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Hydroforming of AZ61A tubular component with various cross sections

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Abstract: The effects of temperature on the mechanical properties and elongation of AZ61A tubular part were derived by uni-axial tension tests at various temperatures. Warm hydroforming of an AZ61A tubular part for passenger car was then numerically and experimentally investigated. The complete processes including bending, pre-forming and hydroforming were analyzed and discussed. Microstructure at the corner of the typical section was observed before and after the final hydroforming process. It is shown that the yielding strength, tensile strength and total elongation increase as temperature increases, while the elongation before necking decreases. The temperature range from 225 ℃ to 250 ℃ is more suitable for hydroforming of the AZ61A magnesium alloy tube with various cross sections. Pre-forming and hydroforming with high strain values are feasible at elevated temperature. Grain refinement is observed at the corner of the part after warm hydroforming. Thinning ratio analysis illustrates that non-uniform deformation at elevated temperature should be considered in process optimization to avoid severe local thinning.

Key words: tube; hydroforming; magnesium alloy; cross section

1 Introduction

As an effective light weight manufacture technology with numerous advantages, such as mass reduction, parts consolidation, improved stiffness and lower cost, tube hydroforming was applied for almost twenty years in automotive industry[1−2].

Recently, new challenges on application of light metals were presented in order to reduce energy consumption and environmental pollution further. With a specific density of 1.75×10^3 kg/m^3, magnesium is almost 80% lighter than steel, which is undoubtedly the highlight for future vehicles. Potential applications of magnesium tubes include space frames, instrument panel beams, seats and window/sunroof frames, engine cradles and sub-frames[3]. However, the elongation of magnesium alloys is only about 15% at room temperature. Warm forming or forming at elevated temperature must be developed to form the complex components[4].

The hot rolling, warm extrusion and warm drawing were investigated on AZ31 and AZ61 magnesium alloys, respectively[5−8]. Warm hydroforming using oil and gas as pressure medium, was presented[9] and applied to formability testing of Mg-alloy tubes[10−11], such as forming of a demonstrator part with square cross section [12], an axle cross member[13] and tees[14]. Typical magnesium alloys such as AZ31, AZ80 and ZM21 were used and the good formability at proper temperatures was achieved. At the same time, the microstructure and the creep behavior of the magnesium alloy tube after hot gas forming were also investigated[15−16]. The highest temperature of 450 ℃ was used in hot gas forming and temperatures lower than 300 ℃ were used in warm oil forming.

However, the automotive components with curved axis and various cross-sections were not mentioned in current studies. In this study, hydroforming of AZ61A tube at elevated temperatures by using oil as hydro-mechanical medium will be studied. The objective is to investigate the process feasibility of warm hydroforming for a typical automotive component.

2 Shape of auto part and formability of AZ61A tube

With a curved axis and three different cross-sections, a tubular axle arm for a passenger car as shown in Fig.1 was selected as demonstration part for the warm

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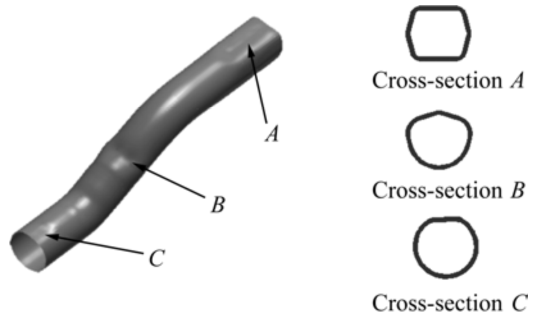


Fig.1 Back axle arm of passenger car

hydroforming of AZ61A. To form this part, main procedures of tube hydroforming, including bending, pre-forming and hydroforming are needed. According to the specifications of the tubular part, an AZ61A tube with diameter of 70 mm, thickness of 4 mm and length of 650 mm was selected.

Plastic deformation characteristics of the AZ61A tube at various temperatures were investigated at first. Tensile tests were carried out at different temperatures including 20, 225, 250, 275 and 300 ℃ at a strain rate of 0.01 s^{-1}. All the tension specimens were cut from the as-extruded tube along axial direction. Fig.2(a) shows the total elongation and elongation before necking at different temperatures. The total elongation increases from 16.8% at room temperature to 69.8% at 300 ℃, but the elongation before necking decreases from 16.8% at room temperature to 6.6% at 300 ℃. To form a component with relatively uniform deformation, the elongation before necking should not be too low. Therefore, the temperature range from 225 ℃ to 250 ℃ is more suitable for the hydroforming of the selected AZ61A tube.

Temperature has a considerable effect on yielding behavior and tensile strength. As shown in Fig.2(b), the yield strength decreases from 290 MPa at room temperature to 60 MPa at 300 ℃. That means that as temperature increases, the internal pressure for hydroforming can be lowered a lot with considerable formability improvement at the same time.

3 Simulations and experiments

To investigate the effect of temperature on the forming process, isothermal simulations for the whole process at different temperatures were carried out by using a commercial code LS-Dyna. In the FEM model, the tube was modeled as an isotropic material obeying Mises yielding criterion and was meshed by Belytschko-Tsay shell elements. The processes including bending, pre-forming and hydroforming were simulated

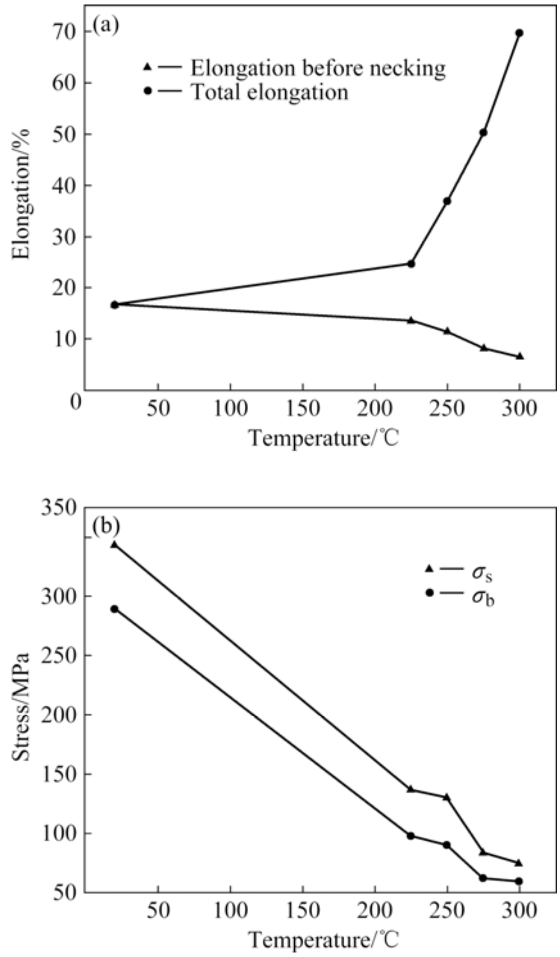


Fig.2 Elongation and strength of AZ61A tube at different temperatures: (a) Elongation; (b) Strength

continuously. Fig.3 shows the model for pre-forming and hydroforming after bending. The tested tensile stress-strain curves were input into the models directly. Coulomb friction model was applied to the interface between the tube and dies, and the friction coefficient of 0.1 was used.

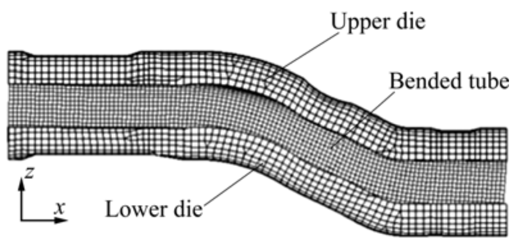


Fig.3 FEM model for simulation of pre-forming and hydroforming

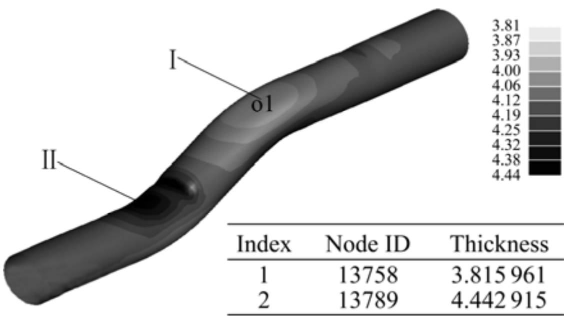
Experiments were also conducted at room temperature and 225 ℃, respectively. All the experiments were carried out on the bending machine and hydroforming press developed by Harbin Institute of Technology.

4 Results and discussion

4.1 Bending and pre-forming

The tubes were bent at room temperature. Fig.4 shows the thickness distribution after bending derived by simulation. The axial tensile stress is maximum at the outside of the bending position (Point I). Therefore, the wall thickness at Point Ⅰ is minimum with a value of 3.81 mm (thinning ratio of 4.8%). The axial compressive stress is maximum at the inner side of the bending position (point Ⅱ). Therefore, the wall thickness is maximum with a value of 4.44 mm at point Ⅱ.

As well known, pre-forming is a key procedure to assure the success of hydroforming. On the tubular part, cross-section A has the minimum radius and is the most difficult feature to form. Fig.5(a) shows the corner radius of cross-section A after pre-forming. It can be seen that smaller corner radius can be achieved as temperature increases. Fig.5(b) shows the effective strain distribution around the cross-section A after pre-forming. The maximum strain on the corner is 0.165, which indicates that the pre-forming process should be conducted at elevated temperature. Otherwise, the corner cracking might occur during the pre-forming. In Fig.6, the experimental results show that the cracking defect occurs at room temperature and the pre-forming succeeds without crack at 225 ℃.



Index	Node ID	Thickness
1	13758	3.815 961
2	13789	4.442 915

Fig.4 Simulated thickness distribution after bending

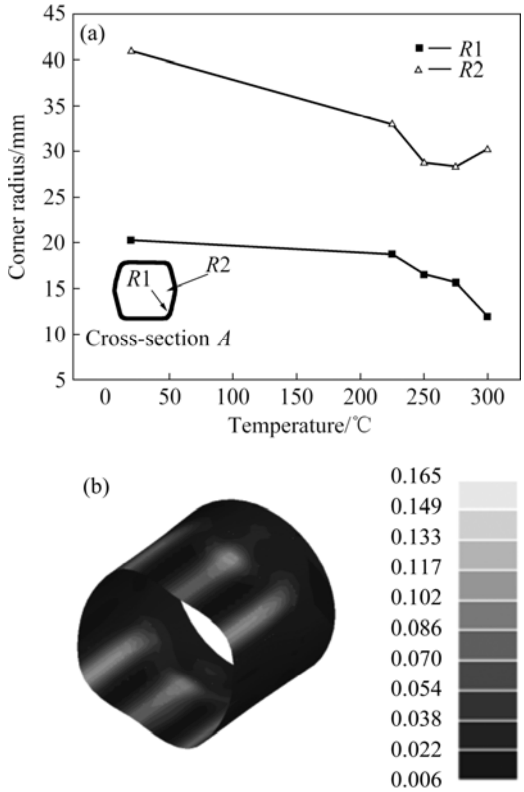


Fig.5 Simulated corner radii after pre-forming at different temperatures and effective strain: (a) Corner radii; (b) Effective strain at 225 ℃

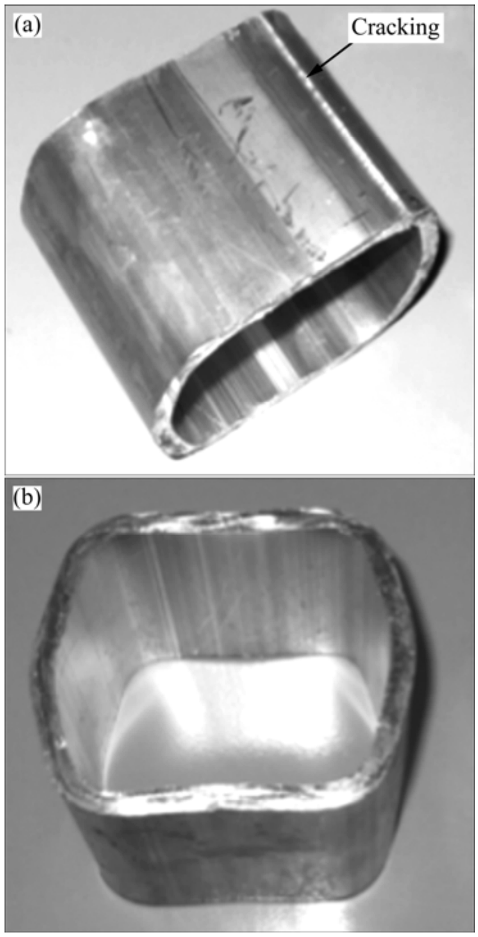


Fig.6 Pre-forming results of cross-section A: (a) Pre-forming at room temperature; (b) Pre-forming at 225 ℃

4.2 Hydroforming part

By using a heated hydroforming die, the pre-formed tubes were formed into the final shape as shown in Fig.7. The hydroforming process was conducted at 225 ℃ with internal pressure of 23 MPa. Fig.8 exhibits the longitudinal grain micro structures at the corner of cross-section A before and after forming. Twinning was absent during the whole forming process. Grain refinement was observed after hydroforming at 225 ℃, where deformation was accompanied by dynamic recrystallization.

Fig.7 Back axle arm formed by warm hydroforming

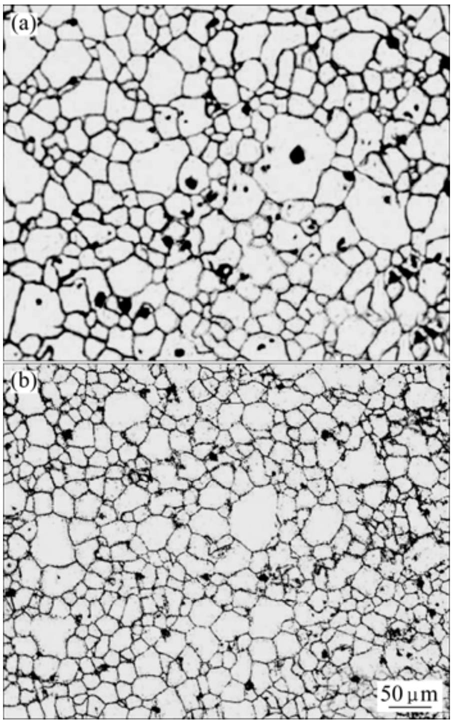


Fig.8 Microstructures at corner of cross-section *A* before and after deformation: (a) Tube blank; (b) Formed component

4.3 Thinning ratio distribution

Thinning ratio distribution was measured at typical points along the two intersecting curves between the longitudinal symmetrical plane and the tubular part surface, as shown in Fig.9.

It can be seen that the maximum thinning ratio appears at point 7′, which is about 14%. The thinning is an accumulated result from bending, performing and hydroforming, and mainly results in hydroforming. Fig.10 shows the stress states at points 4 and 7′ for the whole process in the strain state graph of the plane stress proposed by WANG[17]. σ_z and σ_θ represent the longitudinal stress and circumferential stress, respectively. It can be seen that the double tensile stress is observed at point 7′ during the whole process. Negative thickness strain increment can be then derived by the stress state at point 7′. Therefore, the tube wall at point 7′ decreases continuously from the bending process to the hydroforming process. Fig.10 also reveals that the circumferential stress at point 4 is compressive for the bending processing, but it becomes tensile in the following processes. Longitudinal stress keeps compressive in the whole process. According to the stress state, thickness strain increment at point 4 is found to be positive in the bending process, but it becomes negative in the pre-forming and hydroforming process. Therefore, tube wall at point 4 increases for the bending process, but it decreases in the following two processes.

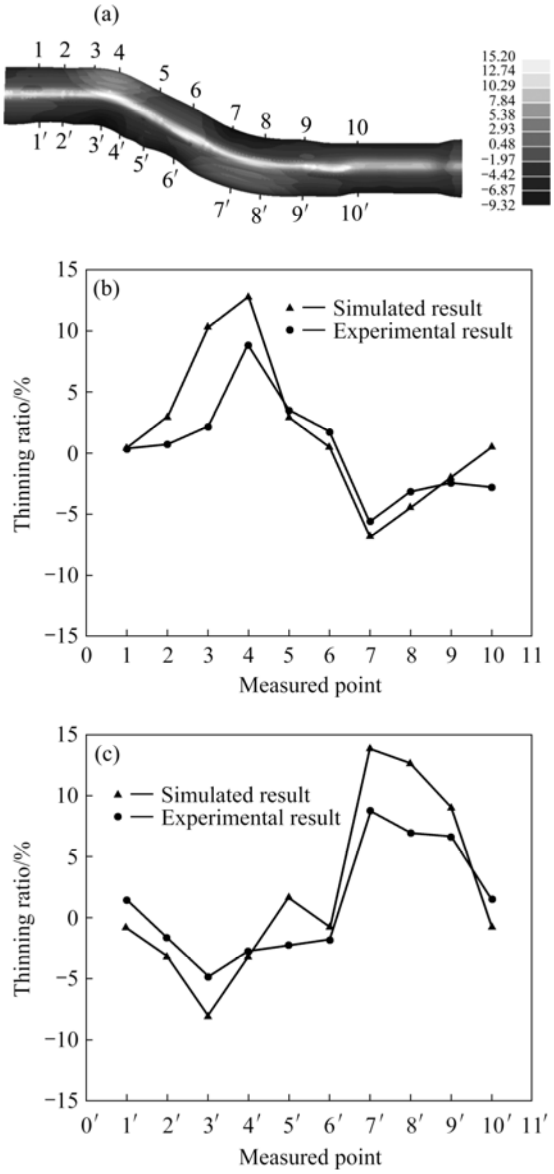


Fig.9 Thinning ratio distribution: (a) Simulated thinning ratio after hydroforming and measured points; (b) Thinning ratio on upper side; (c) Thinning ratio on lower side

5 Conclusions

1) Tensile tests along axial direction show that the formability of the studied AZ61A tube can be improved considerably at elevated temperature. From 225 ℃ to 250 ℃, the total elongation and the elongation before necking have the relatively higher values, which is more suitable for hydroforming of the AZ61A tube. If the

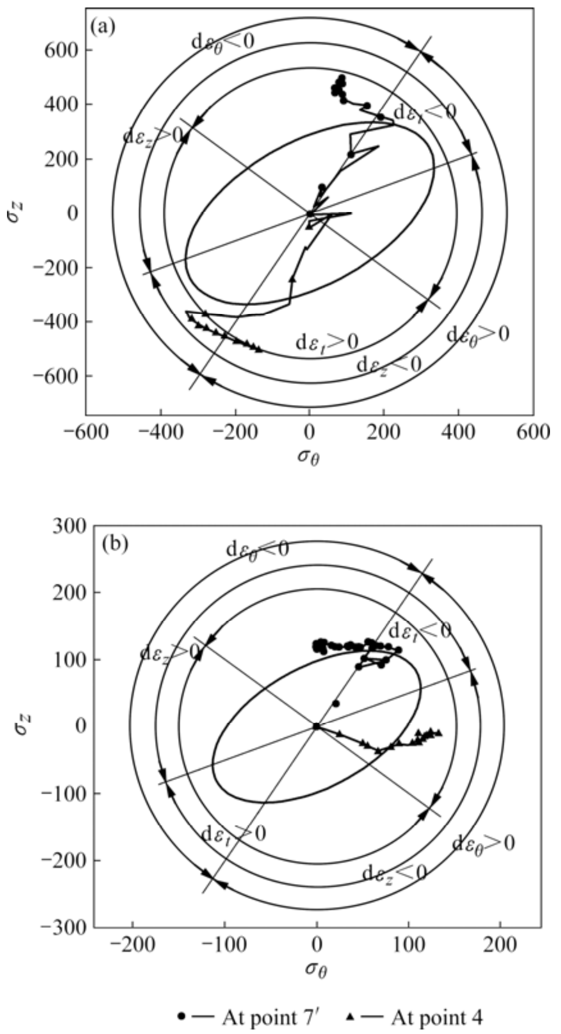


Fig.10 Stress state during whole process: (a) Bending at room temperature; (b) Preforming and hydroforming at 225 ℃

forming temperature is higher than 250 ℃, the nonuniform deformation becomes more serious and is apt to induce local thinning on the formed component.

2) For a tubular part with curved axis, bending is a necessary procedure. Meanwhile, for a component with complex cross sections, pre-form is a way for enhancing the forming precision. Only if the axis of the tubular blank is formed into the curve similar to the final component, and the cross sections are preformed into proper shape, the tubular blank can be put into the hydroforming die without interference and then hydroforming process can be conducted smoothly.

3) From simulation, the maximum effective strain in pre-form is as high as 0.165, therefore, the pre-form procedure should be carried out at at an elevated temperature. Experiments verified that the longitudinal cracking at the radius of the cross section occurring at room temperature can be avoided within pre-form at 225 ℃.

4) After hydroforming at 225 ℃, twinning is absent in the tubular part and grain refinement is observed. It is illustrated that the deformation is accompanied by dynamic recrystallization that causes the softening of the material and increasing the formability.

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