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Electro-dislocation multiplication and strain effect in 2091 Al-Li alloy①

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Abstract: Electro-dislocation multiplication and strain effect were investigated. TEM observation showed that when statically held for 15 min, the microstructure of dislocation cell in the specimens without current pulse turned to subgrains with few dislocations in cold rolled state, but when current pulse charged, there were a lot of dislocations although a more rapid recrystallization occurred concurrently; when deformed, the interior dislocations in the specimens without current pulse were annihilated due to dynamic recrystallization, but were not decreased in the current pulse charged specimens in dynamic recrystallization, instead increased. It is indicated that "electron wind" force created by current pulse produced a shear stress for dislocation slip, and caused a dislocation multiplication in static holding of 2091 Al-Li alloy; when strain exerted, an additional shear stress was provided to increase the effect of current pulse on dislocation multiplication.

Key words: Al-Li alloy; deformation; dislocation multiplication; current pulse

1 INTRODUCTION

Current pulses can promote dislocation slip and atom diffusion[1~8]. The research on current pulses effects has extended to the field of recrystallization to resolve the basic problems about recrystallization and plasticity increasing of those metals which are difficult to process[9~12]. Recently more attention was paid to the study of recrystallization microstructures and subsequent effects on plasticity under the condition of applying current pulses, but the dislocation structural changes were neglected. This paper discussed particularly the effects of current pulses on dislocation structural changes and strain effects. To study dislocation structures with transmission electron microscope (TEM), a plate specimen was used in static holding and dynamic deformation test at high temperature, in which the promotion effect of strain on electro-dislocation multiplication was observed.

2 EXPERIMENTAL MATERIALS AND PROCEDURES

The experimental material was 2091 Al-Li alloy, whose chemical composition (mass fraction, %) was 2.2Li, 2.6Cu, 1.2Mg, 0.15Zr, 0.1Fe, 0.1Si, $\leqslant 10^{-5}$ Na, balance Al. After homogenization at 530 ℃ for 24 h, hot rolling at 500 ℃ from thickness of 35 mm to 10 mm, solution heat treatment at 530 ℃ for 2 h and overaging at 400 ℃ for 32 h, the alloy was cold rolled into a plate of 0.7 mm thickness to increase the current pulse density. The cold rolled plate was machined into specimens with a gauge size of 10 mm × 6 mm × 0.7 mm, then statically held at 500 ℃. Taking the microstructures of specimens held at 500 ℃ for 15 min as original one, the deformation experiment at 500 ℃ and initial strain rate of $3.33 \times 10^{-3}\ s^{-1}$ was proceeded to distinguish the effects of current pulse and strain, the specimens were divided into two groups, one was applied with high density current pulse ($2.0 \times 10^2\ A/mm^2$), the other without. The gauge section was cut off from sample and made into specimens along the plate plane for metallographic microscope and TEM observation. The dislocation and grain microstructures at various conditions were observed and compared with the corresponding results without current pulses.

3 EXPERIMENTAL RESULTS

TEM observation showed that original microstructures in cold rolled specimens were dislocation cell structure with high density which was changed into subgrain with few interior dislocations when statically held at 500 ℃ for 15 min, as shown in Fig. 1. However, more interior dislocations remained in specimens with current pulses at the same process, as shown in Fig. 2. Metallographic microstructure observation showed that the specimens without current pulses nucleated few recrystallized grains, while in those with current pulses were completely recrystallized (Fig. 3). Taking the microstructure in Fig. 1(c) as original one, when deformed at t = 500 ℃, $\dot{\varepsilon} = 3.33 \times 10^{-3}\ s^{-1}$, the interior dislocations in specimens without current pulses decreased until annihilation due to dynamic recrystallization (Fig. 4), and in

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those with current pulses when deformed on same conditions and strains, the interior dislocations were not decreased due to dynamic recrystallization, but increased greatly with deformation, as shown in Fig. 5. Metallographic microstructures observation showed that in both deformation states dynamic recrystallization was nearly completed, and the specimens with current pulses exhibited finer dynamic recrystallized grains as shown in Fig. 6.

4 ANALYSES AND DISCUSSION

4.1 Electro-dislocation multiplication

It can be seen from Fig. 1 that the dislocation cell structure in cold rolled specimen gradually changed into subgrain with a few scattered interior dislocations after static holding at 500 ℃ for 15 min without current pulses. Metallographic microstructures indicate that only a few recrystallized grains nucleated, most of which were unrecrystallized as shown in Fig. 3(a). Obviously the main micro characteristic in cold rolled specimens statically held without current pulses is that the dislocation changes into subgrains by recovery. However, in the static holding (500 ℃, 15 min) with current pulse more interior dislocations remained, and accompanied by active recrystallization, as shown in Fig. 2. The applied current pulses in static holding made grains distinctively finer as shown in Fig. 3(b), which means that the dislocation cell structures in cold rolled specimens after 500 ℃, 15 min static holding were transformed into recrystallized microstructures and the grains were refined, meanwhile a lot of interior dislocations remained. Generally, recrystallization is an annihila-

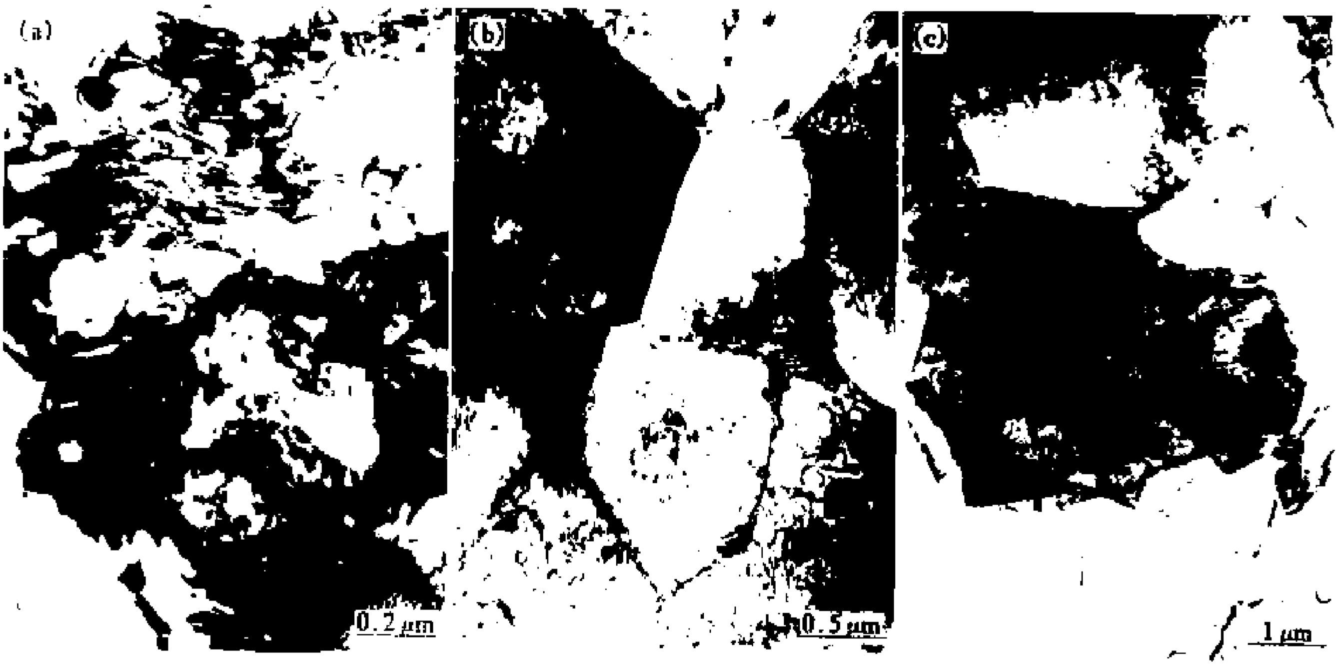

Fig. 1 Original microstructure and static holding microstructure (without current pulse)
(a) —Original microstructure; (b) —Held for 5 min; (c) —Held for 15 min

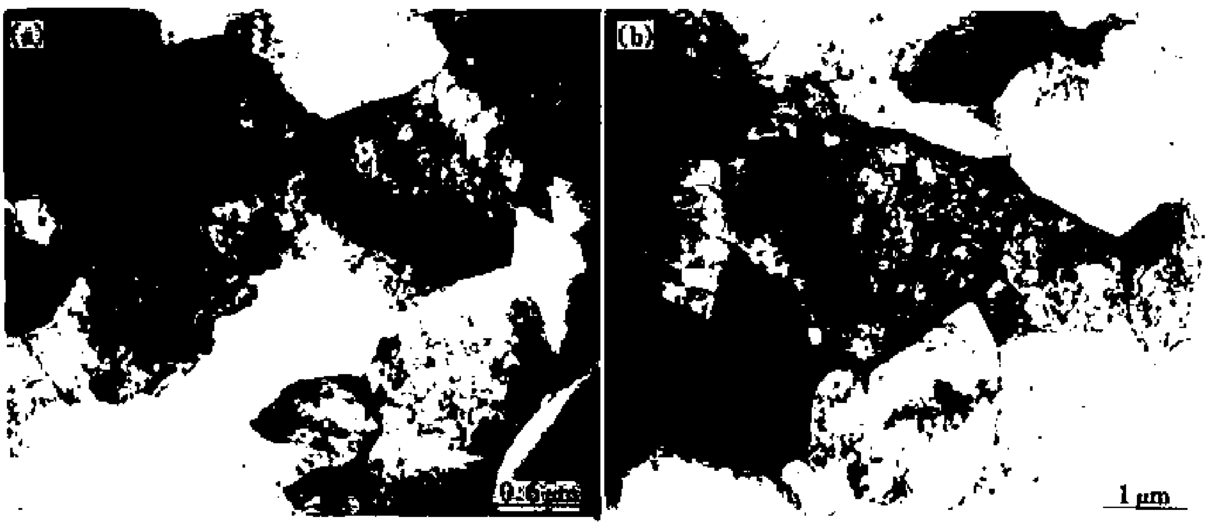

Fig. 2 Static holding microstructure (with current pulse)
(a) —Held for 5 min; (b) —Held for 15 min

tion process of interior dislocations, but the reason why so many interior dislocations still remained while grains were entirely refined by recrystallization is not clear.

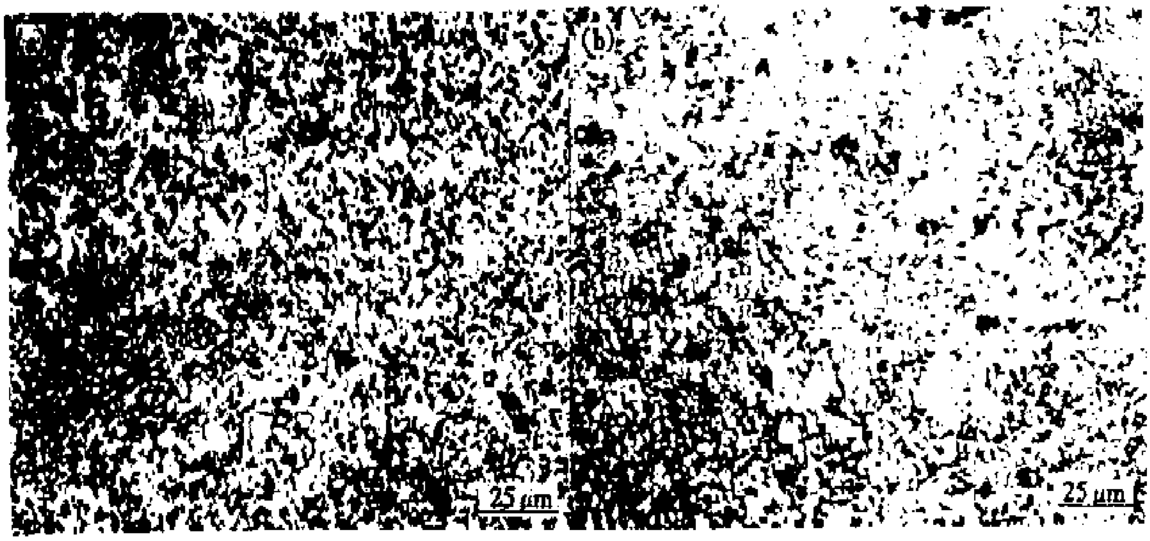

Fig. 3 Metallographic microstructures (held for 15 min)
(a) —Without current pulse; (b) —With current pulse

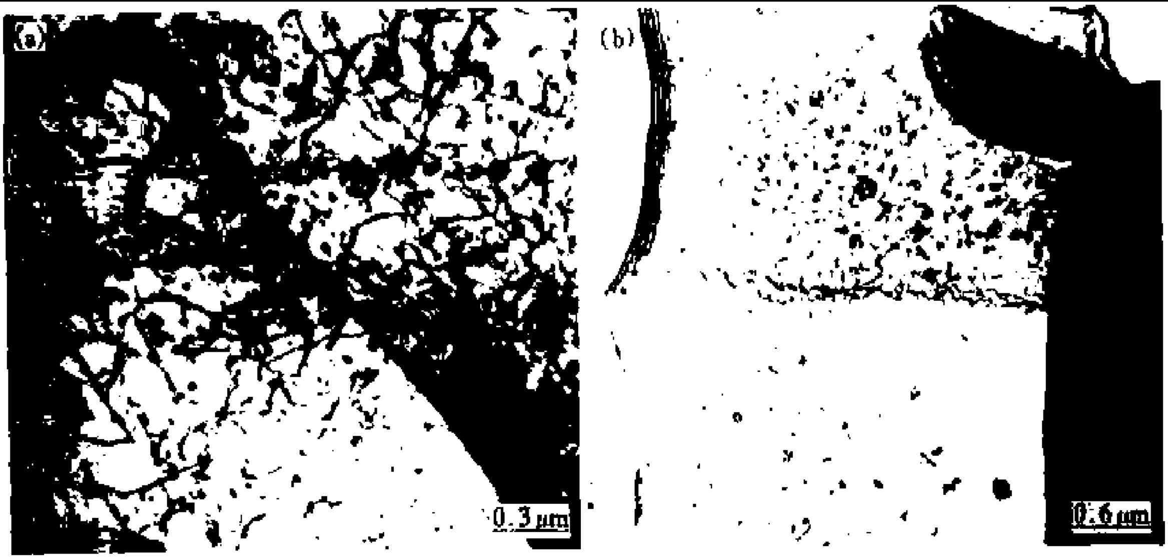

Fig. 4 Deformed microstructures (without current pulse)
(a) —ε= 0.14; (b) —ε= 0.37

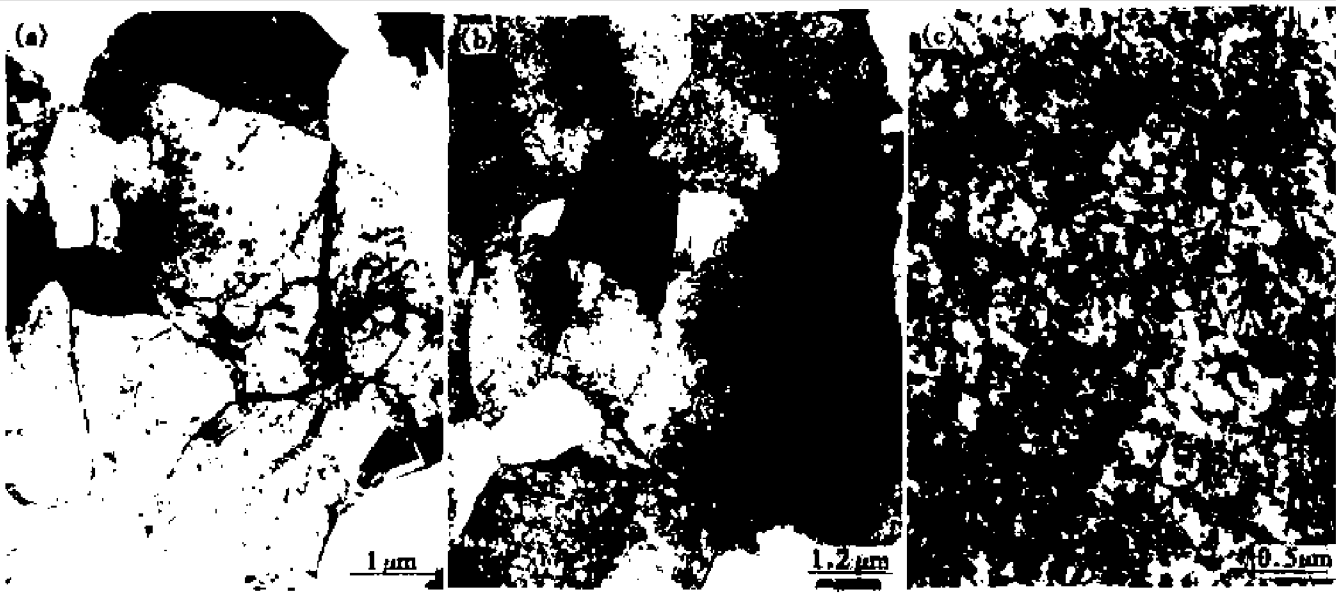

Fig. 5 Deformed microstructures (with current pulse)
(a) —ε= 0.14; (b) —ε= 0.37; (c) —ε= 0.37

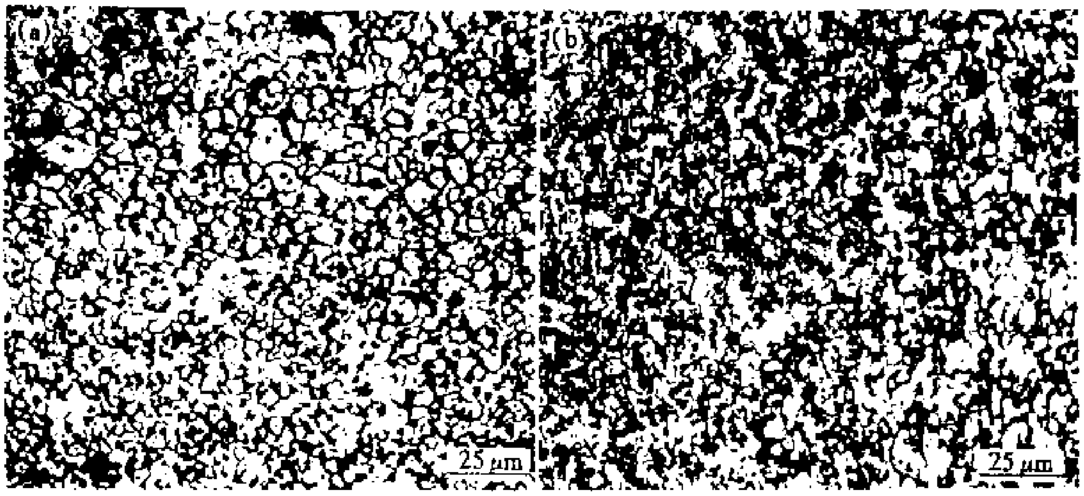

Fig. 6 Metallographic microstructures ($\varepsilon = 0.37$)
(a) —Without current pulse; (b) —With current pulse

The results shown in Fig. 1 indicate that in static holding without current pulses the dislocations remained in cold rolling were changed into subgrains by recovery, but their angles of boundaries are not large since the metallographic microstructures display few recrystallized grains. Normally the more the dislocations forming subgrains are, the larger the angle of the subgrain boundary is, and the easier the recrystallization takes place[13, 14]. On the contrary, this law can also explains why the dislocation remained in cold rolling is not developed enough to form relative high angle subboundary and nucleate more recrystallized grains. However, in static holding with current pulses, recrystallization of refining grains can be fundamentally accomplished to the same primary amount of dislocation, meanwhile many interior dislocations still remained, which indicates that there is inevitably a dislocation multiplication mechanism to continuously create enough dislocations to compensate the dislocations annihilated by recrystallization. This mechanism is called as electro-dislocation multiplication effect of current pulse.

As we know[1], "electron wind" created by current pulses has a propelling force on dislocation, which can be expressed as

$$F/l = K_{ew}J \qquad (1)$$

where F/l is the force on dislocation per unit length; K_{ew} constant; J density of current pulse.

According to dislocation multiplication created by Frank-Read dislocation source, the minimum shear stress needs to be

$$\tau = \mu b/l_0 \qquad (2)$$

where μ is the shear module; b the Burgers vector; l_0 the distance between two pinned points of dislocation.

According to Eqns. (1) and (2), to multiplicate dislocations the "electron wind" force must satisfy

$$K_{ew}J \geqslant \frac{\mu b^2}{l_0} \qquad (3)$$

On the condition that various factors such as the density of current pulse and materials are constant, the value of l_0 for Frank-Read source to create dislocation multiplication must be calculated as

$$l_0 \geqslant \frac{\mu b^2}{K_{ew}J} \qquad (4)$$

Eqn. (4) indicates that the Frank-Read source with a relatively large value of l_0 can easily multiplicate dislocations when other factors are constant.

Consequently, in the static holding process with current pulse, a concurrent process of recrystallization takes place, which nearly completes the refining of grains while a large number of dislocations still remain, and correspondingly, in the process of without current pulse the subgrains contain few interior dislocations and only few recrystallized grains nucleated, which is enough to demonstrate that current pulses cause multiplication of dislocation.

4.2 Strain Effects

Fig. 4 shows that when deformed at high temperature, taking Fig. 1(c) as original microstructure, the interior dislocation gradually decreased until annihilation due to dynamic recrystallization. Metallographic microstructures display that up to $\varepsilon = 0.37$ grains are completely refined by dynamic recrystallization (Fig. 6(a)). However, under the same condition of high temperature deformation with current pulse the interior dislocations increase (Figs. 5(b), (c)) while concurrent dynamic recrystallization refines grains (Figs. 5(a), (b) and Fig. 6(b)). And compared with Fig. 2(c), the effect of electro-dislocation multiplication is more outstanding than that in the static holding one.

It is known that the shear stress induced by exerted stress of deformation can multiplicate dislocations. But, the result in Fig. 4 indicates that the dislocations multiplicated by deformation and those from original microstructure are only enough for the consumption of refining grains in dynamic recrystallization, and few interior dislocations remain. According to the analyses and discussion in section 4. 1 and the result in Fig. 4, it is believed that the shear stress induced by "electron wind" force, which is created by current pulse, together with that induced by exerted stress of deformation, promote dislocation multiplication. That is to say, due to the joint effects of current pulse and deformation stress, the created dislocation multiplication makes a lot of extra dislocations besides the dislocation consumption of dynamic recrystallization in refining grains, which are shown in Figs. 4 and 5.

From the deduction in Eqn. (1) to Eqn. (4), the distance(l_1) between two pinned points of dislocation in the source to create dislocation multiplication can be written as

$$l_1 \geqslant \frac{\mu b^2}{K_{ew} J + \tau_e b} \tag{5}$$

where τ_e is the shear stress created by deformation stress.

Comparing with Eqn. (5) and (4) ($l_0 < l_1$), it can be seen that the common action of deformation stress and current pulse decreases the distance between two ends of dislocation source to multiplicate dislocations, i. e. increases the number of dislocation sources that can multiplicate dislocations. Therefore, it is easy to understand the comparing difference of Fig. 5 and Fig. 2 .

Consequently, because of the action of shear stress induced by deformation stress and current pulse, a lot of dislocation multiplications are created, which leads to a surplus of lots of interior dislocations besides satisfying the consumption of dislocation in dynamic recrystallization; it is the common action caused by deformation stress and current pulse that creates a larger shear stress, operates more dislocation sources and multiplicates more dislocations than the action of current pulse does alone.

5 CONCLUSIONS

The shear stress created by "electron wind" force of current pulse leads to dislocation multiplications in the static holding of 2091 Al-Li alloy, and strains promote the dislocation multiplication of current pulse in 2091 Al-Li alloy.

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