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## Effect of current pulses on fracture morphology in superplastic deformation of 2091 Al-Li alloy<sup>①</sup>

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**Abstract:** The effect of current pulses on the fracture morphology in the superplastic deformation of 2091 Al-Li alloy at two kinds of initial strain rate ( $\dot{\epsilon}_1 = 3.33 \times 10^{-3} \text{ s}^{-1}$ ;  $\dot{\epsilon}_2 = 3.33 \times 10^{-2} \text{ s}^{-1}$ ) was investigated. Experimental results show that current pulse turns fracture of superplastic deformation at low strain rate from local interior fracture morphology to typical fracture by growth and interlinkage of cavities, and at high strain rate from rough grain boundary surface to smooth grain boundary surface. It is indicated that the characteristic, that current pulse promotes atomic diffusion, maintains an equiaxial grain microstructure at low strain rate, and accelerates the development of diffusional type of cavity and relaxes stress concentration at triple junction of grain boundaries at high strain rate, and makes the superplastic deformation at two kinds of strain rate show a normal superplastic fracture morphology.

**Key words:** Al-Li alloy; superplastic deformation; fracture morphology

**Document code:** A

### 1 INTRODUCTION

Generally<sup>[1-4]</sup>, fracture in superplastic deformation is intergranular. But at a certain condition, it can exhibit a local interior fracture. Ref.5 realized that such a particular fracture was created by a high local stress caused by the rotation and rearrangement of the grains with an irregular boundary and a great equiaxial ratio in the superplastic deformation, and which was unfavorable. That current pulse has a characteristic of accelerative atom diffusion and dislocation slip has been accepted<sup>[5-10]</sup>. As for the fracture morphology in Ref.11, it is certain that current pulse creates an important effect on it, in addition, Ref.12 successfully increased the optimum strain rate and superplastic property at high strain rate region in the superplastic deformation of 2091 Al-Li alloy by making use of this characteristic, which demonstrated the active effect of the characteristic that current pulse promoted atom diffusion and dislocation slip on superplastic deformation. Consequently, this paper tries to research the effect of current pulses on the frac-

ture morphology in superplastic deformation and subsequent effect in superplastic property in this view point.

### 2 EXPERIMENTAL METHODS

The material chosen for experiment was 2091 Al-Li alloy, its chemical composition is as listed in Table 1. After homogenization at 530 °C for 24 h, hot rolling at 500 °C (35 → 10 mm), resolution at 530 °C for 2 h and overaging at 400 °C for 32 h, the alloy was cold rolled to 0.7 mm thick plate, and then superplastically tensioned at a given cross beam rate on a shimadzu AG-10 TA electron tension machine. The deforming temperature was 500 °C. The temperature error was controlled within  $\pm 1$  °C, and the deformed specimen was applied with a high density current pulse ( $J = 2.0 \times 10^2 \text{ A/mm}^2$ ). In view of the heating effect of current pulse in the alloy, the thermocouple was brought into contact with the two ends of specimens to directly measure the temperature of specimen itself, instead of indirectly measuring the temperature in fur-

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nance as before. The fracture morphology and microstructure of the specimen superplastically deformed were observed and analyzed on an optical microscope, SEM and TEM, respectively.

**Table 1** Chemical composition of alloy( %)

Element	Content
Al	Balance
Li	2.20
Cu	2.60
Mg	1.20
Zr	0.15
Fe	0.10
Si	0.10

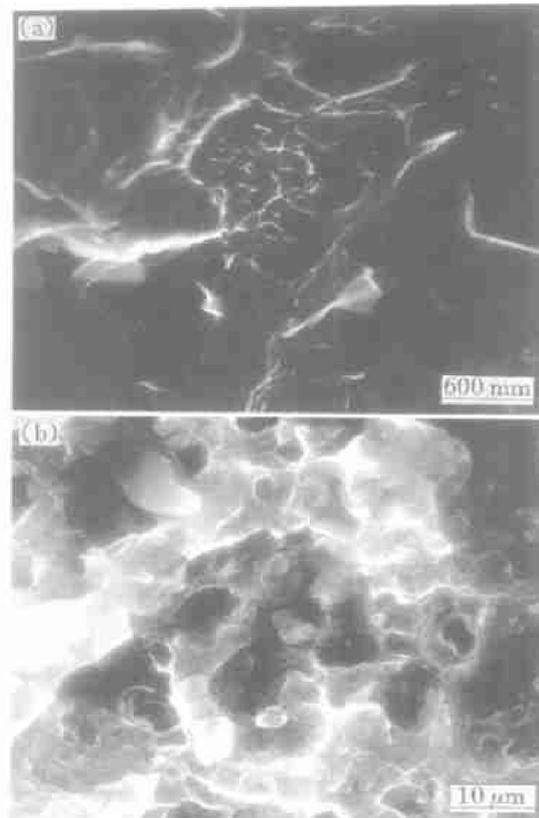
### 3 EXPERIMENTAL RESULTS

The results in superplastic tension are as listed in Table 2. SEM observations of various specimen in fracture state showed that, a local interior fracture existed on the fracture of 2091

**Table 2** Results of superplastic tension

Experimental condition	Elongation/ %
$3.33 \times 10^{-2} \text{ s}^{-1} \quad J = 0 \sim 2.0 \times 10^2 \text{ A/ mm}^2$	490 ~ 620
$3.33 \times 10^{-2} \text{ s}^{-1} \quad J = 0 \sim 2.0 \times 10^2 \text{ A/ mm}^2$	190 ~ 520

Al-Li alloy superplastically deformed at  $\dot{\epsilon}_1 = 3.33 \times 10^{-3} \text{ s}^{-1}$ , in spite of the most of intergranular fracture in Fig.1, when employing current pulses it turned to a complete intergranular fracture with a smooth boundary surface, as shown in Fig.2. Optical microscope and TEM observations showed that in the deformed microstructure unemployed current pulse and dynamic recrystallization were active, grain boundary was irregular with a quite great of ratio of longitudinal size with latitudinal size in grains; when employed current pulse, grain boundary turned to quite regular, the ratio was close to one, the grain was quite equiaxed, and dynamic recrystallization was not too active(see Fig.3), at high strain rate  $\dot{\epsilon}_2 = 3.33 \times 10^{-2} \text{ s}^{-1}$ , although the deformed fracture both unemployed current pulse and employed current pulse appeared to be intergranular, at high magnification the grain boundary surface unemployed current



**Fig.1** Microstructures at fracture

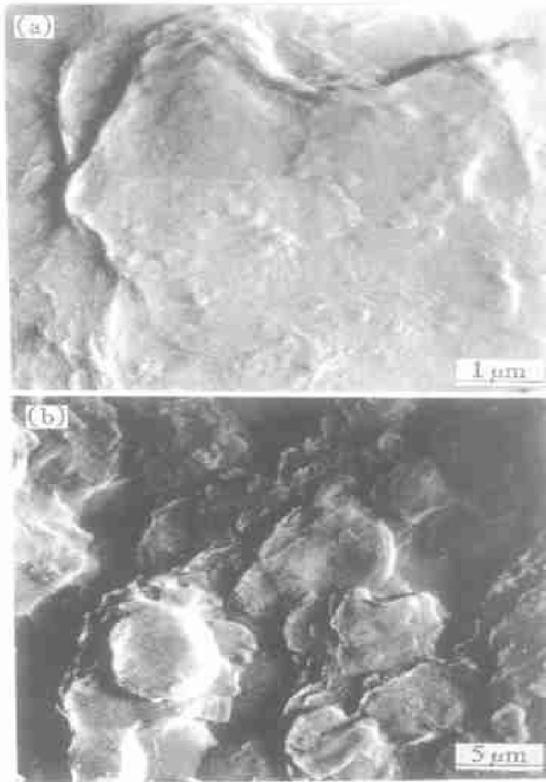
( $\dot{\epsilon} = 3.33 \times 10^{-3} \text{ s}^{-1}$ ,  $J = 0$ )

(a) —At high magnification ; (b) —At low magnification

pulse was quite rough, and that employed current pulse was smooth, as shown in Fig.4, 5. It was found from the cavity nucleation at the initial stage of superplastic deformation that in the unemployed current pulse cavity nucleated in boundary crack, and in the employed current pulse cavity nucleated in atom diffusion, as shown in Fig.6.

### 4 ANALYSES AND DISCUSSION

It can be seen from Table 2 that superplasticity appears at both strain rates of  $\dot{\epsilon}_2 = 3.33 \times 10^{-3} \text{ s}^{-1}$  and  $\dot{\epsilon}_2 = 3.33 \times 10^{-2} \text{ s}^{-1}$ , and applying current pulse increases elongation, especially at high strain rate, from 190 % to 520 %, and exhibits obvious effect. On this bases, we can analyze the experimental results within the range

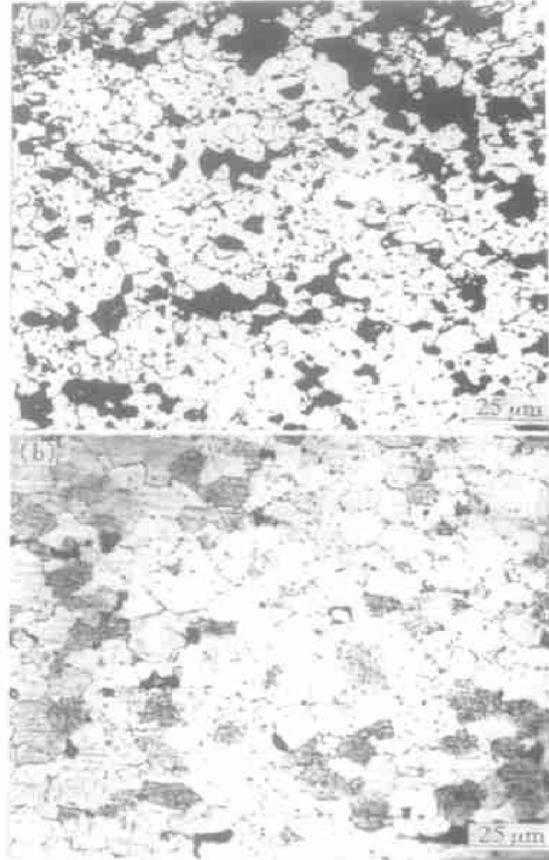


**Fig.2** Microstructures at fracture  
 ( $\dot{\epsilon} = 3.33 \times 10^{-3} \text{ s}^{-1}$ ,  $J = 2.0 \times 10^2 \text{ A/ m m}^2$ )  
 (a) —At high magnification;(b) —At low magnification

of superplasticity .

By examination of Figs .1 , 2 , we can find that in the specimen employed current pulse at low strain rate ( $\dot{\epsilon}_2 = 3.33 \times 10^{-3} \text{ s}^{-1}$ ) , tough combs exist in local position of the fracture , which shows a local interior fracture morphology , and in the specimen employed current pulse , the grain boundary at the fracture displays a quite smooth surface .

By analyzing optical metallographic microstructure , it can be found that a too active dynamic recrystallization in microstructure doesn't stop until last stage of the deformation(see Fig . 3(a)) , which makes grain boundary irregular and unfavorable for grain boundary sliding . On the other hand , the ratio of longitudinal size with latitudinal size in grains at this deformation stage is quite great , which inevitably creates a high stress in subsequent grain rotation and rearrangement in superplastic deformation ,

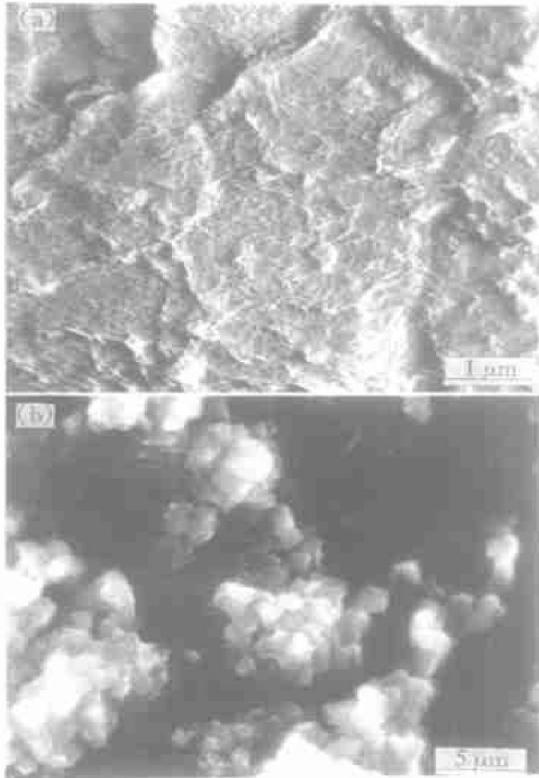


**Fig.3** Optical metallographic microstructures at fracture( $\dot{\epsilon} = 3.33 \times 10^{-3} \text{ s}^{-1}$ )  
 (a) — $J = 0$  ;(b) — $J = 2.0 \times 10^2 \text{ A/ m m}^2$

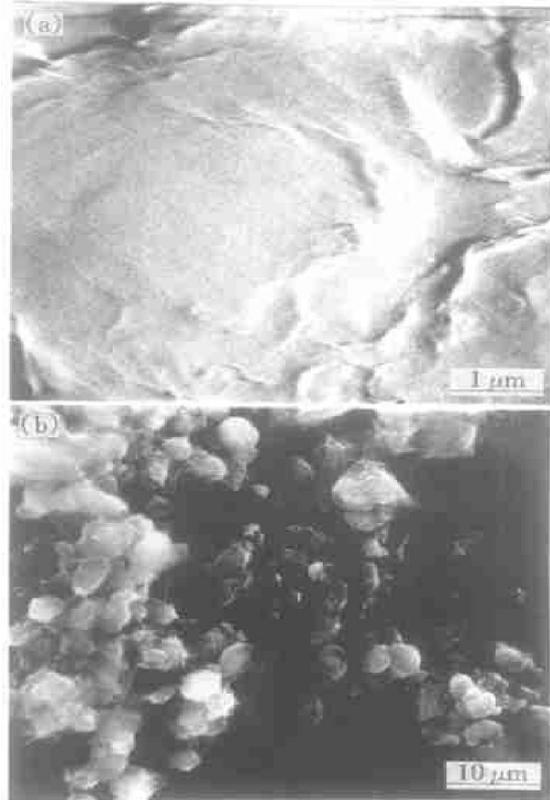
especially a quite high bending stress that is enough to lead to an interior fracture when grains rotate<sup>[5]</sup> . When applying current pulse at the same deformation condition , there is rarely dynamic recrystallization , grain boundary is quite regular , and grain is quite equiaxial . It is because current pulse promotes dislocation slip and atom diffusion , and makes the interior dislocation created in the deformation easily enter into grain boundary by slip and climb , which decreases so much distorted lattice energy that an active dynamic recrystallization has not enough driving force to take place , and grain boundary can remain regular morphology to be favorable for grain boundary sliding . Meanwhile , the function that current pulse promotes atom diffusion , especially short range atom diffusion can

prevent the ratio of longitudinal size with latitudinal size in grains from increasing led by interior dislocation slip in the deformation, and keeps the grains equiaxed. All of the above contribute the grain boundary sliding and grain rotation, and satisfy the need of the typical superplastic deformation for microstructure. Consequently, it is believed that the failure in the superplastic deformation employed current pulse is accomplished by diffusional cavity nucleation, growth and interlinkage, and also that is the reason for grain boundary surface to get smooth, as shown in Fig 2(b).

At high strain rate ( $\dot{\epsilon}_2 = 3.33 \times 10^{-2} \text{ s}^{-1}$ ), although at low magnification both the superplastic deformation unapplied current pulse and applied current pulse show an intergranular fracture morphologies (see Fig.4(a) and Fig.5



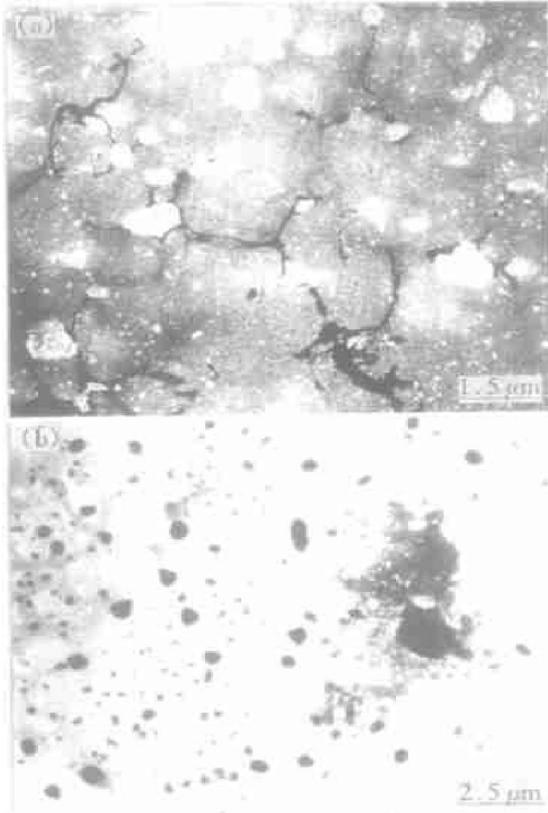
**Fig.4** Microstructures at fracture  
( $\dot{\epsilon}_2 = 3.33 \times 10^{-2} \text{ s}^{-1}$ ,  $J = 0$ )  
(a) —At high magnification;  
(b) —At low magnification



**Fig.5** Microstructures at fractures  
( $\dot{\epsilon}_2 = 3.33 \times 10^{-2} \text{ s}^{-1}$ ,  $J = 2.0 \times 10^2 \text{ A/min}^2$ )  
(a) —At high magnification;  
(b) —At low magnification

(a)), it is found by SEM that on the grain boundary surface in the superplastic deformation unapplied current pulse there are many small pits (see Fig.4(b)), and the grain boundary surface in the superplastic deformation applied current pulse is smooth, as shown in Fig.5(b).

As we know, the normal creep failure at high temperature is created by cavity nucleation, growth and interlinkage<sup>[1~3]</sup>. At high strain rate ( $\dot{\epsilon}_2 = 3.33 \times 10^{-2} \text{ s}^{-1}$ ), the atom diffusion ability in the superplastic deformation unapplied current pulse is relatively low, the cavity nucleated at grain boundary has no time to grow and interlink, the stress concentration at grain boundary cannot be relaxed, and subsequently grain boundary is torn under the action of the stress concentration (see Fig.6(a)), the metallic



**Fig.6** Cavity nucleation  
( $\varepsilon = 3.33 \times 10^{-2} \text{ s}^{-1}$ )

(a)  $-J = 0$ ; (b)  $-J = 2.0 \times 10^2 \text{ A/m}^2$

body between cavities that have not grown up on the grain boundary is tensioned to broken and creates the many small pits as shown in Fig.4 (b).

When applied current pulse, in spite of the fact that it still superplastically deformed at same high strain rate ( $\varepsilon_2 = 3.33 \times 10^{-2} \text{ s}^{-1}$ ), the atom diffusion ability is increased greatly due to the action of current pulses, the cavity nucleated at grain boundary has enough time to grow up and interlink by atom diffusion (see Fig.6 (b)), which gets the grain boundary surface quite smooth, as shown in Fig.5 (b). Simultaneously, the growth of diffusional type of cavity can greatly relax the stress concentration created at the triple junction of grain boundary by grain boundary sliding, on the other hand, that cur-

rent pulse accelerates the process of dislocation slip and climb, especially the acceleration of the later process also greatly relaxes the stress concentration at the triple junction of grain boundary, both remain a good interlinkage of grains at triple junction of grain boundary, and at last make the superplastic elongation double increased.

## 5 CONCLUSIONS

(1) At low strain rate, current pulse promotes atom diffusion, restrains irregular migration of dynamic recrystallization interface, remains a good regular boundary and equiaxed grains, and avoids local interior fracture.

(2) At high strain rate, the characteristic that current pulse promotes dislocation slip, climb and atom diffusion not only relaxes the stress concentration at the triple junction of grain boundary, but also makes contribution to the development of diffusional type cavity, and a normal superplastic fracture is displayed.

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