CONDITIONS FOR THE OCCURRENCE OF SERRATED FLOW IN Al-Li SINGLE CRYSTALS①

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ABSTRACT Serrated flow of Al-Li single crystals was investigated under different aging conditions, temperatures(T) and strain rates($\dot{\varepsilon}$). The results show that dynamic strain aging(DSA) of solute Li atoms alone is not strong enough to make the serrated flow at solid solution state. The occurrence of the serrated flow is related to the shearing of δ' particles. Critical strain of serration can change normally or inversely with T and $\dot{\varepsilon}$, which indicates the serration in Al-Li alloys is a thermally activated process. A proposed mechanism for the occurrence of the serration is that mobile dislocations are pinned when they cross the sheared δ' particles that might be dissolved during deformation, thus induce the serrated flow in the Al-Li single crystal.

Key words Al-Li single crystal serrated flow(PLC effect) aging conditions

1 INTRODUCTION

Al-Li alloy has great potential value for its low density, high special modulus and good cryogenic properties. The deformation of the alloy shows strong serrated flow (Portevin-Le Chatelier effect or PLC effect) with two features as follows.

(1) The serrated flow occurs in certain temperature(T) and strain rate($\dot{\varepsilon}$) range.

(2) The serrated flow is only related to the existence of coherent δ' precipitates, and it does not occur in the alloy in solid solution state. This leads to two explanations of the instability in Al-Li alloy: (a) The dynamic strain aging caused by Li or other constitutional elements, such as Cu, Mg atoms[1-3]; (b) The shearing of the δ' precipitates by gliding dislocations results in the work softening[4, 5].

To clarify the causes and avoid complicated effect of constitutional elements and micro structures in commercial alloys, Al-Li binary single crystals with different aging states were deformed in certain T and $\dot{\varepsilon}$ ranges. The results showed that the PLC effect in Al-Li alloy is related to the shearing of the δ' particles and is a thermally activated process, and also the critical strain of the serration occurrence (ε_c) varies with T and $\dot{\varepsilon}$.

2 EXPERIMENTAL PROCEDURES

Al-Li binary single crystals were grown with modified Bridgman method. After homogenized, the single crystals were cut into the samples of 6. 2 mm × 3. 4 mm × 3. 4 mm. The samples were solution treated at 793 K for 0. 5 h and quenched into water, then they were undergone compression tests either within a few hours(denoted by quenched state) or after aged at room temperature for several days(denoted by NA) or at 448 K for different time. There is no difference in their micro structures between the quenched state and NA state when Li content is below 1. 4% of its solvable limit at room temperature. The sample's number, Li content, orientations of compressive axes and aging processes are summarized in Table 1.

The compressive tests were performed with MTS-880 machine, using displacement

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control at strain rates between $1.4\times10^{-4}\ s^{-1}$ and $2.2\times10^{-2}\ s^{-1}$ in the temperature range of $200 \sim 453$ K. The load-displacement curves were recorded with X-Y recorder.

Table 1 Samples and heat treatment processes

sample	Li content /%	orientation	aging
A	0.90	[134]	quenched state
B1	2.11	[134]	NA
B2, B3, B4, B5	2.11	[134]	448 K and 10, 20, 48, 100 h respectively
C	2.10	[612]	448 K, 20 h

Micro structures were verified with a Hitachi-800 TEM. Slip lines on the sample surfaces were observed with Hitachi S-530 SEM after deformation.

3 RESULTS

The load-displacement curves for the samples B are shown in Fig. 1. The serrated flow occurred for the samples aged at 448 K for $10 \sim 100$ h, and the critical strain ε_c increased with the aging time, which is in accordance with the general change of ε_c. The compression curve for the sample B1 without artificial aging did not exhibit the serrated flow. Thin foils of the sample were examined using TEM, and no δ' precipitates were found.

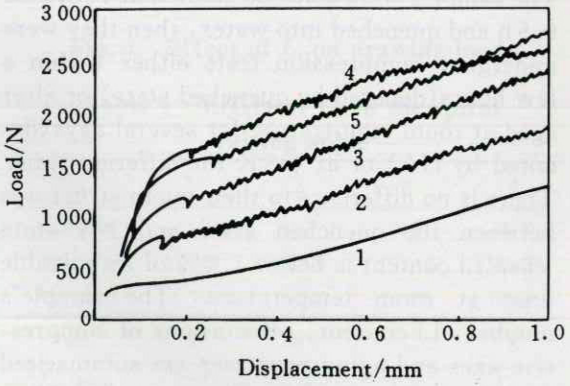

Fig. 1 Load-displacement curves for the samples B

1—NA; 2—448 K, 10 h;
3—448 K, 20 h; 4—448 K, 48 h;
5—448 K, 100 h

In order to make sure whether the serration occurred in Al-Li single crystal in quenched state or not, compression test was performed for the sample A in wide T and $\dot{\varepsilon}$ ranges in which the dynamic strain aging (DSA) of Li atoms occurred[6]. The results are shown in Fig. 2. No serration was found. This means the DSA of Li atoms can not lead to the serrated flow in Al-Li alloy.

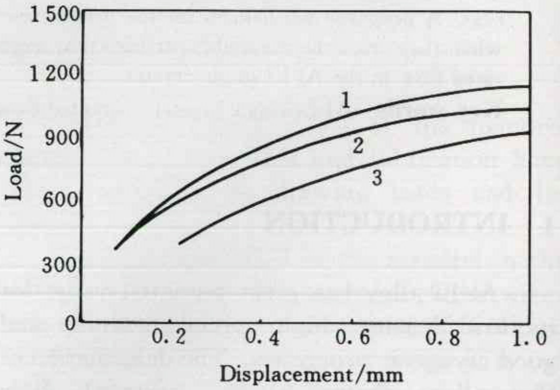

Fig. 2 Load-displacement curves for the samples A

1—293 K, $\dot{\varepsilon}=5.6\times10^{-3}\ s^{-1}$;
2—293 K, $\dot{\varepsilon}=5.6\times10^{-4}\ s^{-1}$;
3—373 K, $\dot{\varepsilon}=5.6\times10^{-3}\ s^{-1}$

The serrated flow usually occurred after a small amount of strain, namely the critical strain ε_c. Fig. 3 shows that ε_c varied with the deformation temperature and strain rate for the sample C. It can be seen that ε_c decreased with increasing T when T is below 333 K ($\dot{\varepsilon}=5.6\times10^{-3}\ s^{-1}$) or decreasing $\dot{\varepsilon}$ when $\dot{\varepsilon}$ is higher than $2.8\times10^{-3}\ s^{-1}$ ($T = 293$ K), which is called as the normal behavior of ε_c. Over this T range and below this $\dot{\varepsilon}$ range, ε_c changed inversely with increasing T or decreasing $\dot{\varepsilon}$. This relation indicated that the PLC effect in Al-Li alloy is a typical thermally activated process. δ' particles at under-aged state are coherent to Al matrix. They were sheared by gliding dislocations when the dislocations crossed the particles, as shown in Fig. 4. It is clear that some δ' particles were cut into two parts. This result has already been confirmed before. The gliding dislocations moved easily on the same slip plane after the δ' particles were sheared, which could induce the so called planar slip as a result.

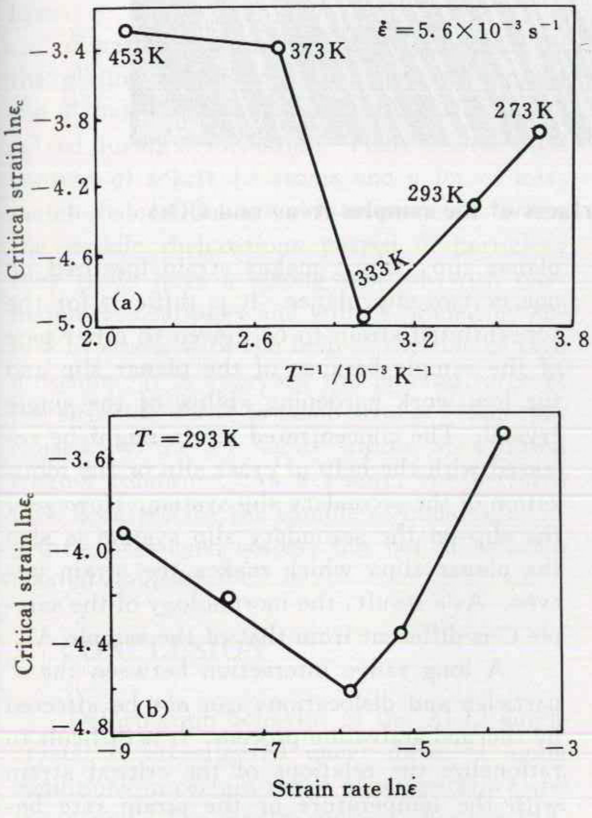

Fig. 3 Critical strain varied with temperatures and strain rates

Fig. 5 shows the slip lines on the surface of the samples A and C, respectively. Compared with relatively homogeneous slip of the sample A, slip lines of the sample C appear as "slip bands" where occurred heavy slips. The slip bands reflected inhomogeneous slip created by the planar slip. This result is the same as those of Tamura's[4] and Miura's[7].

4 DISCUSSION

Occurrence of the PLC effect is generally ascribed to the effect of the dynamic strain ageing on macroscopic plastic flow. The interaction between dislocations and solute atoms forms Cottrell atmosphere, and then the dislocations are pinned by the atmosphere and unpinned at following deformation, which will lead to the serrated flow. In substitution alloys, a critical strain ε_c is necessary to produce enough vacancies to enhance the diffusion rate, and ε_c will decrease with increasing T and decreasing $\dot{\varepsilon}$. According to the classical theory of PLC effect, the aging treatment inhibits the occurrence of serrated flow because of the reduction of content of the solute atoms in the matrix. This deduction is obviously in contradiction to the experimental result in Al-Li single crystal. No serration was found in the sample A although DSA must take place in the sample at least at room temperature and moderate strain rates. In consideration of the weak interaction between Li atoms and dislocations[8], it may be concluded that the DSA of Li atoms in Al-Li alloy can not lead to the serrated flow.

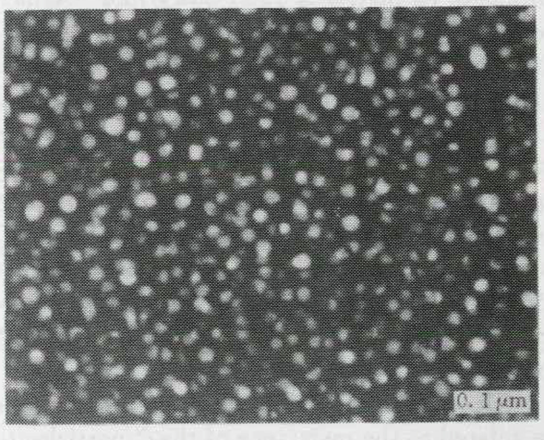

Fig. 4 The shered δ' particles under TEM, $\varepsilon = 0.037$

We can calculate the thermally activated energy of PLC effect from the change of ε_c with T and $\dot{\varepsilon}$ assuming that the PLC effect is controlled by diffusion of Li atoms. Based on the following formula used for data analysis:

$$\dot{\varepsilon} = A\varepsilon_c^{(m+\beta)}\exp(-E/(RT))$$

or $$\dot{\varepsilon} = A\varepsilon_c^{(m+\beta)}T^{-1}\exp(-E/(RT))$$

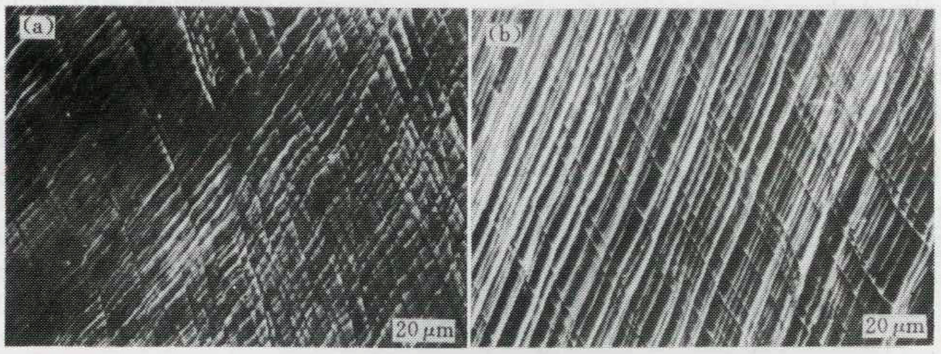

Fig. 5 Slip lines observed on the surfaces of the samples A(a) and C(b)

deduced by McCormick[9], E is obtained to be 23. 5 kJ/mol or 24. 51 kJ/mol respectively. Ref. [10] gave the E to be 51 ± 12 kJ/mol and $m+\beta$ to be 3 ± 0.5 which is too high in comparison with the most values reported in other Al alloys. In our calculation, $m+\beta$ is 1. 786, which is lower than general value $2\sim2.5$ in other Al alloys.

The activation energy of diffusion of Li atoms in Al matrix is 120 ± 10 kJ/mol[10] which appears to be too large to explain the PLC effect in Al-Li alloy. Even the vacancy concentration is taken into account, the estimated activation energy of diffusion of Li atoms can not be in accordance with the activation energy of PLC effect. Though the pipe-diffusion effect may play an important role in the diffusion of Li atoms, no occurrence of the serration in the crystals without δ' particles indicates that the PLC effect must be related to δ' particles.

It is said that the serration in Al-Li alloys is related to the resistance of the δ' particles to the movement of slip bands, and with the conclusion that the disappearance of the serration after peak-aged condition attained[11]. However, serrated flow still occurred for the sample B5 with over-aged state in our experiment. It is pointed out that PLC effect in commercial Al-Li alloys may be influenced by Mg and Cu atoms which themselves can also induce strong serrated flow[12].

The slip is inhomogeneous as a result of planar slip, which makes strain localized on one or two slip planes. It is difficult for the concentrated strain to be moved to other part of the sample because of the planar slip and the low work hardening ability of the single crystal. The concentrated strain might be released with the help of cross slip or the motivation of the secondary slip system. However, the slip on the secondary slip system is also the planar slip, which makes the strain uneven. As a result, the morphology of the sample C is different from that of the sample A.

A long range interaction between the δ' particles and dislocations can not be affected by thermal activation process. It is difficult to rationalize the relations of the critical strain with the temperature or the strain rate because the relations are controlled by the thermally activated process and the PLC effect is related to the long range interaction. The δ' particles should be sheared in the crystals in under-aged and a little over-aged conditions. In view of the fact that the δ' particles were sheared at the beginning of plastic deformation and no serration was observed in the crystals in under-aged condition at 200 K[4], it is concluded that the shearing of the δ' particles is a necessary but not sufficient condition for the occurrence of the PLC effect in Al-Li alloys.

Recently, one argument was made that the competition between δ' dissolution due to the shearing and re-precipitation during deformation can lead to the negative strain rate sensitivity and PLC effect in Al-Li alloys[13], but the change of ε_c with T and $\dot{\varepsilon}$ has not been explained. An U-shape variance of ε_c with increasing temperature and increase of ε_c with strain rates has recently been reported[14]. Another possibility for the occurrence of the serration in Al-Li alloys can be assumed as follows.

δ' particles were continuously sheared by the gliding dislocations, which could induce the δ' particles dissolved, perhaps local dissolved during deformation. There existed high content of solute Li atoms and a lot of mismatch dislocations around the particles. When the mobile dislocations passed δ' particles, they could have a strong reaction with mismatch dislocations, and will be pinned by solute Li atoms with the help of the role of pipe diffusion. It is expected the pinning force at the situation above is much stronger than that caused by the Li solute atoms at solution treated condition. As a result, the serrated flow occurred for the sample at under-aged or a little over-aged states, but not at solution treated condition.

5 CONCLUSION

Deformation behavior of the Al-Li single crystal is investigated under different aging conditions in certain range of temperature and strain rate. The results indicate that the PLC effect in Al-Li alloy is not only related to the shearing of the δ' particles, but also is a thermally activated process. The proposed mechanism for the occurrence of the serration is that the δ' particles are sheared and dissolved during deformation, and might be as the pinning points to the mobile dislocations.

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