ELECTRO-SUPERPLASTICITY IN 2091 Al-Li ALLOY①

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ABSTRACT

Effects of current pulses on superplasticity of cold rolled and 500 ℃, 30 min recrystallized states of 2091 Al-Li alloy were investigated. The tension results showed that current pulses made the elongation of 500 ℃, 30 min recrystallized specimens increase from $\delta = 290\%$ to $\delta = 390\%$, and the optimum strain rate of superplastic deformation in cold rolled specimens increase from $\dot{\varepsilon}_{opt} = 5.0 \times 10^{-3}\ s^{-1}$ to $\dot{\varepsilon}_{opt} = 8.33 \times 10^{-3}\ s^{-1}$, with the same δ_{max}. Investigations of mechanical behaviors indicated that current pulses enhanced the stress strain rate sensitivity exponent (500 ℃, 30 min recrystallized state) and pushed the value of m_{max} towards high strain rate region (cold rolled state). Electron probe analyses showed that current pulses made the solute atom Cu distribute more homogeneously. It was indicated that the enhancement of m value at high strain rate by applying current pulses was because homogeneously distributed solute atoms increased the stress strain rate sensitivity.

Key words: Al-Li alloy current pulse superplasticity

1 INTRODUCTION

Most commercial alloys are used either at rolled state or recrystallized state. Can we find out an approach to obtain superplasticity without the superplastic pretreatment? Electromigration and electroplastic theories developed from the 50's greatly inspire us. The quantitative formula for electromigration can be expressed as follows[1,2]:

$$j_l = \frac{1}{KT} N_l D_l \rho e z_l^* J \qquad (1)$$

$$j_b = \frac{1}{KT} \frac{N_b W}{d} D_b \rho e z_b^* J \qquad (2)$$

where j_l (j_b) — atom flux in grains (at grain boundary); N_l(N_b) — atomic density in grains (at grain boundary); D_l(D_b) — diffusion coefficient in grains (at grain boundary); ρ — resistance; ez_l^* (ez_b^*) — effective charge in grains (at grain boundary); K — Boltsman constant; T — absolute temperature; J — current density; W — effective width of grain boundary; d — grain diameter.

The driving force of dislocations by current pulses in electroplastic theory can be formulated as follows[3-5]:

$$F/l = K_{ew} J \qquad (3)$$

where F/l — the force per unit length of dislocation; K_{ew} — constant.

As we know, the basic mechanisms in superplastic deformation are dislocation motion (including grain boundary dislocation) and atomic diffusion, among which atomic diffusion is the rate controlling process in the micromechanisms of superplastic deformation[6,7]. Therefore, the motion of micromechanisms can be accelerated in case of applying current pulses in the superplastic de-

① supported by Doctor's Foundation of Education Committee of China; manuscript received Nov. 26, 1992
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formation of alloys, which enhances the superplastic properties of alloys.

In view of the conditions of commercial alloys normally used either at recrystallized or rolled state, the effects of current pulses on the superplasticity of 500 ℃, 30 min recrystallized state and cold rolled state of 2091 Al-Li were investigated. The results showed that current pulses increased the elongations of recrystallized specimens up to 100% at the strain rate range of $8.33\times10^{-4}\sim8.33\times10^{-3}\ s^{-1}$ and the optimum strain rate of cold rolled specimens from $5.0\times10^{-3}\ s^{-1}$ to $8.33\times10^{-3}\ s^{-1}$ with the same maximum elongation.

2 EXPERIMENTAL MATERIAL AND PROCEDURE

The experimental material is 2091 Al-Li alloy, its chemical composition is shown in Table 1. Undergoing 530 ℃, 24 h homogeneous process and 500 ℃ hot rolling (35 mm→10 mm), the alloy was cold rolled to a 0.7 mm thick plate in order to increase the current density per unit area, with the total reduction up to 93%. The recrystallized specimens were obtained by recrystallizing cold rolled specimens at 500 ℃ for 30 min in salt bath furnace. The superplastic deformation of specimens was carried out on a Shimadzu AG-10TA tension machine made in Japan. Considering the slight heating effect of low frequency current pulses, the thermocouples were brought into contact with two ends of specimens, and measuring and controlling the actual temperature of specimens were taken as criterion. The value of the stress jumping over stress tip value into stable flow ($\varepsilon=0.6$) at a given strain rate was taken in plotting the curves of $\lg\sigma$-$\lg\dot{\varepsilon}$. The original microstructures of two state specimens were observed with an optical microscope. Effects of current pulses on the area distribution of Cu atoms were analyzed with an electron probe.

Table 1 Chemical composition of the alloy

Elements	Al	Li	Cu	Mg
Contents/wt.-%	bal	2.2	2.6	1.2
Elements	Zr	Fe	Si	
Contents/wt.-%	0.15	0.1	0.1	

3 EXPERIMENTAL RESULTS

The superplastic deformating results of two kinds of original states of specimens are shown in Figs. 1 and 2. It can be seen from Fig. 1 that current pulses enhance the optimum strain rate of superplastic deformation of cold rolled specimens from $\dot{\varepsilon}=5.0\times10^{-3}\ s^{-1}$ to $\dot{\varepsilon}=8.33\times10^{-3}\ s^{-1}$, without decrease of the maximum elongation (δ_{max}). In Fig. 2, current pulses increase the elongation of 500 ℃, 30 min recrystallized specimens up to 100% at the strain rate range from $8.33\times10^{-4}\ s^{-1}$ to $8.33\times10^{-3}\ s^{-1}$. Mechanical behavior analyses indicate that current pulses move the maximum value of m of cold rolled specimens towards high strain rate, and increase the value of m of recrystallized specimens, as shown in Fig. 3 (a), (b). The tension curves of superplastic deformation of recrystallized specimens show a wave type of σ-ε curves when applying current pulses at a deformating strain rate of $\dot{\varepsilon}=8.33\times10^{-4}\ s^{-1}$, as shown in Fig. 4(a), (b). The optical microstructure observation shows an average grain size about 15 μm in 500 ℃, 30 min recrystallized specimens, as shown in Fig. 5. Electron probe analyses results show that current pulses make the Cu atoms in the specimens held at high temperature (500 ℃) distribute

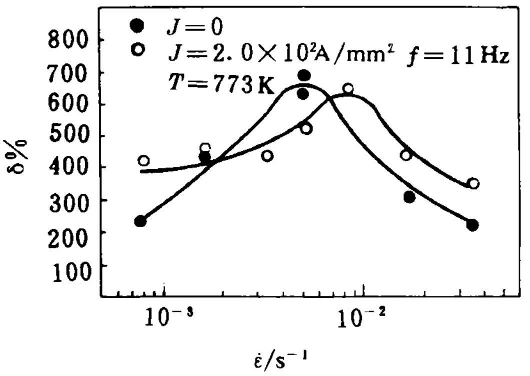

Fig. 1 δ-ε̇ curves of cold rolled specimens

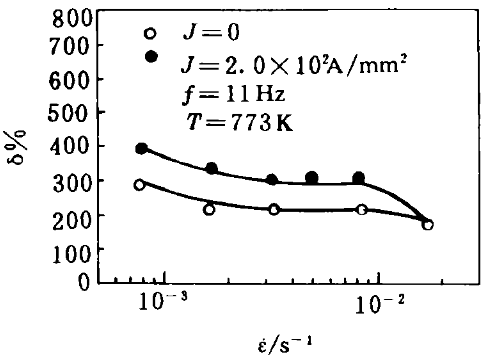

Fig. 2 δ-ε̇ curves of recrystallized specimens

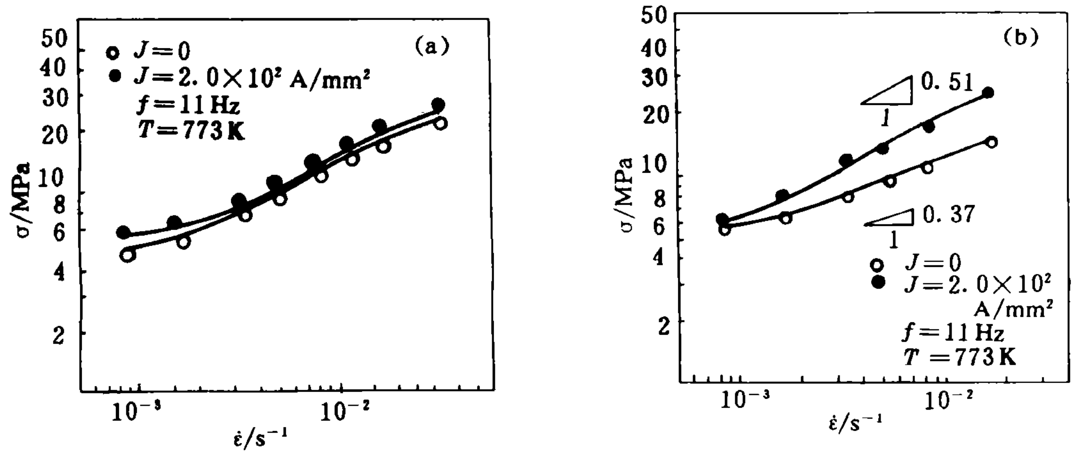

Fig. 3 lgσ-lgε̇ curves

(a)—cold rolled specimens; (b)—recrystallized specimens

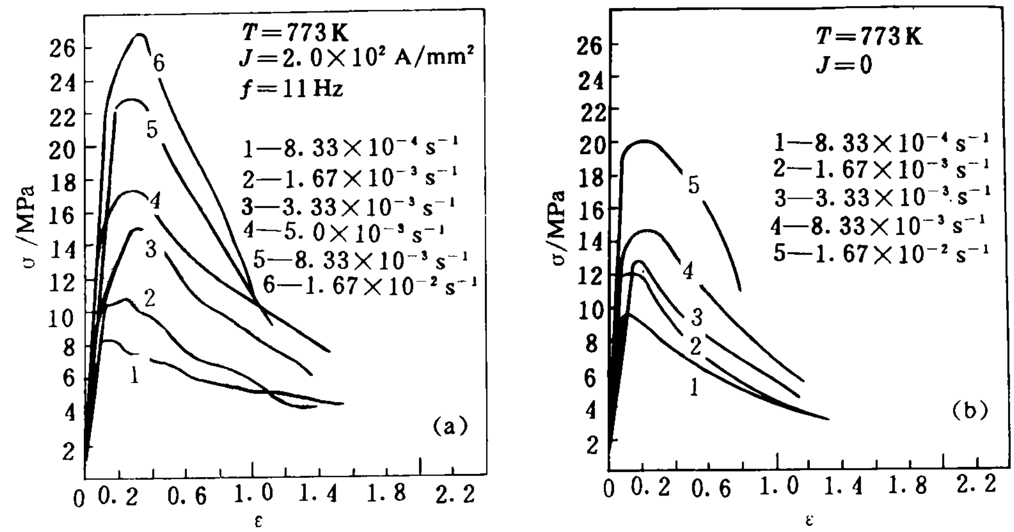

Fig. 4 σ-ε curves of recrystallized specimens

(a)— $J = 2.0\times10^2$ A/mm²; (b)— $J = 0$

homogeneously in a shorter time, as shown in Fig. 6 (a), (b).

4 ANALYSES AND DISCUSSIONS

Testing results show that current pulses move the maximum elongation and the maximum m value of cold rolled specimens towards high strain rate, and enhance the elongation and the m value of recrystallized specimens, in spite of a concurrently slight increase in flow stress of superplastic deformation, as shown in Figs. 1~3. As we know, the principal mechanisms in superplastic deformation are dislocation slip, including grain boundary dislocation, and atomic diffusion, which is a rate controlling process in micromechamism motion of deformation[6,7]. Acceleration of atomic diffusion will speed up the total micromechanism movement, and increase the optimum strain rate of superplastic deformation of cold rolled specimens and move the m value towards high strain rate range. As for recrystallized specimens, it is easy to create dislocation pile up in the deformation due to a large average grain size ($\bar{d} \sim 15$ μm), which causes a large stress concentration at grain boundary. In order to relax the stress concentration, atomic diffusion especially appears to be important, and current pulses just have the characteristic of promoting atomic diffusions. The relaxation of stress concentration accomodates grain boundary sliding, and also restrains cavity nucleation and growth.

Fig. 5 Original microstructure of 500 ℃, 30 min recrystallized specimen, ×400

Someone may ask, now that current pulses promote atomic diffusions and relax the stress concentration caused by dislocation pile ups at grain boundary, why does the flow stress increase? As we stated above, the temperature of superplastic deformation is high (500 ℃), close to the solution temperature (530 ℃) of the alloy, at such a temperature, the Al_3Zr particles precipitated in hot rolling alone can not solubilize. Therefore, the superplastic deformation of the alloy can be treated as solid solution deformation, and its flow behavior ought to follow Eq. (4)[8,9]:

$$\sigma = \sigma_f + M\alpha\mu b\sqrt{\rho} \qquad (4)$$

where σ—applied stress, σ_f—friction of dislocation motion; M —Tailoy factor; α—constant (about 1); μ —shear module; b —Burgers vector; ρ—dislocation density in motion. Among which, σ_f is related to solute atom type and its density (content) and distribution, and is a function sensitive to the rate of dislocation slip. As for cold rolled specimens, a lot of dislocations were stored in the microstructure. Before grains are refined (at initial stage of deformation), dislocation slip is dominant in micromechanism of deformation. Therefore, both the first term and the second term in Eq. (1) increase, and enhance the deformating stress, because applying current pulses increase mobile dislocation density, and dislocation slip rate concurrently. As for recrystallized specimens, applying current pulses is bound to

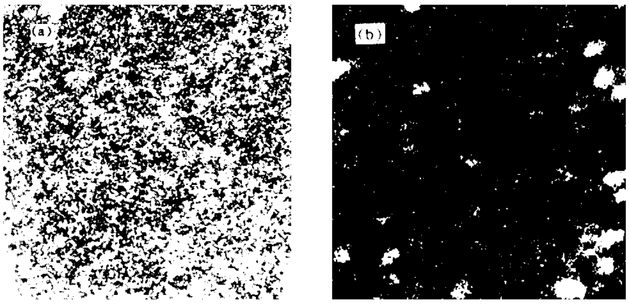

Fig. 6 Distribution of copper atom, $\times 400$

(a)—held at 500 ℃ for 5 min ($J = 2.0 \times 10^2$ A/mm^2); (b)—held at 500 ℃ for 15 min($J = 0$)

increase dislocation slip rate, and enhance deformation stress, because of large grain size, and enhancement of contribution of dislocation slip to deformation in micromechanisms[10,11]. In view of solute atoms, current pulses ($J = 2.0 \times 10^2$ A/mm^2) make solute atom Cu distribute more homogeneously in a shorter time (see Fig. 6), which leads to a decrease in average spacing of solute atoms. Therefore, it increases the resistance to dislocation slip and causes a increase in σ_f[12]. All these indicate that increase in flow stress led by applying current pulses results from increase in mobile dislocation density in grains and resistance to dislocation slip. As for dislocation pile up at grain boundary, the increase in climb rate of dislocations of pile up decreases stress concentration at grain boundary, restains cavity nucleation and growth at grain boundary, and avoids premature failure of specimens because current pulses increase the rate of atomic diffusion.

In view of mechanical behaviors, a decreased spacing of solute atoms by applying current pulses increases the sensitivity of σ_f to strain rate ($\sigma_f \sim v/l$), because σ_f is a sensitive function of dislocation slip rate proportional to strain rate ($\dot{\varepsilon} \sim v$), which leads to an increase in flow stress with strain at a more rapid rate when applying current pulses, and the value of m of superplastic deformation, (Fig. 3). It is well known that the value of m expresses the ability of resistance to the necking of specimens. The increase in the value of m is sure to enhance superplastic properties.

The wave type of σ-ε curves exhibited in Fig. 4 indicates that applying current pulses decreases the strain (ε_r) to complete dynamic recrystallization in the deformation, promotes dynamic recrystallization, reduces flow stress (comparing Fig. 4(a) with Fig. 4 (b)), which is favorable of accomodating grain boundary sliding and increasing superplastic properties[13].

Accordingly, applying current pulses promotes atomic diffusion in superplastic deformation of cold rolled and recrystallized specimens, which on the one hand, directly accomodates grain boundary sliding; on the other hand, reduces atomic spacing of solute, increases the sensitivity of flow stress to strain rate, (i. e. m) and the ability of resistance to necking of specimens. Concurrently, current pulses also promote dynamic recrystallization in the deformation. All these factors cause the favorable effects on superplastic deformation. Such a phenomenon that current pulses enhance superplastic properties is called electrosuperplasticity, which is in no doubt valuable to the superplastic forming of commercial alloys.

5 CONCLUSIONS

From the results, analyses and discussion above, it can be seen that current pulses promote atomic diffusions, dislocation slip, and increase the *m* value in superplastic deformation, and concurrently accelerate dynamic recrystallization in the deformation, which accordingly increases superplastic properties of 2091 Al-Li alloy.

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amounts. Too long holding time not only reduces cavity amounts effectually, but result in grain growth and strength decreas on the other hand. It can globularise cavity, and further improve material ductility.

5 CONCLUSION

(1) The original cavity in PM alloy begins disappearing when the alloy is superplastically deformed at the strain 0.3～0.4. In the case, the strength and the ductility at room temperature can reach the highest.

(2) The annealing for 15 h at 450 C after superplastic deformed can globlarise large size cavities, make fine cavities close, and result in the improvement of room temperature strength and ductility.

(3) The high strain rate is the specific characteristic of PM alloy, and when the strain rate reaches $8.33\times10^{-3}\ s^{-1}\sim4.17\times10^{-2}\ s^{-1}$, the elongation above 230% can be obtained.

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