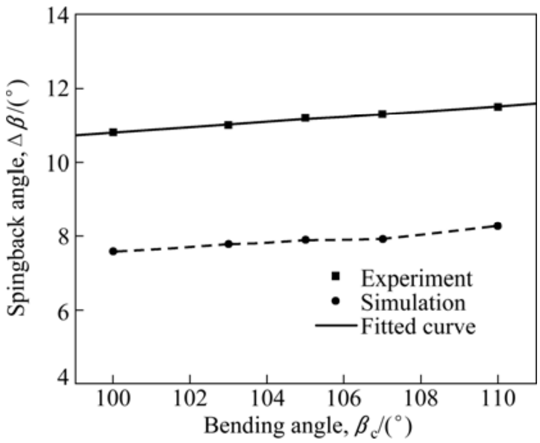

Fig. 8 Effect of bending angle on springback angle

When the bending angles increase from 100° to 110° the experimental springback angle increases from 10.8° to 11.5°. The relationship between the bending angle and the springback angle seems to be linear and the following equation is obtained by using least square method:

$$\Delta\beta=3.74+0.07\beta_c \quad (2)$$

where $\Delta\beta$ is the springback angel, and β_c is the bending angle before springback.

Figure 9 shows the relationship between the bending angle and the springback ratio. With the bending angle increasing from 100° to 110°, the springback ratio increases from 10.48% to 11.16%.

With bending angle increasing, the deformation area and the bending moment increase, so the elastic energy increases, which causes the increase of the springback angle and springback ratio.

4.4 Effect of pre-tension amount on springbak angle

For a given forming temperature of 160 °C and bending angle of 103°, the effect of the pre-tension amount on the springback angle is shown in Fig. 10. The springback decreases with pre-tension amount increasing. The finite element simulation results have the same tendency with the experiment results, while the former is a little smaller than the latter.

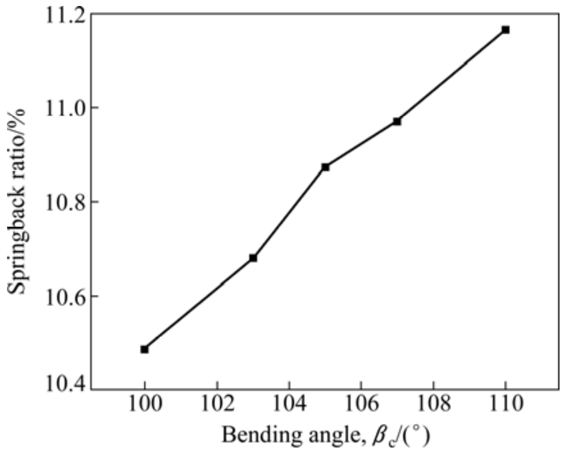

Fig. 9 Effect of bending angle on springback ratio

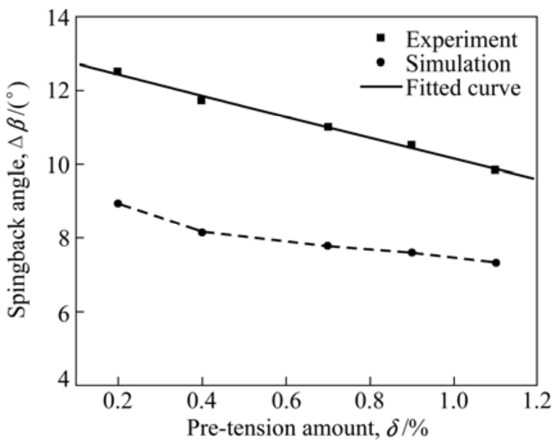

Fig. 10 Effect of pre-tension amount on springback angle

When the pre-tension amount increases from 0.2% to 1.1% the experimental springback angle decreases from 12.5° to 9.8°. The relationship between the pre-tension amount and the springback angle seems to be linear and the following equation is obtained by using least square method:

$$\Delta\beta=12.98-2.86\delta \quad (3)$$

where $\Delta\beta$ is the springback angle, and δ is the pre-tension amount.

The curve of pre-tension amount and springback ratio of the profile is shown in Fig. 11. When the pre-tension amount increases from 0.2% to 1.1% the springback ratio decreases from 12.14% to 9.51%.

With pre-tension amount increasing, the stress distribution of profile is changed, the compression stress of the inside of profile decreases, which causes the decrease of springback angle and springback ratio.

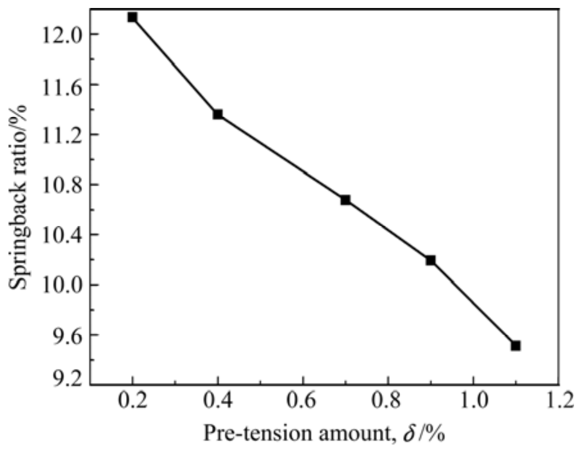

Fig. 11 Effect of pre-tension amount on springback ratio

5 Conclusions

1) The AZ31 bent profile with high surface quality can be obtained by using the warm tension-rotation bending process.

2) With the forming temperature increasing from 100 °C to 200 °C, the numerical and experimental springback angles of AZ31 bent profile all decrease, the experimental springback angle decreases from 11.6° to 10.7°, and the springback ratio reduces from 11.26% to 10.39%. The relationship between the forming temperature and springback angle seems to be linear.

3) With bending angle increasing from 100° to 110°, the numerical and experimental springback angles of AZ31 bent profile all increase, the experimental springback angle increases from 10.8° to 11.5°, and the springback ratio increases from 10.48% to 11.16%.

4) With pre-tension amount increasing from 0.2% to 1.1%, the numerical and experimental springback angles of AZ31 bent profile all decrease, the experimental springback angle decreases from 12.5° to 9.8°, and the springback ratio decreases from 12.14% to 9.51%.

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References

[1] KUO C C, LIN B T. Optimization of springback for AZ31 magnesium alloy sheets in the L-bending process based on the Taguchi method [J]. International Journal of Advanced Manufacturing Technology, 2012, 58(1−4): 161−173.

[2] KIM D, KIM J H, LEE M G, LEE Y S, KANG S H. Experimental investigation into effect of annealing treatment on springback of magnesium alloy sheets [J]. Materials Research Innovations, 2011,

151: s183−s186.

[3] QUAN G Z, KU T W, KANG B S. Improvement of formability for multi-point bending process of AZ31B sheet material using elastic cushion [J]. International Journal of Precision Engineering and Manufacturing, 2011, 12(6): 1023−1030.

[4] HAMA T, KARIYAZAKI Y, OCHI K, FUJIMOTO H, TAKUDA H. Springback characteristics of magnesium alloy sheet AZ31B in draw-bending [J]. Materials Transactions, 2010, 51(4): 685−693.

[5] GAO J, YUE Z, RUAN L. Temperature influences on springback of AZ31 sheet [J]. Advanced Materials Research, 2010, 102−104: 484−487.

[6] LEE M G, KIM S J, WAGONER R H, CHUNG K, KIM H Y. Constitutive modeling for anisotropic/asymmetric hardening behavior of magnesium alloy sheets: Application to sheet springback [J]. International Journal of Plasticity, 2009, 25(1): 70−104.

[7] PALUMBO G, SORGENTE D, TRICARICO L. Tangential bending and stretching of thin magnesium alloy sheets in warm conditions [J]. Materials & Design, 2009, 30(3): 653−660.

[8] PALUMBO G, SORGENTE D, TRICARICO L. Numerical-experimental analysis of thin magnesium alloy stripes subjected to stretch-bending [J]. Journal of Materials Processing Technology, 2008, 201(1−3): 183−188.

[9] KIM H J, CHOI S C, LEE K T, KIM H Y. Experimental determination of forming limit diagram and springback characteristics of AZ31B Mg alloy sheets at elevated temperatures [J]. Materials Transactions, 2008, 49(5): 1112−1119.

[10] LEE M G, CHOI J G, KIM H Y, WAGONER R H, LEE J K. Experimental study of springback in draw bend test of AZ31B magnesium alloy sheet [J]. Advanced Materials Research, 2007, 389: 26−28.

[11] BRUNI C, FORCELLESE A, GABRIELLI F, SIMONCINI M. Air bending of AZ31 magnesium alloy in warm and hot forming conditions [J]. Journal of Materials Processing Technology, 2006, 177(1−3): 373−376.

[12] CHEN F K, CHANG C K. Formability of stamping magnesium alloy AZ31 sheets [J]. Journal of Materials Processing Technology, 2003, 142(3): 643−647.

[13] ZHANG Lei, YANG Xu-yue, HUO Qing-huan, TIAN Fang, ZHANG Yu-jing, ZHOU Xiao-jie, CHEN Jia. Structure evolution of AZ31 Mg alloy sheet during bidirectional cyclic bending at low temperature and subsequent annealing [J]. Acta Metallurgica Sinica, 2011, 47(8): 990−996. (in Chinese)

[14] HUANG Guang-sheng, LI Hong-cheng, SONG Bo, ZHANG Lei. Tensile properties and microstructure of AZ31B magnesium alloy sheet processed by repeated unidirectional bending [J]. Transactions of Nonferrous Metals Society of China, 2010, 20(1): 28−33.

[15] HUANG Guang-sheng, SONG Bo, XU Wei, ZHANG Lei. Structure and properties of AZ31B magnesium alloy sheets processed by repeatedly unidirectional bending at different temperatures [J]. Transactions of Nonferrous Metals Society of China, 2010, 20(10): 1815−1821.

[16] ZHANG Hua, HUANG Guang-sheng, SONG Bo, ZHANG Lei, KONG De-qiang. Influence of microstructure and texture on formability of AZ31B magnesium alloy sheets [J]. Transactions of Nonferrous Metals Society of China, 2011, 21(4): 844−850.

[17] LUO A A, SACHDEV A K, MISHRA R K, KUBIC R C. Bendability and microstructure of magnesium alloy tubes at room and elevated temperatures [C]// Magnesium Technology. Warrendale: The Mineral, Metal and Materials Society, 2005: 145−148.

[18] WU W Y, ZHANG P, ZENG X Q, JIN L, YAO S S, LUO A A. Bendability of the wrought magnesium alloy AM30 tubes using a rotary draw bender [J]. Materials Science and Engineering A, 2008, 486(1−2): 596−601.

[19] WU W Y, JIN L, DONG J, PENG L M, YAO S S. Bending mechanisms in AM30 alloy tube using a rotary draw bender [J]. Materials and Manufacturing Processes, 2010, 25(12): 1359−1364.

[20] JIN L, DONG J, LUO A A, MISHRA R K, SACHDEV A K, WU W Y. Microstructure evolution of Mg−3%Al−1%Zn alloy tube during warm bending [J]. Journal of Materials Science, 2012, 47(8): 3801−3807.

AZ31 镁合金挤压型材温热张力绕弯成形过程中的回弹特征

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摘 要：采用数值模拟和实验方法研究薄壁、多筋 AZ31 镁合金挤压型材的温热张力绕弯成形工艺，分析工艺参数对 AZ31 弯曲型材回弹特征的影响。结果表明：当成形温度由 100 ℃升高至 200 ℃时，AZ31 镁合金型材弯曲件回弹角的实验值和模拟值均减小，实验回弹角由 11.6°降低至 10.7°，回弹率由 11.26%降低至 10.39%，回弹角与成形温度的关系近似为线性关系。当弯曲角由 100°增加至 110°时，AZ31 镁合金型材弯曲件回弹角的实验值和模拟值都增加，实验回弹角由 10.8°增加至 11.5°，回弹率由 10.48%增加至 11.16%。当预拉伸量由 0.2%增加至 1.1%时，AZ31 镁合金型材弯曲件回弹角的实验值和模拟值都减小，实验回弹角由 12.5 °降低至 9.8 °，回弹率由 12.14%降低至 9.51%。

关键词：AZ31 镁合金；挤压型材；张力绕弯；数值模拟；回弹

(Edited by CHEN Wei-ping)