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Warm hydroforming of magnesium alloy tube with large expansion ratio

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Abstract: Process of warm tube hydroforming was experimentally investigated for forming an AZ31B magnesium alloy tubular part with a large expansion ratio. Effects of temperature on the mechanical properties and formability were studied by uniaxial tensile test and hydraulic bulge test. Total elongation increases with temperature up to 250 °C, but uniform elongation and maximum expansion ratio get the highest value at 175 °C. Different axial feeding amounts were applied in experiments to determine the reasonable loading path. A preform with useful wrinkles was then realized and the tubular part with an expansion ratio of 50% was formed. Finally, mechanical condition to produce useful wrinkles is deduced and the result illustrates that useful wrinkles are easier to be obtained for tube with higher strain hardening coefficient value and tubular part with smaller expansion ratio.
Key words: warm hydroforming; magnesium alloy; tube; expansion ratio; hydraulic bulge test; wrinkle

1 Introduction

As the lightest metal material in common use, more and more magnesium alloy sheets and tubes have been applied in automotive and aircraft industries to meet the demand of fuel saving[1]. However, their applications are often restricted due to their poor formability at room temperature[2]. To solve this problem, hydroforming at an elevated temperature, or called warm tube hydroforming, becomes more and more attractive[3−4].

In the past decade, some investigations have been reported on warm hydroforming of magnesium alloy sheets[5]. Usually, formability of the magnesium alloy sheets is improved with increasing temperature at a proper strain rate (usually lower than 10^{-3} s^{-1})[6]. However, if magnesium tube is formed at elevated temperatures and higher strain rate (higher than 10^{-2} s^{-1}), the formability cannot be improved with temperature monotonously[7]. Poor formability limits the application of tube hydroforming of magnesium alloy[8]. Obviously, a process with relatively high strain rate and low temperature has the advantages of high productivity and low energy consumption.

Some efforts were made for AZ31B magnesium alloy tubes extruded over spider dies and it was found that the formability of the tubes could not be improved from 200 °C to 400 °C and burst usually occurred at the seams[9]. The other way to improve formability is to change the mechanical condition of the deforming material, combined with proper temperature and strain rate[10]. Using wrinkled part as a preform for this method has been proved for many tube hydroforming cases[11−12].

The present work is purposed on finding the proper forming temperature range of an AZ31B magnesium alloy tube and a reasonable loading path to realize relatively ideal mechanical condition. Limited by the thermal resistance of available oil medium, the highest temperature of hydroforming is only about 280 °C, though theoretically the temperature up to 330 °C is possible[13]. Therefore, only the formability below 250 °C is applied, and as an example, the process to form a tubular part with 50% expansion ratio is experimentally investigated and analyzed.

2 Determination of forming temperature

The outside diameter and wall thickness of the original tube blank are 44 mm and 1.8 mm, respectively. The chemical composition of the tube material is shown in Table 1. The reasonable forming temperature is determined by the uniaxial tension test and hydraulic bulge test. Tests were carried out at 20, 150, 175, 225 and 250 °C, respectively.

Tensile samples were cut off along the axial

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Table 1 Chemical composition of AZ31B alloy (mass fraction, %)

Al	Zn	Mn	Ca	Si	Mg
2.72	0.86	0.21	<0.001	0.016	Bal.

direction of the tube and tested with a strain rate of 0.01 s^{-1}. Fig.1 shows the true stress−true strain curves and elongations at different temperatures. From Fig.1(a), it can be seen that the yielding strength and tensile strength decrease as temperature increases, while the total strain increases. Fig.1 also reveals that the strain corresponding to the tensile strength decreases when temperature changes from 175 °C to 250 °C, while the softening parts of the stress−strain curves extend with temperature. This means that non-uniform deformation starts earlier at higher temperature.

Defining the elongation corresponding to the tensile strength as uniform elongation, the uniform elongation and the total elongation at different temperatures can be drawn as curves in Fig.1(b). It can be seen that below 175 °C, the uniform elongation increases with temperature, but above 175 °C, it decreases with increasing temperature. Non-uniform elongation will

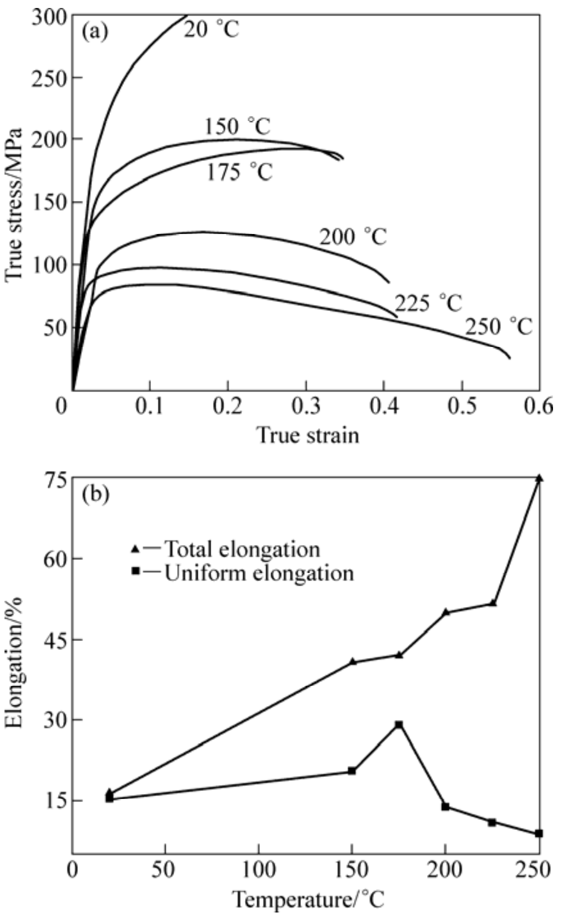

Fig.1 True stress−true strain curves and elongations determined by tensile tests at strain rate of 0.01 s^{-1}: (a) True stress−true strain curve; (b) Elongation

induce unstable local deformation and affect the thickness uniformity of a formed part. Therefore, in view of controlling thickness uniformity of the process at a high strain rate, 175 °C might be a reasonable forming temperature. For further confirmation, the hydraulic bulge tests were conducted.

The length of the bulging zone is 66 mm, about 1.5*d*. The hydraulic bulge tests were conducted with a speed of 6 MPa/min. Maximum expansion ratio (MER) η is defined as

$$\eta = \frac{D-d}{d} \times 100\% \tag{1}$$

where D is the maximum outer diameter of the tube and d is the initial outer diameter of the tube.

Fig.2 shows the bulging results and MERs at different temperatures. It can be seen that the MER

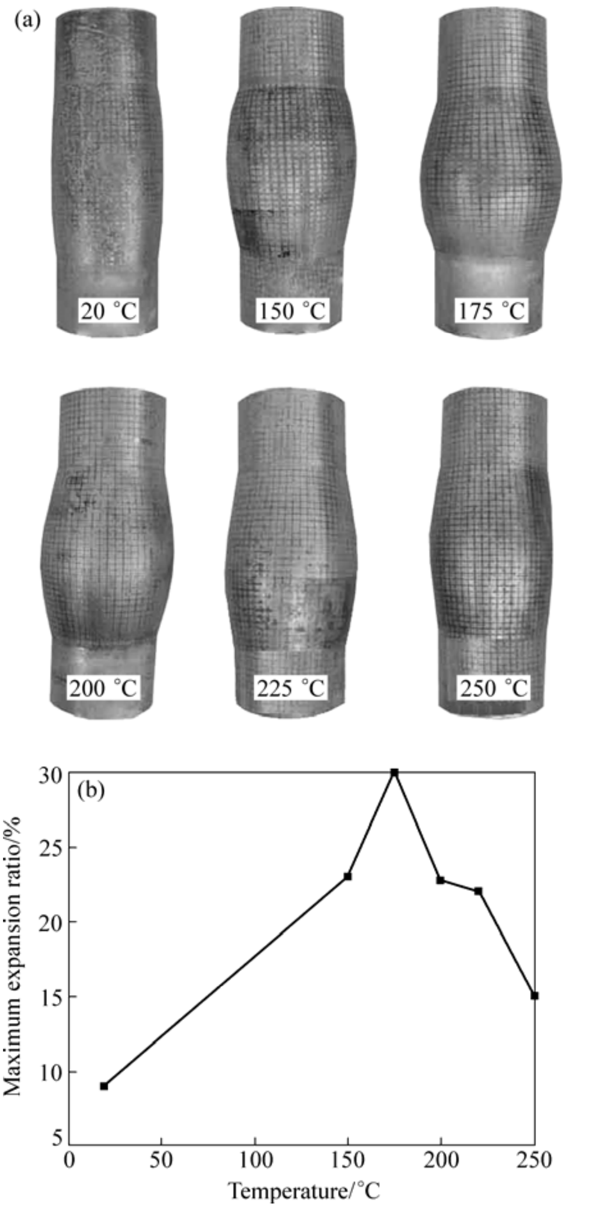

Fig.2 Hydraulic bulge test results (a) and MER (b) at different temperatures

follows the similar rule as same as the uniform elongation shown in Fig.1(b). The maximum MER is 30%, which appears at 175 °C. Therefore, the best temperature for forming the magnesium alloy tubular part below 250 °C can be confirmed to be 175 °C.

3 Warm tube hydroforming

3.1 Geometry of tubular part

Though the MER got from the hydraulic bulge tests is only 30%, for verifying how the axial feeding and the preform affect the expansion ratio, a tubular part with an expansion ratio of 50% was designed and tried to produce through warm hydroforming. The shape and dimensions of the tubular part are shown in Fig.3. The diameter at the two ends of the tubular part is 44 mm, while the diameter in the forming zone is 66 mm.

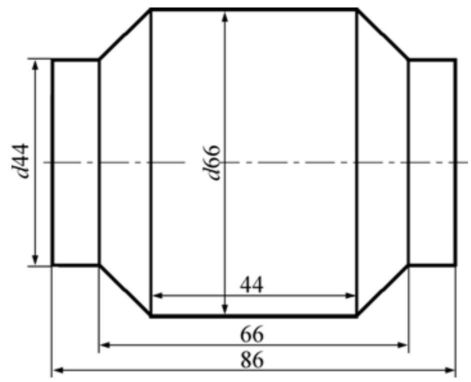

Fig.3 Scheme of tubular part (unit: mm)

3.2 Experiments

Experiments were conducted using the warm hydroforming system developed by Harbin Institute of Technology (HIT), China. A special oil is adopted in the system as heating and pressurizing medium with the highest temperature up to 300 °C. The built-in pressure intensifier can generate pressure up to 100 MPa. The principle of the experimental setup is shown in Fig.4. Die temperature is elevated by the heaters embedded in the die and controlled by a PID device.

According to the unit-axial tension test and hydraulic bulge test, 175 °C is chosen as the forming temperature. Therefore, tube was firstly heated to 175 °C indirectly by the dies and the injected hot oil. Then, it is kept at 175 °C for 2 min, which makes the temperature field stable. After that, tubes were hydroformed with three different loading paths as shown in Fig.5, respectively. The internal pressure is kept constant during feeding. After feeding is finished, internal pressure is enhanced to 40 MPa for final calibration.

Fig.6 shows the experimental results. For the case with loading path L1, the axial feeding was not enough. The middle of the forming zone did not supplied with

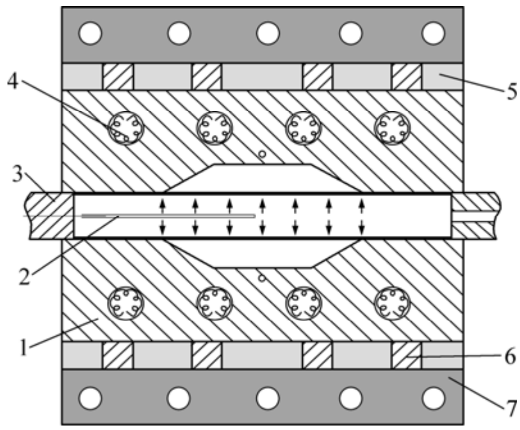

Fig.4 Principle diagram of experimental setup: 1—Die; 2—Thermal couple; 3—Punch; 4—Heating element; 5—Thermal isolator; 6—Cushion; 7—Water cooling plate

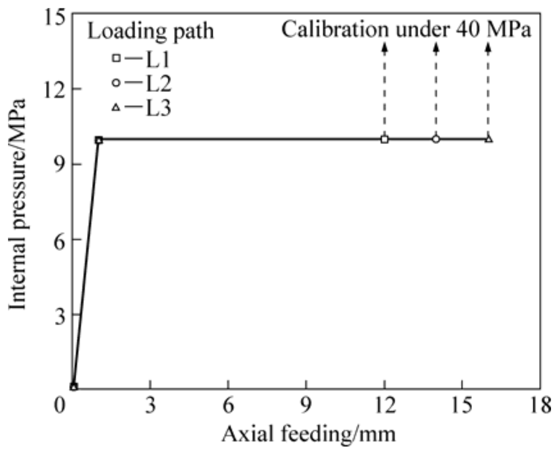

Fig.5 Loading paths for forming part with expansion ratio of 50%

enough material during the calibration so that excessive thinning and cracking occurred, as shown in Fig.6(a). For the case with loading path L3, the axial feeding was excessive so that wrinkles appeared and could not be flattened, as shown in Fig.6(b).

A sound part with expansion ratio of 50% was successfully formed with loading path L2, as shown in Fig.6(c). Fig.7 shows the thinning ratio distribution along the axial direction of the successful part. Thickness at the feeding zone is larger than that at other positions. In the forming zone, the thickness is not uniform. The maximum thinning ratio is 17.4%, which satisfies the practical demand. Actually, the successful part was formed from the preform with useful wrinkles as shown in Fig.8. How to get the useful wrinkle is the key to form the part with large expansion ratio.

3.3 Mechanical condition for useful wrinkles

According to Ref.[14], wrinkles were classified as bursting wrinkles, dead wrinkles and useful wrinkles for

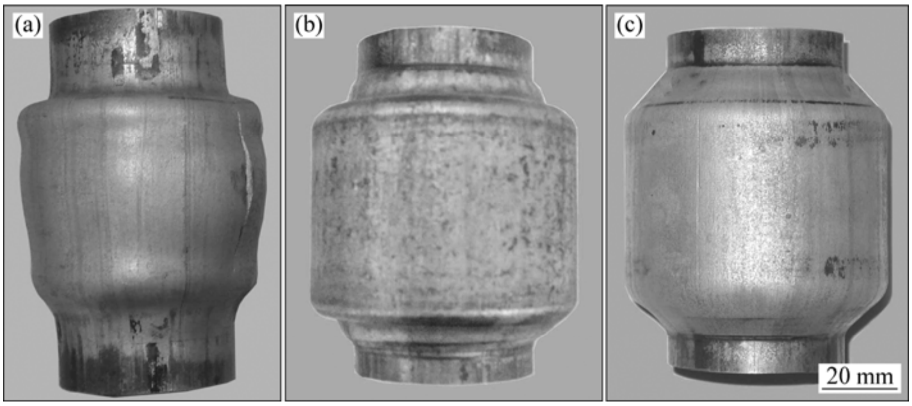

Fig.6 Experimental results under different loading paths: (a) Bursting; (b) Dead wrinkles; (c) Successful part

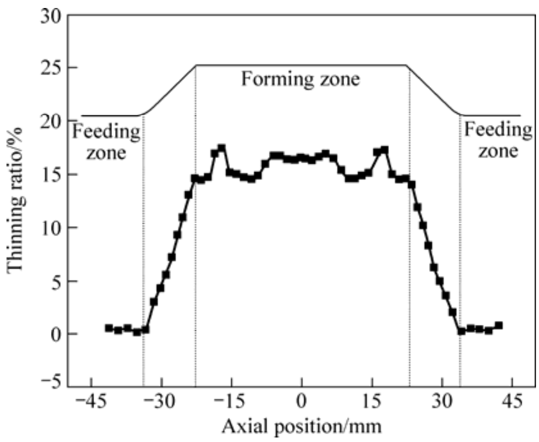

Fig.7 Thickness distribution of final part

Fig.8 Preform with useful wrinkles

forming a tubular part with large expansion ratio. Useful wrinkles should meet both the stress condition and the geometrical condition. The mechanical condition was expressed as the one that the axial strain should be negative to avoid serious thickness reduction and bursting. The geometrical condition was expressed as the one that the surface area of the wrinkled tube blank should be a little smaller than that of the part to be formed.

For the case with loading path L3, surface area of the wrinkled tube was greater than that of the tubular part, which induced dead wrinkles. However, for paths L1 and L2, the mechanical conditions were not explicit because the axial strain was impossible to be measured during the forming process. Therefore, the mechanical condition should be more clearly derived for identifying the bursting wrinkles and the useful wrinkles.

Axial strain and circumferential strain are named as ε_z and ε_θ, respectively. The maximum expansion ratio of the final part is defined as η. Then, the circumferential strain ε_θ at the forming zone of the final part can be expressed as $\ln(1+\eta)$. Necking will occur when thickness strain reaches $-n$[15], where n is the strain hardening coefficient. Therefore, the axial strain ε_z at the forming zone of the final part should meet the following inequation so as to avoid necking:

$$\varepsilon_z < n - \ln(1+\eta) \tag{2}$$

According to the increment plastic theory, the plastic strain increments should meet Eq.(3):

$$\frac{\mathrm{d}\varepsilon_z}{\mathrm{d}\varepsilon_\theta} = \frac{2\alpha - 1}{2 - \alpha} \tag{3}$$

where α is the ratio of the axial stress to the circumferential stress during the final calibration. Therefore, the mechanical condition is that the axial strain ε'_z at the top zone of the wrinkles for the useful wrinkles should meet the condition expressed by Eq.(4):

$$\varepsilon'_z < n - \ln(1+\eta) - \ln\frac{(1+\eta)d}{D'}\frac{2\alpha - 1}{2 - \alpha} \tag{4}$$

where D' is the outer diameter at the top zone of the useful wrinkles.

The right part of Eq.(4) is named as the critical axial strain. Assuming that the stress ratio is α=1.0 and d/D' is 0.8, the curves of the critical axial strains versus η for different n values are shown in Fig.9. It can be seen that the absolute value of the critical axial strain decreases with increasing n value and decreasing η value. The smaller the absolute value of the critical axial strain, the easier the useful wrinkles can be produced. Therefore, useful wrinkles are apt to be formed for tube with higher n value, especially in the forming of a tubular part with smaller expansion ratio.

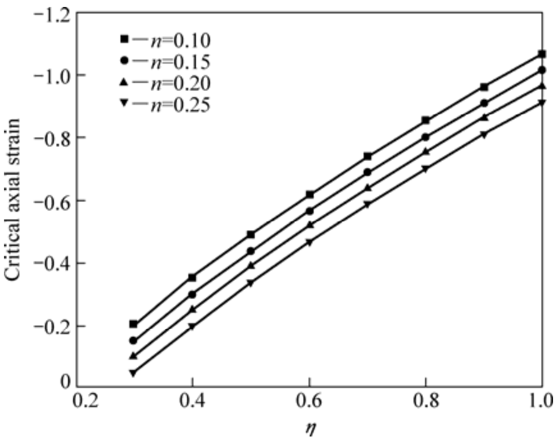

Fig.9 Critical axial strain versus η for different n values

4 Conclusions

1) At a certain quasi-static strain rate, if thickness uniformity is considered as the most important standard, the formability of an AZ31B magnesium alloy tube should be evaluated by the uniform elongation instead of the total elongation. Uniform elongation at 175 °C has the highest value when the tensile test was conducted at a strain rate of 0.01 s^{-1}.

2) Wrinkles with a certain shape and amount might be useful to increase the expansion ratio limit in warm tube hydroforming. The higher the strain hardening coefficient value of a material, the easier the useful wrinkles can be produced. If the expansion ratio of the tubular part is smaller, it is easier to obtain useful wrinkles.

3) Through forming a tubular part with an expansion ratio of 50%, the efficiency of warm hydroforming with useful wrinkle is verified. The most serious thinning is located at the top zone of the wrinkles and is limited to 17.4%.

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