Study on superplastic gas-bulging properties and microstructure evolution of as-rolled 2A97 Al-Li alloy

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Abstract. In this paper, the forming properties of as-rolled 2A97 Al-Li alloy at 370 ~430 ℃ and 0.02~0.08 MPa/min were studied by Superplastic gas-bulging experiment, the microstructure and mechanical properties of 2A97 Al-Li alloy after deformation were evaluated and analysed by means of EBSD, TEM and other testing methods. The results show that the as-rolled 2A97 Al-Li alloy has good superplastic deformation ability, the optimum forming parameters are 390℃, 0.06 MPa/min, and the maximum height of cap cone is 74 mm under these conditions. Dynamic recry -stallization of rolled microstructure occurs during superplastic deformation, the microstructure after superplastic deformation is fine, equiaxed and the average grain size is less than 5 μm. The material keeps good strength and plasticity after superplastic deformation, the tensile fracture shows obvious ductile fracture characteristics, and there are a lot of dimples with regular shape and uniform distribution on the fracture surface. After superplastic forming, it undergoes 520 ℃/2h solution treatment, water quenching, and aging at 165 ℃/36h, the properties of 2A97 Al- Li were as follows: tensile strength 527MPa, yield strength 441MPa, and elongation 8.3%, respectively.

1. Introduction

Aluminum lithium alloy is a lightweight alloy with low density, high specific strength, and specific stiffness, as well as excellent low-temperature performance, corrosion resistance, and superplasticity. It has excellent comprehensive performance and great development potential, and is considered an ideal structural material for aircraft and ships in the 21st century [1-4]. Although the density of aluminum lithium alloy is about 10% lower than that of conventional aluminum lithium alloy, its elastic modulus has increased by 10%. Replacing conventional aluminum alloys with aluminum lithium alloys can reduce component weight by 10% to 15%, while increasing stiffness by 15% to 20% [5]. Therefore, aluminum lithium alloy, as a lightweight and high-strength structural material, will have broad application prospects in aerospace and other fields in the future. Superplastic forming (SPF) is a method of forming by utilizing the superplasticity of materials under specific temperature and strain rate conditions. It can achieve overall and near net forming of complex structures [6-8]. Research has shown that Al-Li alloy has good superplasticity [9-11], the rolled 2A97 aluminum lithium alloy with high deformation energy obtained through special deformation and heat treatment also has good superplastic deformation ability, with superplastic tensile elongation reaching over 500%. It mainly achieves grain refinement through dynamic recrystallization during superplastic deformation to obtain high elongation [12-15]. There is little research on the superplastic bulging performance of the rolled 2A97 aluminum lithium alloy and the microstructure evolution law of the material during the bulging process.

This article takes the rolled 2A97 as the research object, and studies the superplastic forming performance and wall thickness distribution of the rolled 2A97 aluminum lithium alloy under complex stress states through gas pressure bulging tests of cap shaped and rectangular shaped parts. The optimal bulging process parameters of the material are obtained. At the same time, microstructure evolution laws of materials in different deformation zones are studied using microstructural analysis methods such as OM、EDSB and SEM. And the mechanical properties after superplastic forming are tested.

2. Materials and Experimental Procedure

2.1 Materials

The material in this paper is an Al-Cu-Li alloy supplied by Southwest Aluminum (Group) Co.,Ltd.,China , referred to as 2A97 alloy. The nominal chemical composition of the sheet was Al–3.8Cu–1.4Li–0.5Mg–0.5Zn–0.3Mn–0.2Ti–0.2Si–0.1Zr –0.06Fe–0.006Be (wt %). The material used is 1.5 mm thick warm rolled plates, and was specifically thermomechanical treatment for superplastic forming. After casting and homogenizing, the alloy is hot rolled to 25mm in thickness to break down the as-cast structure. The material is solution treated at 520°C for 2h to take most of the copper into solid solution, and aged at 400°C for 48 h to obtain the uniform distribution and a larger volume fraction of the second phase particles. And then the plate is warm rolled with intermediate annealing to avoid rolling cracking. Finally, retain 20%~30% deformation for cold rolling to as-received state[16]. The microstructure of the as-received 2A97 alloy is shown in Fig.1. It can be seen that there are a certain amount of pancake-shaped grains elongated in the longitudinal rolling direction (RD).

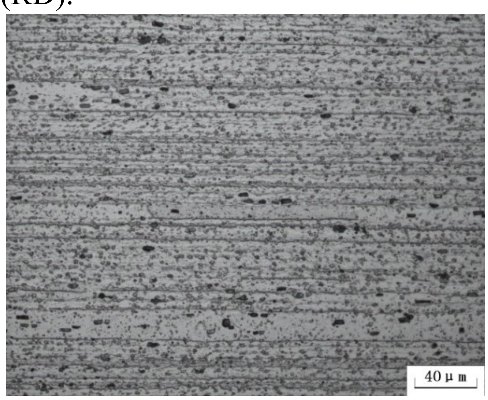
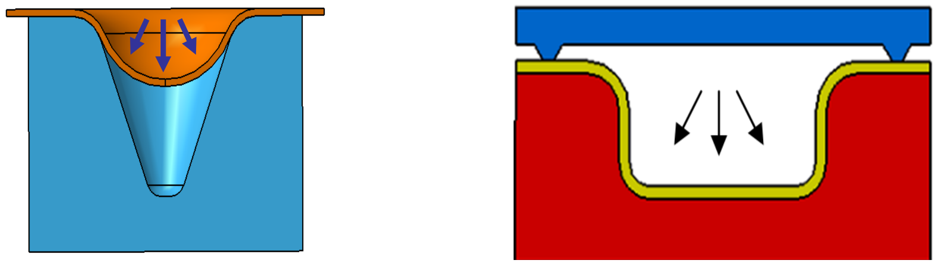


Fig.1 Microstructure of as-received 2A97 alloy

2.2 Experimental Procedure

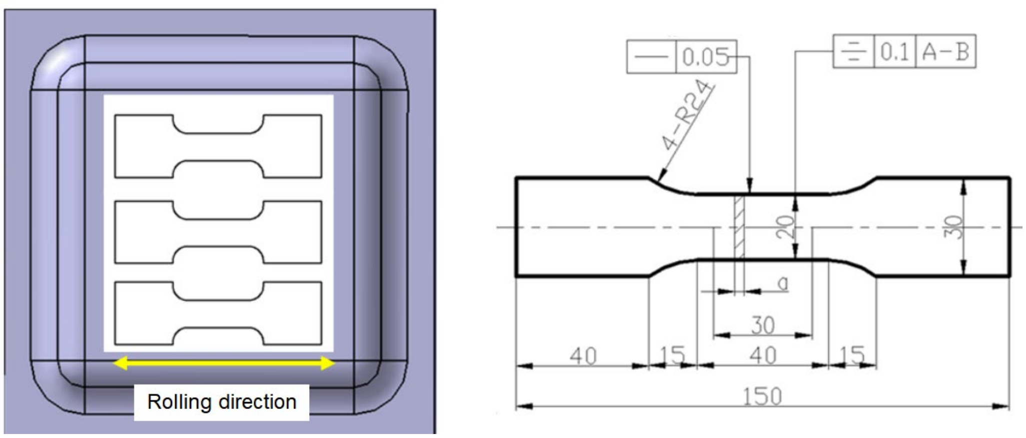
The superplastic bulging tests of the cap cone and rectangular shaped parts were conducted on a 60t superplastic forming testing machine, which consists of three parts: a hydraulic press, a heating device, and an air source control cabinet. Firstly, the mold was loaded into the forming equipment, and thermocouples were inserted into the upper and lower molds to monitor the mold temperature in real time. When the mold temperature reached the target temperature, the forming sheet was loaded into the forming sheet, which was kept at the forming temperature for 20 minutes before superplastic bulging, After the superplastic bulging test is completed, turn off the heating system and remove the parts. The superplastic bulging process of the cap cone is shown in Fig. 2(a). The superplastic bulging temperature is 390~430 ℃, and the gas pressure loading rate is 0.02~0.06 MPa/min. All experiments stopped pressurizing after the cap cone broke. By conducting superplastic bulging tests on cap cones under different temperatures and pressure loading rates, the forming limit, wall thickness distribution characteristics and microstructure evolution of rolled

2A97 aluminum lithium alloy in different deformation conditions were studied. The superplastic forming tests of the rectangular shaped part were conducted under the optimal forming process parameters. The forming height of the rectangular shaped part was 40mm, and the forming process was shown in Fig.2(b). The tensile samples were cut from the bottom of the rectangular shaped part, which are shown in Fig.3 and some samples were subjected to solution treatment at 520 °C/2h. After water quenching, it was artificially aged at 165 °C/36h to test the mechanical properties of the aged material.



(a) the cap cone (b) rectangular part

Fig.2 Schematic diagram of the bulging process of the cap cone and rectangular part



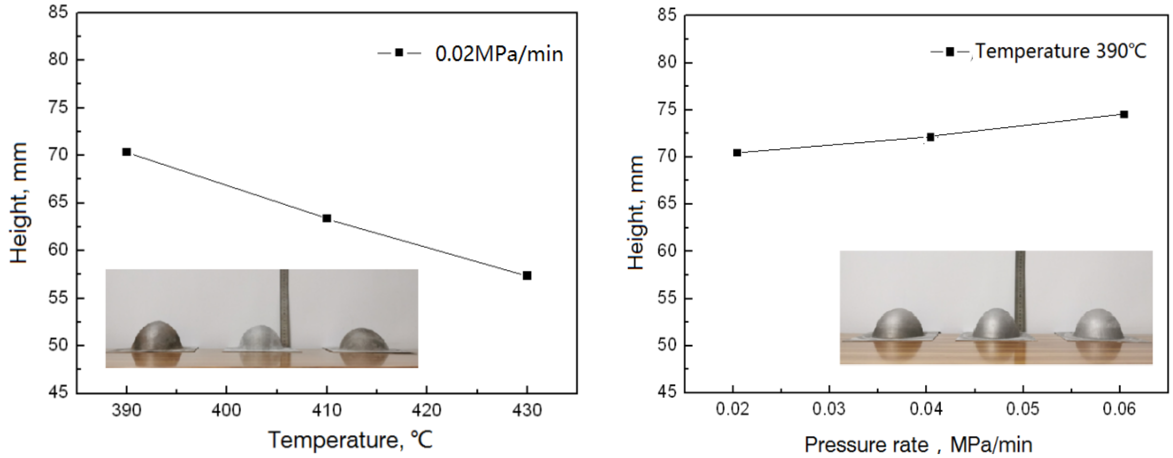
(a) Sampling position for tensile specimens (b) Size of tensile specimens

Fig.3 Dimensions of Room Temperature Tensile Specimen

3. Results and Discussion

3.1 Cap cone forming test results

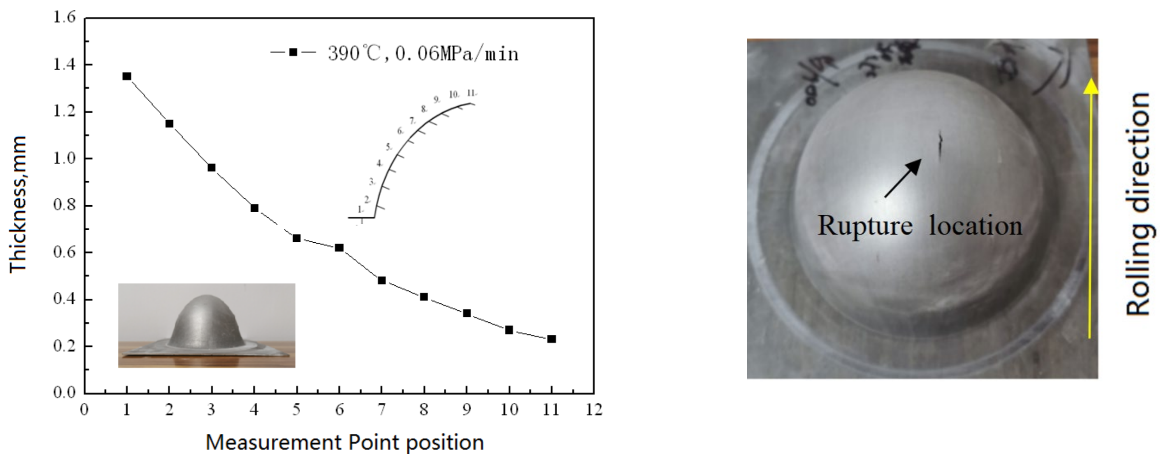
The test results of free bulging tests of cap cone are shown in Fig.4. From Fig.4 (a), it can be seen that 2A97 Al-Li alloy is relatively sensitive to temperature. When the pressure rate is 0.02 MPa/min, the height of the cap cone decreases with the increase of the temperature. When forming at 390 °C, the forming height is 70.5mm. When the temperature rises to 410 °C and 430 °C, the forming heights decrease to 63.5mm and 57.6mmm respectively. In order to study the effect of pressure rate on the forming performance, bulging tests were conducted at three pressure rates of 0.02MPa/min, 0.04MPa/min, and 0.06MPa/min at 390 °C. The results are shown in Fig. 4 (b). As the increase of pressure rate, the forming height slightly improves. When the pressure rate of superplastic forming increases from 0.02MPa/min to 0.06MPa/min, the forming height increases from 70.5mm to 74mm. The optimal forming process for 2A97 Al-Li alloy was obtained at 390 °C and 0.06MPa/min, and the forming height was 74mm.



(a) different temperatures at 0.02MPa/min (b) different pressure rate at 390℃

Fig.4 The height of cap cone with deformation conditions

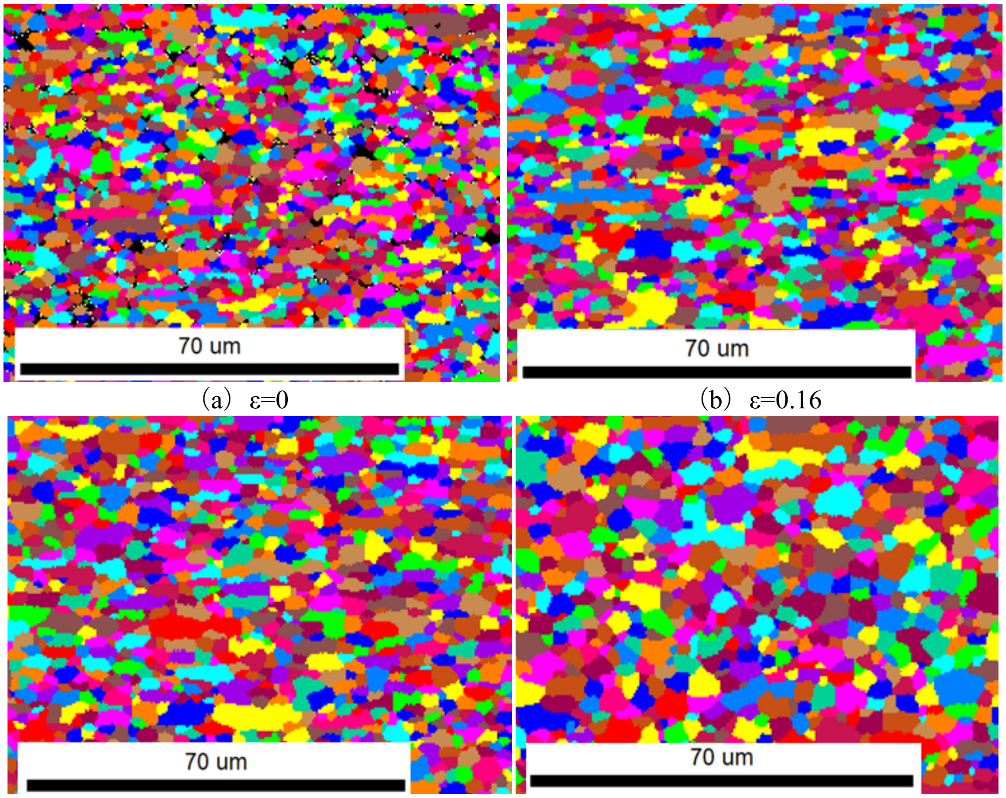
Fig.5 shows the wall thickness distribution of the cap cone after superplastic bulging at 390 ℃ and 0.06MPa/min along the dome height direction. It can be seen from the figure that the wall thickness decreases uniformly along the height direction, and the surface quality of the formed cap cone is smooth and free of orange peel. This indicates that the deformation is relatively uniform, and the fracture at the fracture area cracks along the rolling direction. The wall thickness of the material in the fracture area is only 0.23mm, it indicates that 2A97 aluminum lithium alloy has good formability and deformation uniformity under this condition.



(a) thickness distribution (b) Fracture zone morphology

Fig.5 Experimental results of cap cone forming (390 ℃, 0.06MPa/min)

Fig. 6 shows the microstructure corresponding to different strains of the cap cone after superplastic forming at 390 ℃ and 0.06MPa/min. Figure 16 (a) shows the material structure in the undeformed zone of the cap cone, which has only undergone high-temperature thermal cycling. Static recrystallization has occurred in this region, but the degree of recrystallization is not complete. As the deformation increases, the degree of recrystallization increases. The recrystallization and grain growth exist during the deformation process. When the strain reaches 1.37, the elongated structure almost disappears, the grain morphology tends to be equiaxed, and the structure is more uniform, with an average grain size of about 3.8 μm. Dynamic recrystallization is the main deformation mechanism during the superplastic deformation process of as-rolled 2A97 Al-Li alloy, fine-grained structure and good deformation ability are obtained through it during the deformation.



(a) ε=0 (b) ε=0.16

(c) ε=0.53 (d) ε=1.37

Fig.6 Microstructure of cap cone with different strains (390 ℃, 0.06MPa/min))

3.2 Rectangular part forming test results

Rectangular parts of 2A97 Al-Li alloy were formed at temperature 390 ℃. The pressure pathway of the rectangular part is first added to 0.6MPa for 10 minutes, and then pressurized to 1.2MPa at a rate of 0.06MPa/min. Under these conditions, the superplastic formed rectangular part and the distribution of wall thickness are shown in Fig.7. It can be seen that the bottom corner position in contact with the concave mold has the largest deformation, with the thinnest wall thickness of 0.78mm and a reduction rate of 42%. The wall thickness at the center of the box bottom position is 1.15mm, because this position first contacts the mold during the forming process, and the friction between the sheet and the mold limits the flow of materials in this area.

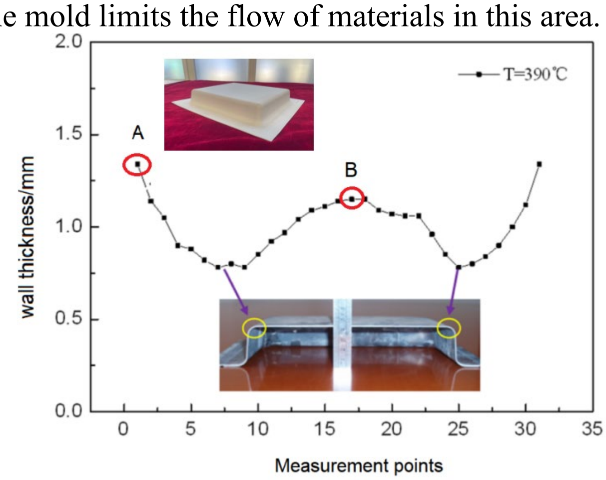
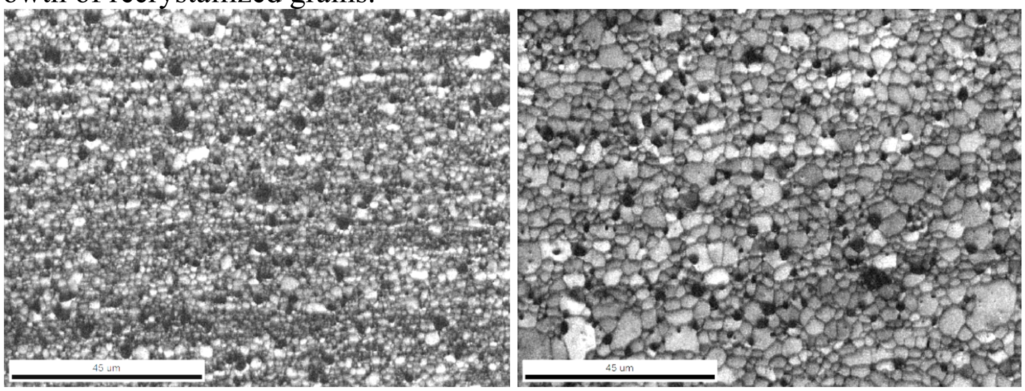


Fig.7 The distribution of wall thickness of rectangular part

Fig.8 shows the microstructure of the undeformed zone (point A in Fig. 7) and the deformed zone (point B in Fig. 7) of the rectangular shaped part. It can be seen that the undeformed zone has undergone significant recrystallization, with very fine recrystallized grains, with an average grain size of only 1.26 μm. Compared with the undeformed zone structure, the deformation zone structure at the bottom of the rectangular part undergoes complete recrystallization and grains grow, but the grains remain fine and equiaxed. The grain boundaries are clearly visible, and the average grain size is about 2.05 μm. This also indicates that during superplastic deformation, not only dynamic recrystallization occurs under the action of deformation force, but also accompanied by the growth of recrystallized grains.



(a) undeformed zone (Point A) (b) deformed zone (Point B)

Fig.8 Organization of rectangular part at different positions

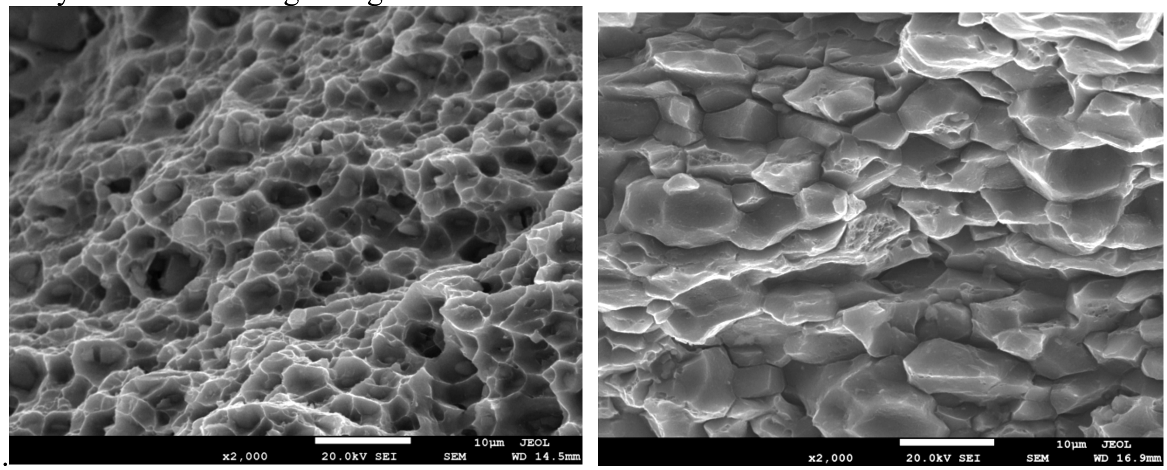
3.3 Performance evaluation after superplastic forming

Take tensile specimen from the rectangular parts is shown in Fig.3. The tensile test results in different states are shown in table 1. It indicates that the original plate is in the rolled state with low performance. The tensile strength in the rolling direction is 339.6 MPa, the yield strength is 316.7 MPa, and the elongation is very low, only 3.8%. After superplastic deformation, the tensile strength remains almost unchanged, and the yield strength slightly decreases. However, the plasticity at room temperature has been greatly improved, the elongation has increased from 3.8% of the original sheet to 14%. After superplastic deformation, the sample was subjected to 520 ℃ /2h solid solution treatment followed by water quenching, then aged by 165 ℃/36h , the properties of 2A97 Al-Li alloy were as follows: $R_{m=}$527MPa， $R_{p0.2}$=441MPa，A= 8.3%. Aging heat treatment can effectively improve the mechanical properties of 2A97 Al-Li alloy after superplastic deformation.

Table 1 Mechanical properties of 2A97 Al-Li in different states

Material Status	Rm， MPa	Rp0.2， MPa	A， %
Original material	339.6	316.7	3.8
After SPF	345	235.6	14
SPF+520℃/2h+165℃/36h	527	441	8.3

Fig.9 (a) and (b) show the fracture morphology of the specimens after superplastic forming and aging tensile fracture at 520 ℃/2h+165 ℃/36h, respectively. The tensile fracture of 2A97 Al-Li alloy after superplastic forming exhibits typical ductile fracture characteristics, with a large number of deep dimples in the fracture surface, and the size of the dimples is very small, about 1-3 μ m. The shape of the dimples is regular and evenly distributed, mainly due to the uniform and fine microstructure of the material after superplastic forming, which greatly improves its plasticity. After single stage aging at 165 ℃/36h, the fracture surface is convex and uneven, mainly composed of rock sugar like particles. The size of rock sugar particles is relatively small and evenly distributed. The tensile fracture shows obvious intergranular fracture characteristics, belonging to a typical brittle fracture surface. The main reason is that during single stage aging at 165 ℃/36h, a large number of continuously distributed second phases are precipitated at the grain boundaries, and they reduce the strength of grain boundaries.



（a）fracture morphology of SPF （b）SPF + 165℃/36h aging

Fig.9 Tensile fracture morphology of 2A97 Al-Li alloy after SPF

4. Summary

(1) The as-rolled 2A97 Al-Li alloy has good superplastic deformation ability, As the temperature decreases and the pressure rate increases, the forming height of the cap cone increases .The optimum forming parameters are 390℃, 0.06 MPa/min, and the maximum height of cap cone is 74 mm under these conditions.

(2) The observation results of different deformation zones of 2A97 Al Li alloy after superplastic deformation indicate that dynamic recrystallization is the main deformation mechanism of as-rolled 2A97 alloy. Fine grain structures are obtained through dynamic recrystallization, with the average grain size of less than 5μm.

(3) Aging heat treatment can effectively improve the mechanical properties of 2A97 Al-Li alloy after superplastic deformation. After being quenched in solution water at 520 ℃/2h and aged at 165 ℃/36h, the tensile strength, yield strength, and elongation of 2A97 Al-Li alloy respectively are 527MPa, 441MPa and 8.3%。

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