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Effect of electric current pulse on grain growth in superplastic deformation of 2091 Al-Li alloy ①

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Abstract: The effect of electric current pulse on the grain growth in the superplastic deformation of 2091 Al-Li alloy was investigated. Optical metallographic microstructure observation and average linear intercept measuring results show that at same strain, the grain size in the superplastic deformation loaded with electric current pulse is smaller than that unemploying electric current pulse, and so does the grain growth rate. TEM observation shows that the dislocation density at grain boundary in the superplastic deformation applied with electric current pulse is lower than that unemploying electric current pulse. It indicates that electric current pulse increases the rate of dislocation slip and climb in grain boundary, which leads to a decrease of both the density of the dislocation slipping across grain boundary at same strain rate and the driving force for grain growth, therefore the rate of grain growth decreases. The established model for grain growth shows an exponential relation of grain size with strain.

Key words: Al-Li alloy; grain growth; current pulse; superplastic; deformation

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1 INTRODUCTION

The characteristic that electric current pulse promotes atom diffusion and dislocation motion was gradually recognized from the failure analysis on integrated circuit in 1970s[1-10]. The electric current pulse was used to increase plastic property, improve the formability of less-deformable metals[11, 12], and study the effects of current pulse on recrystallization[13-18] respectively in 1980s. In this respect, Conrad and Lai have done a lot of work, in which Cu, Al and Ti were main experimental materials for deformation employed with a maximum current density from 10^2 to 10^3 A/mm^2. The frequency of electric current pulse was smaller than 10 Hz, and the pulse duration was varied from 50 to 200 μs. Current pulse can enhance nucleation rate of recrystallization, lowered down the grain growth rate of recrystallized grain and promoted recrystallization. It was successful to employ current pulse to enhance the property in supperplastic deformation of metals, especially at high strain rate[19-21]. Furthermore the probing in mechanism of current pulses on superplastic deformation and the establishment of rate equation of superplastic deformation with current pulses have proved a good understanding on the effects of electric current pulse[22]. As a continuation this work analyzes the grain growth in the superplastic deformation under the action of electric current pulse.

2 EXPERIMENTAL

The expesimental material in present study is 2091 Al-Li alloy, and its chemical composition in mass fraction (%) is: 2.2Li, 2.6Cu, 1.2Mg, 0.15Zr, 0.1Fe, 0.1Si, ≤10^{-5}Na, balanced Al. After homogenization at 530 ℃ for 24 h, hot rolled at 500 ℃ from 35 mm to 10 mm, solution at 530 ℃ for 2 h, and overaging at 400 ℃ for 32 h, the alloy is cold rolled to 0.7 mm thick plate. Then specimens are superplastically deformed at 500 ℃ with temperature error controlled within ±1 ℃ on a Shimadzu AG-10TA tension machine, while applying direct electric current pulse of half triangle wave in form with a maximum current density of 2.0×10^2 A/mm^2 and at a constant pulse frequency of 11 Hz.

The grain size at various deformed state is measured with average linear intercept method and the change of grain growth with strain in the superplastic deformation at low strain rate ($\dot{\varepsilon}$= 3.33×10^{-3} s^{-1}) and high strain rate($\dot{\varepsilon}$= 3.33×10^{-2} s^{-1}) is observed on a Polyvar-Met optical metallographic microscope. The dislocation structures at various state of cold-rolling, holding period before deformation and superplastic deformation to various strains are observed on an H-800 transmission electronic microscope (TEM).

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3 RESULTS

It is shown that by metallographic linear intercept method and metallographic observations, at low strain rate ($\dot{\varepsilon}=3.33\times10^{-3}s^{-1}$) the average grain size in the specimens with current pulse is measured as 2.7 μm, 5 μm, 11 μm with an equiaxed grain morphology, as shown in Figs. 1(a), (b), (c) and that in those without current pulse is measured as 3.2 μm, 7 μm, 12 μm with an irregular grain morphology, as shown in Figs. 2 (a), (b), (c) when $\varepsilon=0.37$, 1.03, 1.77(fractured), respectively. However at high strain rate ($\dot{\varepsilon}=3.33\times10^{-2}s^{-1}$) the average grain size in the specimens with current pulse is measured as 2.3 μm, 3 μm, 9 μm when being deformed at $\varepsilon=0.37$, 0.58, 1.84(fractured), respectively, as shown in Fig. 3, and that in those without current pulse is measured as 5.3 μm, 2.8 μm, 5.0 μm when $\varepsilon=0.37$, 0.58 and 1.06(fractured), respectively, as shown in Fig. 4. The above grain size measured at various strain and strain rate is plotted in Fig. 5. It is worth to point out that grain in the specimen without current pulse are not fully refined when being deformed at a high strain rate because only local recrystallization occurred at grain boundary at initial stage of deformation and when being deformed at $\varepsilon=0.58$ the grains are refined to the smallest size (2.8 μm) as shown in Fig. 4 (a), (b) and Fig. 5(b). TEM observations show that in cold-rolled specimen there is a high density of dislocation cell structure (as shown in Fig. 6(a)), which turns to a subgrain with migratory boundary of recrystallization after being held at 500 ℃ for 15 min (as shown in Fig. 6 (b)). Taking that in Fig. 6 (b) as original micro-

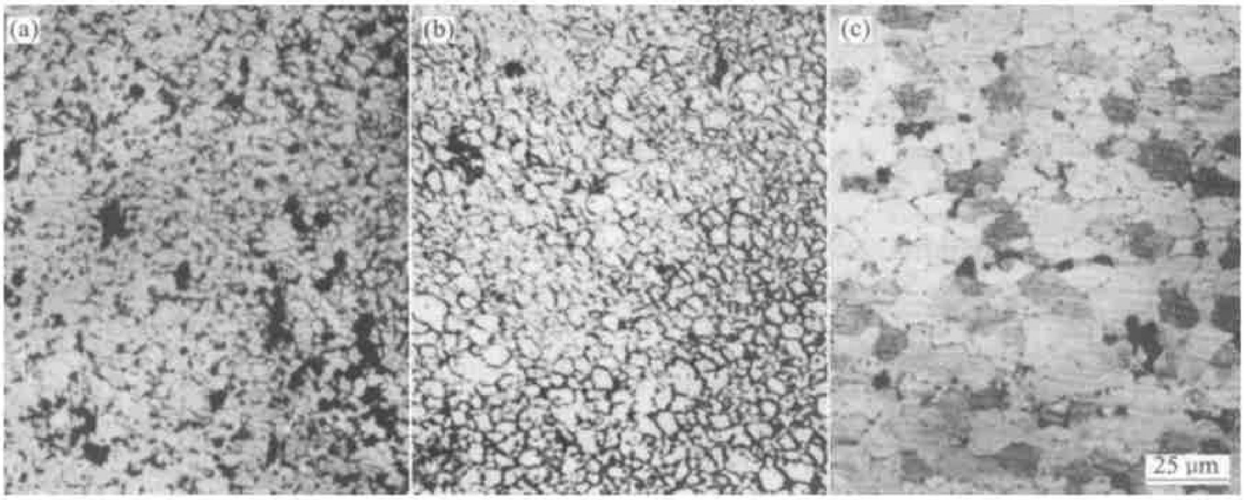

Fig. 1 Grain microstructures of Al-Li alloy with pulse current being 2.0×10^{2} A/mm^{2}
($\dot{\varepsilon}=3.33\times10^{-3}s^{-1}$)
(a) —$\varepsilon=0.37$; (b) —$\varepsilon=1.03$; (c) —$\varepsilon=1.99$(fractured)

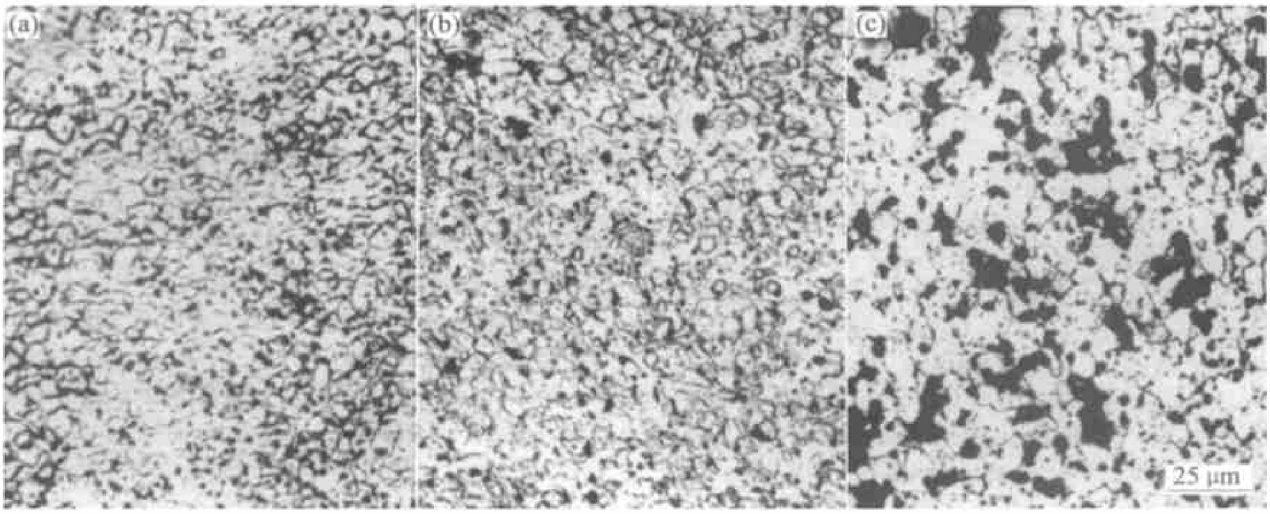

Fig. 2 Grain microstructures of Al-Li alloy without pulse current
($\dot{\varepsilon}=3.33\times10^{-3}s^{-1}$, $J=0$)
(a) —$\varepsilon=0.37$; (b) —$\varepsilon=1.03$; (c) —$\varepsilon=1.77$(fractured)

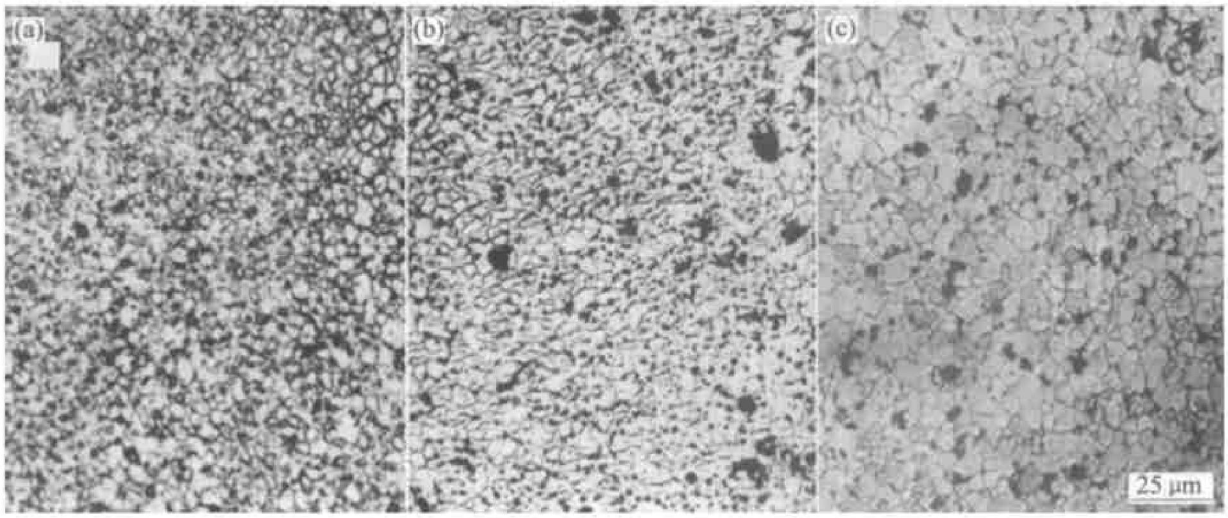

Fig. 3 Grain microstructures of Al-Li alloy with pulse current being 2.0×10^2 A/mm^2
($\dot{\varepsilon}=3.33\times10^{-2}\mathrm{s}^{-1}$)
(a) —ε= 0.37; (b) —ε= 1.03; (c) —ε= 1.84(fractured)

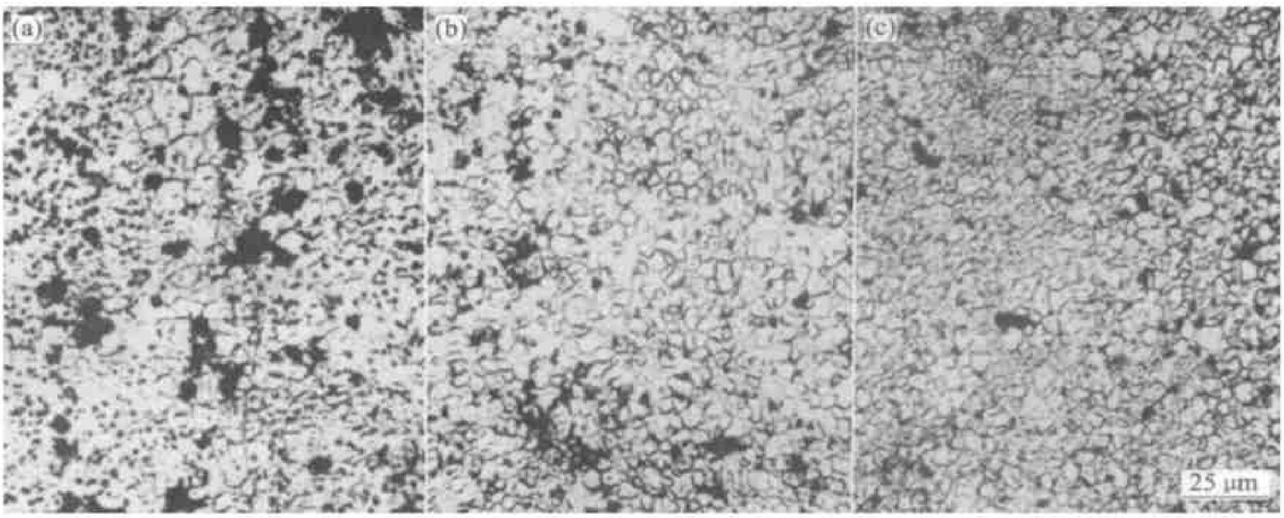

Fig. 4 Grain microstructures of Al-Li alloy without pulse current
($\dot{\varepsilon}=3.33\times10^{-2}\mathrm{s}^{-1}$, $J=0$)
(a) —ε= 0.37; (b) —ε= 0.58; (c) —ε= 1.06(fractured)

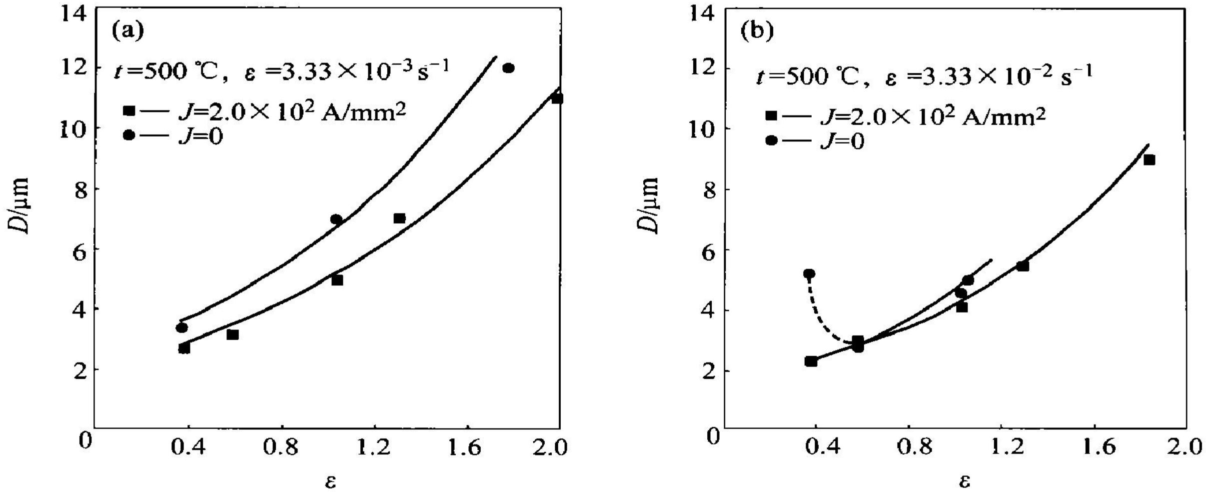

Fig. 5 Relation of average grain size with strain
(a) —$\dot{\varepsilon}=3.33\times10^{-3}\mathrm{s}^{-1}$; (b) —$\dot{\varepsilon}=3.33\times10^{-2}\mathrm{s}^{-1}$

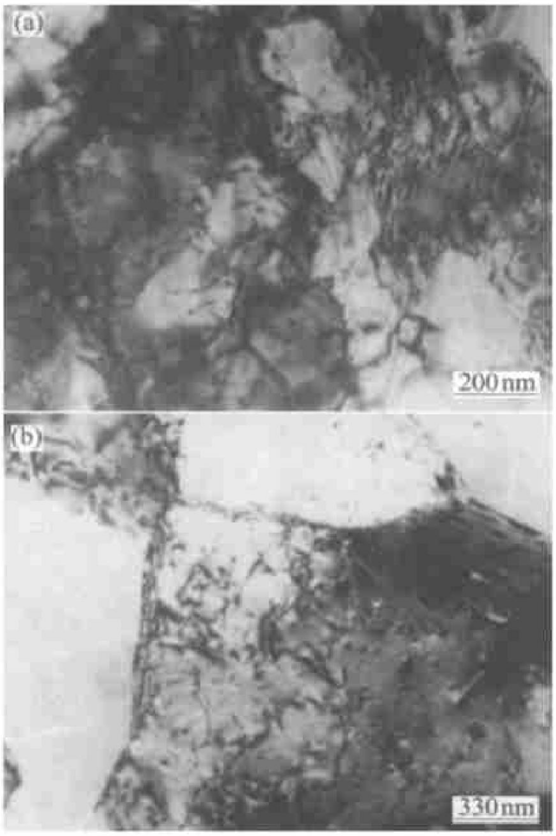

Fig. 6 Original dislocation structures before deformation

(a) —Cold rolled state; (b) —Held at 500 ℃ for 15 min

structure for superplastic deformation, little dislocation lies without tangling at grain boundary in the specimens with current pulse, whereas the opposite result occurred in those without current pulse at both low strain rate and high strain rate, as shown in Fig. 7 and 8.

4 ANALYSES AND DISCUSSION

4.1 Analyses on grain growth

It is shown from Fig. 1 to Fig. 5 that electric current pulse decreases the rate of grain growth whether the specimen is deformed at low strain rate ($\dot{\varepsilon} = 3.33 \times 10^{-3} s^{-1}$) or at high strain rate ($\dot{\varepsilon} = 3.33 \times 10^{-2} s^{-1}$), and meanwhile the grain growth rate at high strain rate is smaller than that at low strain rate whether the specimen in superplastic deformation is applied current pulse or not.

Ref. [23] realized that the driving force for grain growth in superplastic deformation is closely related with mobile dislocation in grain boundary. The higher the density of mobile dislocation in grain boundary is, the faster the grain grows. Normally grain boundary sliding rate is related to the density of grain boundary dislocation and the rate of dislocation slipping on grain boundary is controlled by the climbing rate of itself. After applying electric current pulses in

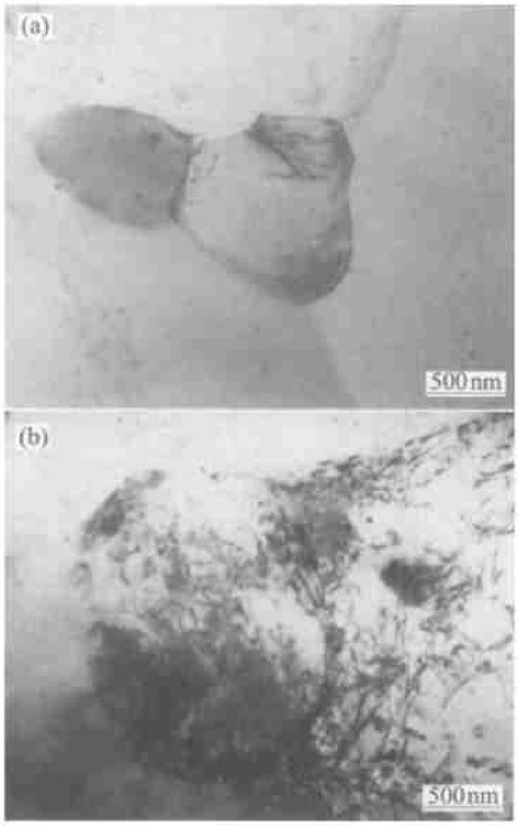

Fig. 7 Dislocation structures at grain boundary

($\dot{\varepsilon} = 3.33 \times 10^{-3} s^{-1}$, $\varepsilon = 1.03$)

(a) —$J = 2.0 \times 10^2 A/mm$; (b) —$J = 0$

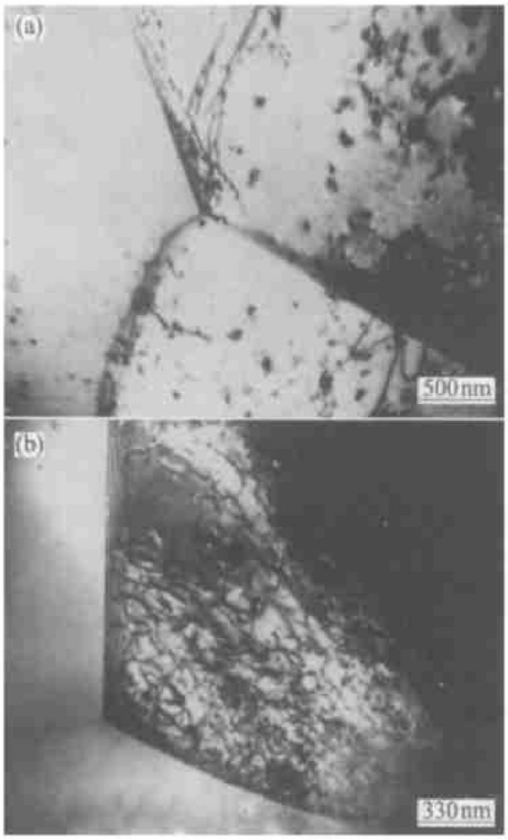

Fig. 8 Dislocation structures at grain boundary

($\dot{\varepsilon} = 3.33 \times 10^{-2} s^{-1}$, fractured)

(a) —$J = 2.0 \times 10^2 A/mm^2$, $\varepsilon = 1.84$;

(b) —$J = 0$, $\varepsilon = 1.06$

the superplastic deformation the climb process of dislocation on grain boundary is accelerated because current pulse promote atom diffusion, which leads to a rapid slipping rate of dislocation, decrease of the mobile dislocation density on grain boundary needed at a given exerted strain rate, as well as the driving force for grain growth in the superplastic deformation, and finally the rate of grain growth lowers.

The reason why grain growth rate at high strain rate is smaller than that at low strain rate lies in two respects: deformation time and the inertia of grain boundary sliding. The former is because the increase in the exerted strain rate leads to less time needed for a given strain, and atom diffusion in grain growth strongly depends on time, therefore at the same strain grain grows slowly at high strain rate compared to that at low strain rate. The latter is because with the exerted strain rate increasing the dominant mechanism in superplastic deformation changes from grain boundary sliding to interior dislocation slipping, and grain boundary dislocation becomes inert, which leads to less mobile dislocation on grain boundary.

Consequently current pulse lowers down the grain growth rate in superplastic deformation by enhancing the slipping rate of grain boundary dislocation and reducing the density of mobile dislocation on grain boundary at a given exerted strain rate. The effect of strain rate on grain growth lies in the facts as follows: 1) dependence of atom diffusion on time; 2) dependence of grain growth in superplastic deformation on active level of grain boundary sliding for a unit strain.

4.2 Model for grain growth

2091 Al-Li alloy pretreated in cold rolled state obtains superplasticity by grain refining in dynamic recrystallization. After dynamic recrystallization, the microstructure in alloy steps into superplastic flow, whose grain growth will be affected by high temperature besides superplastic deformation. The former is a normal grain growth at annealing, and the latter is affected by the density of grain boundary dislocation and deformation stress.

The driving force of grain boundary migration created by the exerted stress can be written as

$$P_b = \sigma\rho_b \Delta b \quad (1)$$

$$\rho_b = c_0 \dot{\varepsilon}_v t_b / b \quad (2)$$

where σ is the exerted stress, ρ_b the density of grain boundary dislocation, Δb the effective burgers vector of direction misfit dislocation in grain boundary, c_0 a constant, $\dot{\varepsilon}_v$ the intergranular strain rate, t_b the time that dislocation slips cross grain boundary.

Because current pulse applies a shear stress ($K_{ew} J/2$), the stress term is rewritten as

$$P_b = \left(\sigma + \frac{1}{2}K_{ew}J\right)\rho_b \Delta b \quad (3)$$

The driving force for grain growing at annealing is the surface tension of grain boundary, which can be expressed as

$$P_\gamma = \gamma / R_\gamma \quad (4)$$

$$R_\gamma = (\rho_b \cdot 2\sin\varphi)^{-1}$$

where γ is the surface energy of grain boundary, R_γ the local radius of grain boundary, φ the convex angle of grain boundary.

Because the migrating rate of grain boundary (v_m) is proportional to the total driving force ($P_\sigma + P_\gamma$):

$$v_m = M_b(P_\sigma + P_\gamma) \quad (5)$$

where M_b is the mobile factor of grain boundary.

According to Eqns. (1)−(5) the migrating rate of grain boundary (v_m) can be given by

$$v_m = M_b\left[\left(\sigma + \frac{1}{2}K_{ew}J\right)\Delta b + 2\gamma\sin\varphi\right] \cdot c_0\frac{\Delta b}{b}\dot{\varepsilon}_v t_b \quad (6)$$

It is known in traditional superplastic theories[24, 25] that the slipping of grain boundary dislocation is controlled by its climb at the triple junction of grain boundary, from which it is deduced that the time (t_b) needed for grain boundary dislocation slipping cross grain boundary is in inverse proportion to its climbing rate at the triple junction of grain boundary in superplastic deformation. According to Ref. [26], the climbing rate of dislocation in grain boundary can be written as

$$v_c = \frac{2\pi\Omega}{L^2 b} \cdot \frac{D_b}{kT}\Gamma_0 \quad (7)$$

where L is the distance from dislocation source to its annihilation place, Γ_0 is the dislocation line tension.

Supposing $\Omega = b^3$, $R = c_1 D$, $\Gamma_0 = br(\tau + K_{ew}J)$, and inserting them into Eqn. (7), v_c can be given by

$$v_c = \frac{2\pi b^3}{c_1^2} \cdot \frac{D_b}{LTD^2} r(\tau + K_{ew}J) \quad (8)$$

where c_1 is a constant; D the grain size, r the curvature radius of dislocation line.

Because a certain elastic strain will occur before dislocation climbs in the triple junction of grain boundary, its curvature radius changes from r_0 to r, therefore r_0 and r meet the following relation:

$$\frac{r}{r_0} = \frac{\tau + K_{ew}J}{G} \quad (9)$$

where G is the shear modulus.

Supposing $r_0 = c_2 D$, $\tau = \frac{\sigma}{2}$, and inserting them into Eqns. (8) and (9), v_c can be rewritten as:

$$v_c = \frac{\pi c_2}{2c_1^2} \cdot \frac{D_b b^3}{GkT} \cdot \frac{(\sigma + 2K_{ew}J)^2}{D} \quad (10)$$

Due to $t_b = 1/v_c$, t_b can be given by

$$t_b = \frac{2c_1^2}{\pi c_2} \cdot \frac{GkT}{D_b b^3} \cdot \frac{D}{(\sigma + 2K_{ew}J)^2} \quad (11)$$

Inserting Eqn. (11) into Eqn. (6), it can be obtained:

$$v_m=\frac{2c_0c_1^2\Delta bM_b}{\pi c_2}\cdot\frac{GkT\,\dot{\varepsilon}_v}{D_bb^4}\left[\left(\sigma+\frac{1}{2}K_{ew}J\right)\Delta b+2\gamma\sin\varphi\right]\cdot\frac{D}{(\sigma+2K_{ew}J)^2}\qquad(12)$$

Because grain growth rate dD/dt is in direct proportion to migration rate of grain boundary (v_m): $dD/dt=c_3v_m$, Eqn. (12) is rewritten as

$$\frac{dD}{dt}=A\,\dot{\varepsilon}_v\,T\cdot\frac{(\sigma+\frac{1}{2}K_{ew}J)\Delta b+2\sin\varphi}{(\sigma+2K_{ew}J)^2}D\qquad(13)$$

where $A=\dfrac{2c_0c_1^2c_3\Delta bM_bGk}{\pi c_2D_b\,b^4}$.

Integrating Eqn. (13), the grain size can be given by

$$D(\varepsilon)=D_0\exp\left[AT\frac{\dot{\varepsilon}_v}{\dot{\varepsilon}}\cdot\frac{(\sigma+\frac{1}{2}K_{ew}J)\Delta b+2\sin\varphi}{(\sigma+2K_{ew}J)^2}\cdot(\varepsilon-\varepsilon_0)\right]\qquad(\varepsilon\geqslant\varepsilon_0)\qquad(14)$$

According to Eqn. (14), both current pulse and strain rate lower down the grain growth rate, which is in accord with the experimental results, as shown in Fig. 5. In order to confirm whether the experimental results in Fig. 5 demonstrate the exponential relation of grain size with strain in Eqn. (14), the results in Fig. 5 are regraphed as figures of $\lg D$ —ε, as shown in Fig. 9. According to Fig. 9, all of the four groups of grain size (D) in Fig. 5 perfectly satisfy a linear relationship with strain, which expresses the grain growth model given by Eqn. (14), can really reveal the law of grain growth in the superplastic deformation of 2091 Al-Li alloy. It is worth to point out that because the grain growth model developed in Eqn. (14) is only suited for explaining the grain growth caused by the stress and temperature in superplastic deformation, it can not be applied to the grain refining at the initial stage of superplastic deformation, therefore the data of grain size before $\varepsilon=0.58$ of the specimen being unemployed with current pulses is ignored in Fig. 9(b).

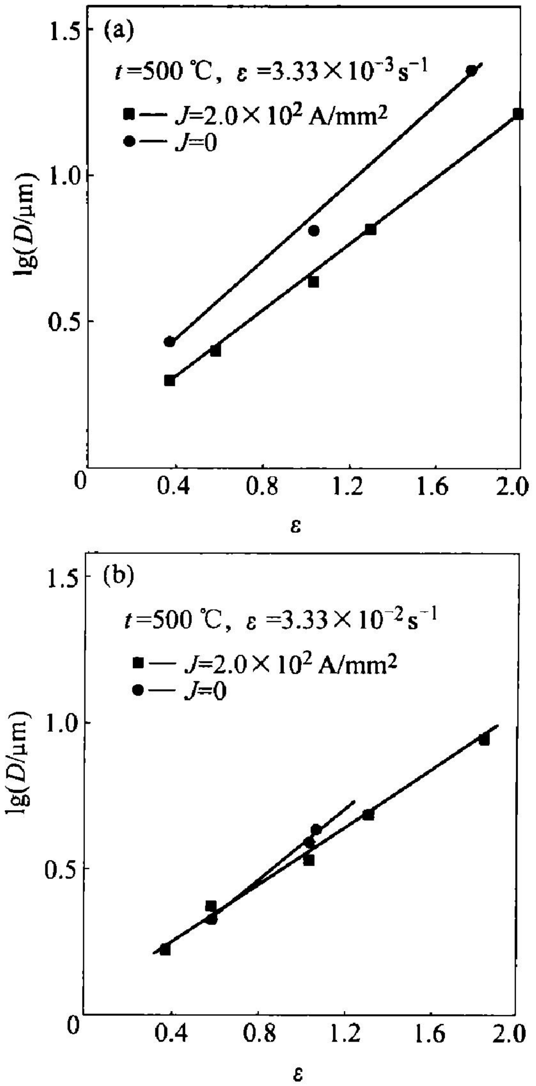

Fig. 9 Relation of $\lg D$ with ε
(a) —$\dot{\varepsilon}=3.33\times10^{-3}s^{-1}$; (b) —$\dot{\varepsilon}=3.33\times10^{-2}s^{-1}$

5 CONCLUSIONS

1) Electric current pulse decreases the driving force and rate of grain growth in superplastic deformation by enhancing the climb and slip rate of grain boundary dislocation and therefore lowering down the density of dislocation on grain boundary at a given exerted strain rate.

2) The increase in strain rate converts the grain boundary sliding from dominant mechanism to accommodating mechanism which decreases the number of mobile dislocation on grain boundary, and leaves insufficient time for atom in alloy to diffuse, therefore decreases the grain growth rate.

3) The law of grain growth in the superplastic deformation of 2091 Al-L alloy can be expressed by the following equation:

$$D(\varepsilon)=D_0\exp\left[AT\frac{\dot{\varepsilon}_v}{\dot{\varepsilon}}\cdot\frac{(\sigma+\frac{1}{2}K_{ew}J)\Delta b+2\sin\varphi}{(\sigma+2K_{ew}J)^2}\cdot(\varepsilon-\varepsilon_0)\right]\qquad(\varepsilon\geqslant\varepsilon_0)$$

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