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Study on the Formability and Deformation Behavior of AZ31B Tube at Elevated Temperature by Tube Bulging Test

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Internal high pressure forming of tube is widely used to form complex tubular part with different cross sections and curved axis. The ability of tube to undergo expansion deformation is crucial for the forming process. To evaluate the formability of AZ31B extruded tube, bulging test was carried out at different temperatures from RT up to 480 °C. Bursting pressure and maximum expansion ratio (MER) of the tube were obtained. The fracture surface after bursting was analyzed and compared with that obtained by tensile test along axial direction. Hardness changes in different positions along axial direction were also measured. Results show that the MER value remain almost unchanged from RT to 100 °C. In the temperature interval between 100 and 480 °C, an oblique *N* model can be used to describe the variation of MER value. The first peak and the bottom MER value occurred at 160 and 330 °C, respectively, and about 30.3% expansion ratio was reached at 480 °C. The bursting pressure decreased almost linearly as testing temperature increased. The fracture mode also changed from intercrystalline fracture to gliding fracture. However, burnt structure happened when the forming temperature was about 480 °C. The hardness value of the tube decreased significantly after the bulging test.

Keywords elevated temperature, fracture surface, internal high pressure forming, maximum expansion ratio (MER), tube bulging test

1. Introduction

Internal high-pressure forming of tube is one advanced method to manufacture tubular components in automotive and aerospace industries to reach the aim of weight reduction and energy saving. Light-weight materials, such as aluminum and magnesium alloys are becoming very promising materials in realizing further fuel cost reduction and engineering design flexibility (Ref 1). However, due to their poor formability at RT, traditional tube hydroforming technique for steel tube cannot be applied for light-weight materials. In addition, aluminum and magnesium tube are generally manufactured by extrusion, which will result in considerable property differences along extrusion direction and hoop direction (Ref 2). This anisotropic characteristic of these tubes will decrease the whole formability for hydroforming process (Ref 3).

Traditional tensile test using flat- or arc-shaped specimen is often used to test the mechanical properties of tube, especially along axial direction. As for extruded tubes with considerable property difference along axial direction and hoop direction, tensile tests should be carried out separately along both directions. However, no accurate data in hoop direction can be obtained if traditional tensile test is used, because work hardening will cause considerable errors in characterizing the mechanical properties, especially for tube with small radius (Ref 4). *Ring stretch tensile test* was first proposed by Price (Ref 5) to analyze the failure of Zircaloy cladding under transverse plane-strain deformation. In this test, two D-blocks were inserted in the ring specimen first, and then were separated reversely to cause deformation of the specimen. Later, Cohen et al. (Ref 6) and Wang et al. (Ref 7) developed this testing method to better describe the anisotropic characteristic of extruded tubes. In the analytic model they developed, friction between the D-blocks and specimen was neglected, which may be invalid when testing at elevated temperature. Later, He et al. (Ref 8) investigated the effect of friction between specimen and D-blocks. It was shown that uneven deformation will happen and necking and fracturing tend to occur near the edge of gauge section. Therefore, special attention should be paid to measuring and analyzing the strain distribution.

Nowadays, hydro-bulge test (also called *free expansion test*) is often used instead of tensile test to evaluate the property of tube, because no additional deformation will be caused during specimen preparation (Ref 9). In addition, the stress-state in hydro-bulge test is quite similar to hydroforming process, which can reveal the characteristic of tube better (Ref 10).

A tube bulge test system was developed by Fuchizawa and Narazaki (Ref 11). Axial force and internal pressure can be controlled separately to change the forming condition, i.e., the stress state of the tube. Fuchizawa et al. (Ref 12) determined the forming limit diagram (FLD) of aluminum alloy tube using this

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testing system later. At the same time, one simple testing die-set was also developed, which can change the stress state of tube by using tube specimen with different expansion length. However, the ends of tube were fixed during hydro-bulging, and the tube will be expanded under biaxial tension stress state.

As for light weight material tube, forming temperature is one of the most important factors on the formability. Hwang and Lin (Ref 13) investigated the anisotropic effects of A6061 tube during bulge forming in an open die. The mathematica model considering anisotropic effects can predict the forming pressure profile and maximum bulge height more accurately than the model considering isotropy. Liu and Wu (Ref 14) studied the microstructure evaluation of AZ31 magnesium alloy tube after hot metal gas forming, with special attention on the anisotropic characteristic of extruded tubes. EBSD data showed that, despite the (0001) fiber texture, there were still many grains favoring basal slip along both the axial and hoop directions. Based on hydro-bulge test, He et al. (Ref 9) tested and evaluated the formability of AZ31B magnesium alloy tubes at elevated temperatures. The tube tested was manufactured by bridge die extrusion, and the weld lines along extrusion direction tend to fracture first especially at elevated temperature. Later, He et al. (Ref 15) tested the mechanical properties of AZ31B seamless tube manufactured by pierce-type extrusion by bulging test and ring hoop tension test. However, the testing temperature of bulging test was only up to 230 °C due to the limited resistant-temperature of the heat transfer oil used as pressure media.

In this article, tube bulging test will be used to investigate the formability of AZ31B extruded tube at temperature interval from RT to 480 °C. Compressed gas will be used as forming media at high temperature. The variations of maximum expansion ratio (MER) and bursting pressure with testing temperature will be analyzed. The fracture mechanism of the tube and the corresponding hardness change will be investigated meanwhile.

2. Experimental

As mentioned above, tube bulging test can reveal the formability of tube for internal high-pressure forming process. In order to test and evaluate the formability of tube, special set-up for tube bulging test was designed and manufactured, and bulging tests of AZ31B tube at different temperatures were realized on this set-up.

2.1 Experiment Setup

Figure 1 shows the schematic diagram of tube bulging test. The tube will be placed in the dies and sealed by punches. When the desired temperature is reached, heated oil or other pressure media will be filled into the tube continuously until bursting happens. The length of expansion zone can be determined according to the tube diameter and other specified requirement. The tube ends can be fixed, free, or force/stroke controlled. For each end condition, corresponding sealing method needs to be used. Bursting pressure, diameter change, and thickness distribution can be recorded and measured to describe the deformation process.

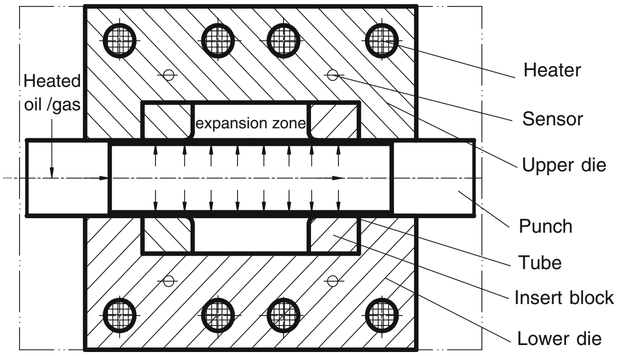

Fig. 1 Schematic diagram of tube bulging test

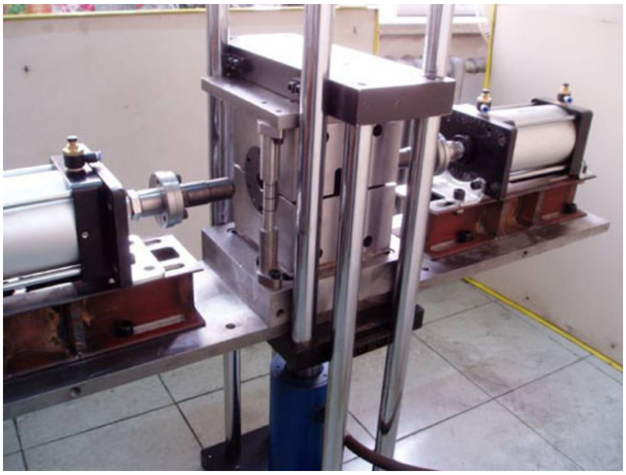

Fig. 2 Experimental set-up for tube bulging test

Figure 2 shows the set-up for tube bulging test developed by the Engineering Research Center of Hydroforming in Harbin Institute of Technology (ERCH/HIT). This set-up can also be used for forming of tubular part at elevated temperature. The upper and lower dies are heated by cartridge heater, and the temperature of each die is PID controlled. The length of expansion zone can be adjusted by changing the insert blocks. Limited by the working temperature of cartridge heater, the highest forming temperature of this set-up is 500 °C, which is enough for the testing of typical aluminum alloy and magnesium alloy tube. The power of the cartridge heater is 4.5 kW. The dies can be heated to 500 °C in 30 min. In order to keep the temperature of the dies more stable, heat insulation board around the dies was used. When the testing temperature is lower than 300 °C, special heat transfer oil will be used as pressure media. For higher temperature, no heat transfer oil can work stably, and alternative forming media with high temperature resistance should be used. High pressure gas such as compressed air or N_2 is a good choice. However, gas cannot be used instead of liquid pressure media at low temperature because high pressure (higher than 10 MPa) is usually required at this condition. The energy stored in compressed gas cannot be released quickly as liquid media when bursting occurs.

2.2 Experiment Procedure

Based on the set-up developed in HIT, bulging test of AZ31B tube was carried out at different temperatures. The tube tested was manufactured by pre-pierce die extrusion, and is

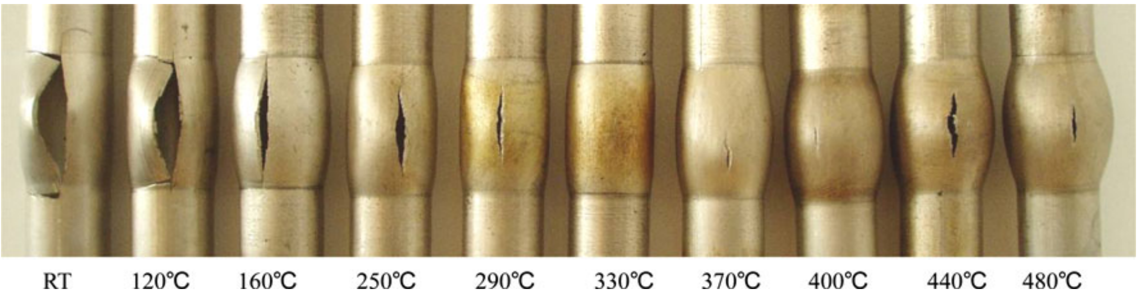

Fig. 3 Tested tube specimen at different temperatures

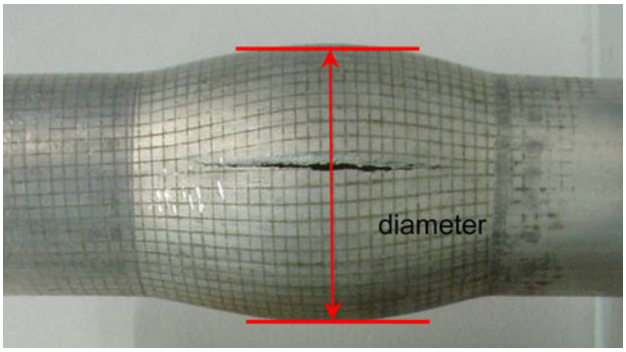

Fig. 4 The measuring position of diameter after bursting

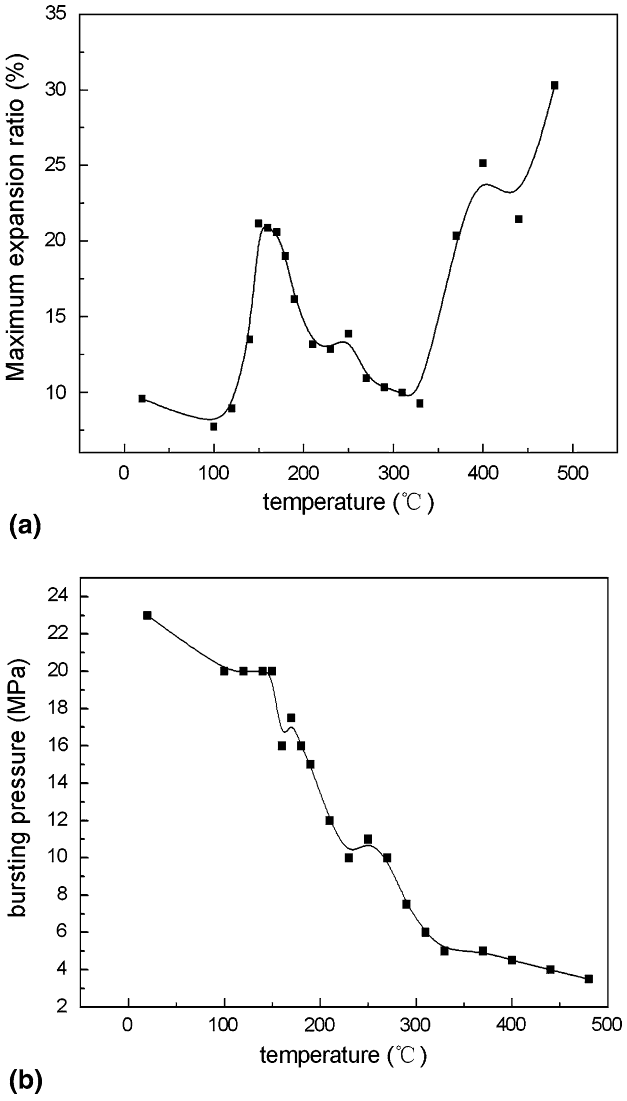

Fig. 5 Maximum expansion ratio and bursting pressure at different temperatures. (a) Maximum expansion ratio; (b) bursting pressure

35 mm in diameter and 2 mm in thickness. The length of expansion zone was 55 mm.

As is well known, in order to get a comparable testing result for the formability of material, it is better to control the deformation speed or the strain rate of the specimen. In other words, the testing conditions such as strain rate or testing temperature should be clarified when presenting the material properties. In tube bulging test when liquid pressure media is used, certain deformation speed or strain rate can be followed by controlling the flow volume of incompressible liquid. Unfortunately, for tests at high temperature, it is difficult to realize this condition when gas is used as pressure media. The high compressibility of gas makes it almost impossible to bulge the tube at a constant speed or strain rate. Of course, analytic or numeric models may be used to calculate the ideal pressure law during each test. However, the high temperature flow stress curve of the material including the softening period should be tested and modeled accurately. Moreover, quick and effective adjusting of the pressure should be realized at high pressure level and high forming speed, which is different from traditional superplastic forming process.

Before testing, the upper and lower dies were heated to the desired temperature first. Then, the tube specimen was positioned into the die. At temperatures lower than 300 °C, heat transfer oil preheated to about 100 °C, was filled into the tube. When the temperature of the heat transfer oil inside the tube reached the testing temperature, preheated oil was then pumped into the tube continuously until bursting happen. The flow rate of the heat transfer oil was about 10 mL/s. As for testing temperature higher than 300 °C, compressed N_2 was released from high pressure gas tank to the tube when the desired tube temperature was reached. By using high pressure solenoid valve and high speed switch valve, the increasing rate of gas pressure was controlled at 0.5 MPa/min in the test. The highest testing temperature was up to 480 °C. The time required for each test was about 3-5 min, not including the time for preheating the dies. Less time was needed for tests at high temperature when compressed gas was used, due to the low thermal capacity of gas.

3. Results and Discussion

Figure 3 shows the tested tube specimen. The fracture surface is quite different when tested at different temperatures. When tested at low temperature, fracture happened in all the deforming zones, and no plastic deformation appeared near the fracture. The bursting line expanded even along hoop direction, which means high density of energy was stored before bursting happen. The fracture surface was flat and smooth. As temperature increased, the bursting line became short, and no smooth fracture surface can be seen.

For each test, the pressure at which bursting happened was recorded. The change of tube diameter was measured. The characteristic of fracture surface was analyzed also. The change of hardness before and after tube bulging test was also investigated.

3.1 Maximum Expansion Ratio

In order to evaluate the formability of the tube for stable deformation, diameter in the middle of the expansion zone after testing was measured. The measuring position is shown in Fig. 4. According to the measured diameter, MER, λ, is calculated as below:

$$\lambda = \frac{D_{\max} - D_0}{D_0} \times 100\% \qquad \text{(Eq 1)}$$

where, $D_{\max}$ is the diameter measured after testing, and D_0 is the original tube diameter.

The calculated MER is given in Fig. 5, together with the bursting pressure for each test. It can be seen from Fig. 5(a) that, from RT to 100 °C, the MER value did not change significantly and was about 8%. After 100 °C, the MER value began to

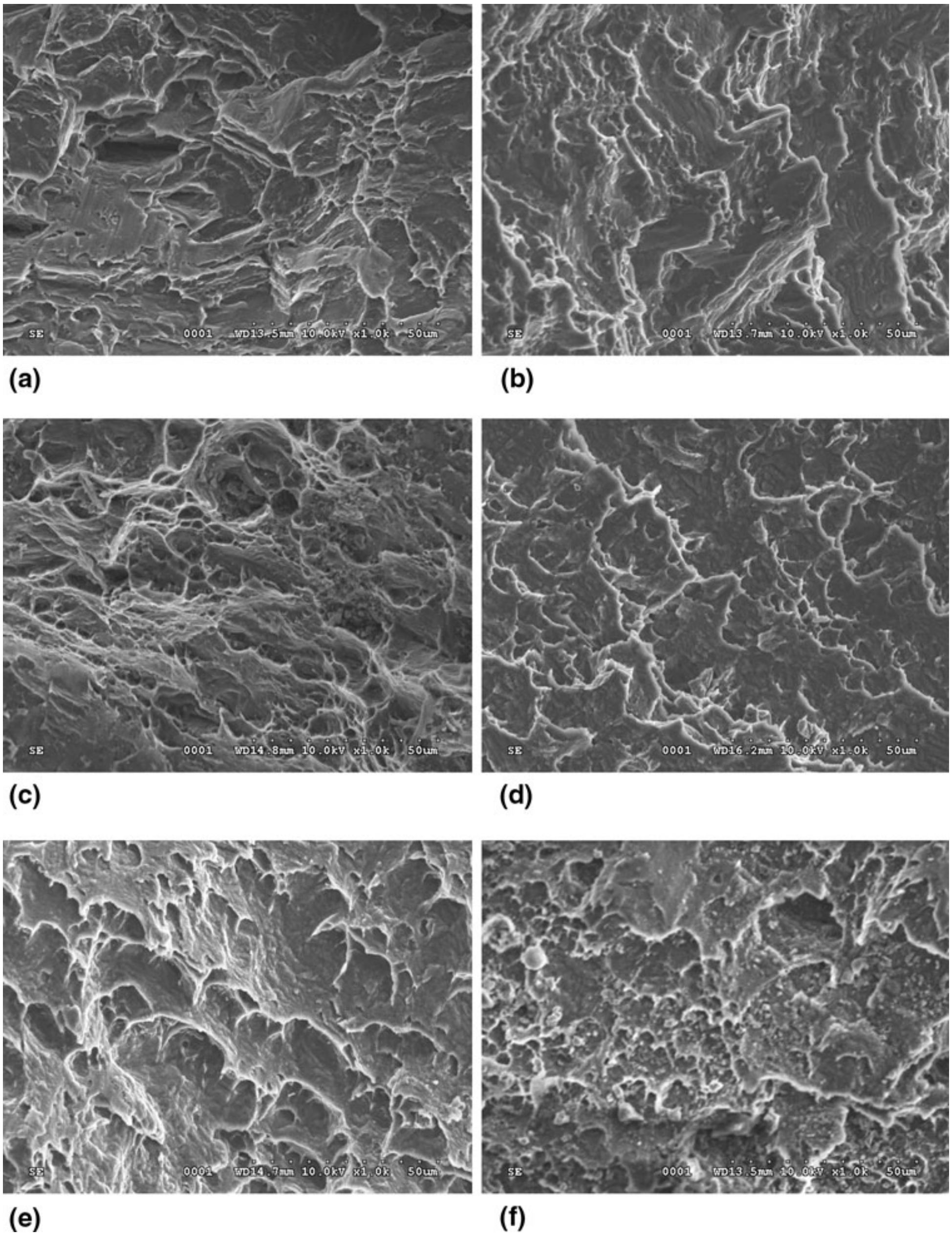

Fig. 6 SEM images of tube bulging fracture at different temperatures. (a) RT; (b) 120 °C; (c) 160 °C; (d) 330 °C; (e) 420 °C; (f) 480 °C

change greatly, and an oblique *N* model was followed at the temperature interval from 100 to 480 °C. The MER reached the first peak value 21% at 160 °C. As temperature increased further, the MER value began to decrease quickly and reached the bottom value of 10% at 330 °C, which is about the same value as RT. After 330 °C, the MER value began to increase again, until 30.3% expansion ratio was reached at 480 °C.

From Fig. 5(b), it can be seen that the bursting pressure decreased almost linearly as temperature increased, from 23 MPa at RT to only 3.5 MPa at 480 °C.

From the results given in Fig. 5, it is easy to find that the changing tendency of the formability of AZ31B seamless tube is quite different with the properties obtained by axial tension tests (Ref 9). In axial tension test, the total elongation increased continuously as temperature increased, and about 60% elongation was reached at 350 °C. As mentioned above, in tube bulging process, the deformation mainly occurred along hoop direction. It is reasonable to conclude that there exits significant property difference along axial and hoop directions of the tested AZ31B extruded tube.

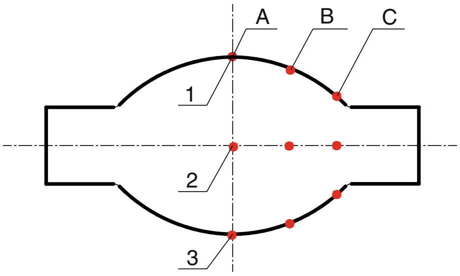

Fig. 8 Measuring point for hardness after tube bulging test

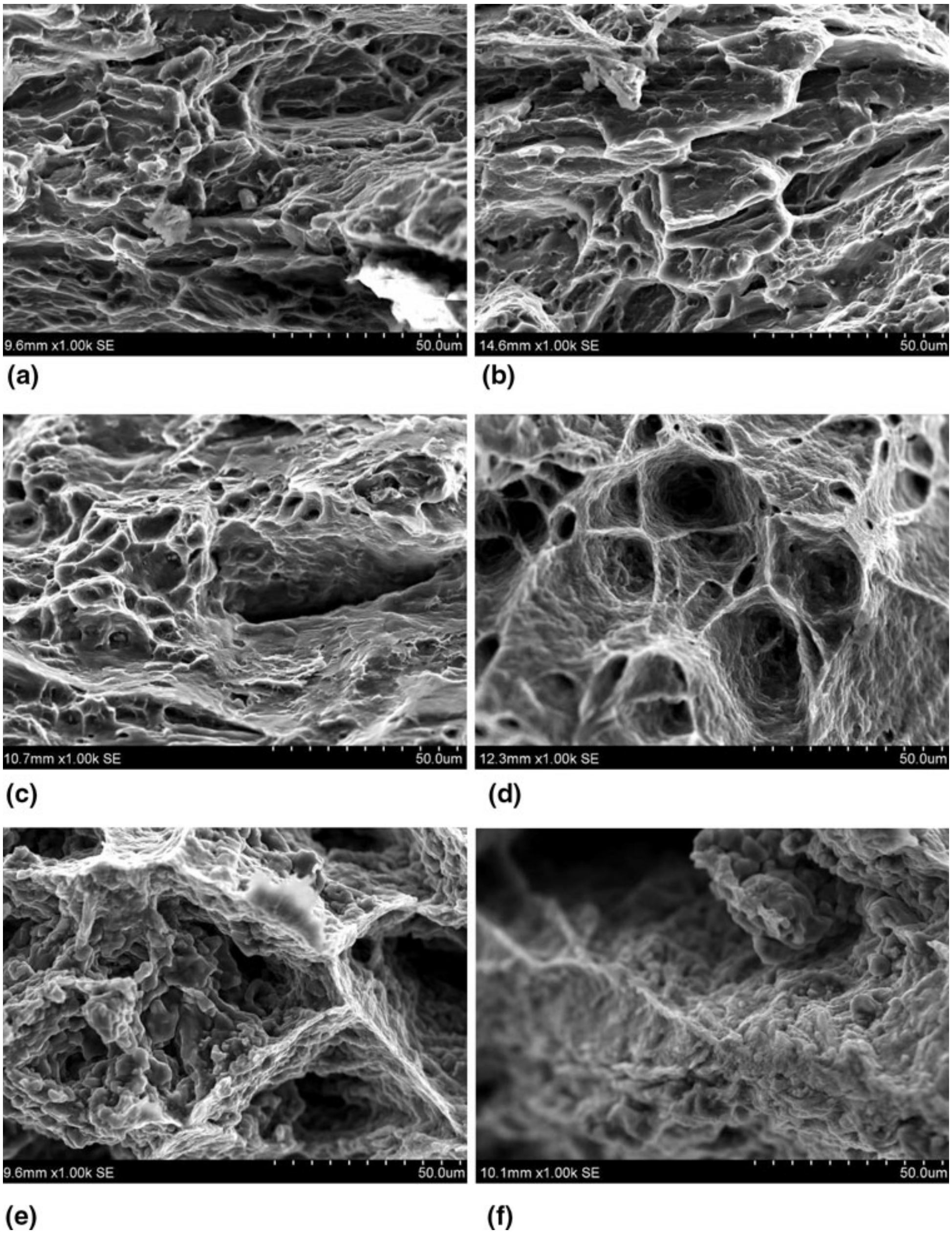

Fig. 7 SEM images of tension fracture at different temperatures. (a) RT; (b) 120 °C; (c) 160 °C; (d) 330 °C; (e) 420 °C; (f) 480 °C

Table.1 HRV values at RT of tubes tested at different temperatures

Measuring point	160 °C			330 °C			480 °C		
	A	B	C	A	B	C	A	B	C
1	63.92	61.01	45.74	55.62	54.10	54.20	57.06	56.79	54.02
2	59.38	60.82	59.19	53.35	53.40	53.40	55.34	53.21	52.81
3	57.08	48.32	47.75	53.27	53.20	53.10	53.20	56.01	54.10

3.2 Fracture Behaviour

Figure 6 shows the SEM images of the fracture surface after tube bulging test at different temperatures. It can be seen that from RT to 120 °C, the fracture model is intercrystalline (intergranular) fracture. As temperature increased, cleavage fracture, tear ridge, and dimples can all be seen on the fracture surface (Fig. 6c), and a hybrid tough and brittle fracture characteristic appears. More dimples can be seen all over the fracture surface as temperatures increased further (Fig. 6d-e). However, burnt structure as shown in Fig. 6(f) appears, and the mechanical properties, fatigue and anti-corrosion properties of the tested tube, will decrease rapidly.

In order to compare the fracture behavior of the tube along different directions, the fracture surface in tensile test along axial direction was also analyzed. Figure 7 shows the SEM images of the fracture surface after axial tension test at different temperatures. It can be seen that the fracture appearance after axial tension is similar to that after bulging test. At low temperature, obvious brittle fracture can be seen. At elevated temperature, ductile and mixed-mode fractures occurred. At too high temperature, burnt structure appeared.

3.3 Hardness Distribution

Vickers hardness test of the tube was carried out before and after bulging test. The measuring points are shown in Fig. 8. Along hoop direction, point 1 is near to the fracture surface. All the measuring tests were carried out at RT.

The Vickers hardness value of the original tube at RT is HV85. The RT hardnesses of the tube tested at three typical temperatures are listed in Table 1.

From the results listed above, it can be seen that the Vickers hardness after bulging test decreased considerably compared with original tube. However, there is no great difference for the RT Vickers hardness of tubes bulging tested at different temperatures. In other words, the Vickers hardness of the bulging tested tube was at a same level of about HV55. For one tested tube, along axial direction, the hardness value at point A is higher than those at point B and point C. Along hoop direction, the hardness value at point 1 is higher than those at point 2 and point 3. This means that the hardness near the center position where larger deformation happened is a little higher than those near ends, and the hardness near the fracture is also higher than those at other positions.

4. Conclusions

In this article, the formability of AZ31B magnesium alloy tube was tested and evaluated by bulging test with internal pressure. The fracture mechanism of the tube and the corresponding hardness change were investigated. Results show that

(1) MER value remains almost unchanged from RT to 100 °C. After that, the MER value changed in an oblique *N* model. The first peak and the bottom MER value occurred at 160 and 330 °C, respectively, and about 30.3% expansion ratio was reached at 480 °C. The bursting pressure decreased almost linearly as temperature increased.
(2) At low temperature, the fracture mode was mainly intercrystalline fracture. As temperature increased, small dimples can be seen on the fracture surface, and the number of plastic dimples increased at higher temperature. However, burnt structure appeared when tested at 480 °C.
(3) The hardness value of the tube decreased significantly after the bulging test at elevated temperature. The hardnesses of tubes tested at different temperatures were at the same level of about HV55. For one tested tube, the hardness value near the fracture position is a little higher than those at other positions.

Acknowledgments

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