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Dynamic recrystallization during hot torsion of Al-9Mg alloy①

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Abstract: Specimens of single phase Al-9Mg alloy have been deformed by hot torsion at 300 ~ 450 ℃ and strain rates of $0.005 \sim 1.587\,s^{-1}$ to true strain of 5.5 followed by water quenching immediately. The dynamic restoration mechanisms during hot torsion were examined by the true stress-true strain curves, optical and electron microscopy. It has been shown that dynamic recrystallization occurs and the dynamic recrystallization behaviour is similar to that of those materials with a low stacking fault energy. The microstructural observations indicate that a large number of dislocations appear in a certain crystallographic orientation in the dynamically recrystallized grains. High resolution streak images show that the very fine regions of stacking faults exist in the matrix of Al-9Mg alloy.

Key words: Al-9Mg alloy; dynamic recrystallization; torsion; stacking faults **Document code**: A

1 INTRODUCTION

The occurrence of dynamic recrystallization during the hot deformation of those metals that recover only relatively slowly has been well established. These metals, such as lead, gold, silver, nickel, copper, γ-iron and alloys based on them, have low stacking fault energies. In recent years, it has been found that the dynamic recrystallization can occur in aluminium alloys with relatively higher stacking fault energy (SFE)[1~10]. Truszkowski *et al*[11] have suggested that the addition of 1% Mg to Al reduce the SFE from $200\,J/m^2$ to about $50\,J/m^2$, therefore Al-Mg alloys would be expected to dynamically recrystallize. It should be noted that the measurements of SFE taken by Truszkowski *et al* were based on the measurement of texture intensity ratios, but the relationship between SFE and texture cannot be substantiated fully, then these values are not considered to be reliable. Sheppard *et al*[5,6] have reported that the dynamic recrystallization occurs in Al-5Mg and Al-7Mg alloys and concluded that increasing additions of Mg modify the structure and substructure and high solute content Mg hinders dislocation motion, and nucleation of dynamic recrystallization takes place at dislocation clusters and / or at small particles.

McQueen and co-workers[12] have suggested that no evidence was found for discontinuous dynamic recrystallization, a repeating process in which strain free grains nucleate, grow, deform and give rise to new nuclei in Al-Mg alloys. Dynamic recovery in the solute drag regime leads to geometric dynamic recrystallization in a manner very similar to that already established for pure aluminum, suggesting that geometric dynamic recrystallization may occur generally in materials with high SFE deformed to large strains.

In recent years, Lin *et al*[13] have systematically studied the dynamic restoration processes of Al-alloys during hot deformation using various parameters(temperature, strain rate and amount of strains), as well as various modes of deformation (tension, compression, torsion, rolling and extrusion), using polarized optical microscopy, X-ray photography and TEM. The materials used were precipitation-hardened 2024 alloy and binary Al-Mg alloys with 2%, 4%, and 6% Mg. Experimental results show that dynamic recrystallization can occur under certain conditions

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in all these alloys. Discontinuous dynamic recrystallization is one of the dynamic restoration mechanisms during hot deformation. Dynamic recovery, continuous dynamic recrystallization and geometric dynamic recrystallization also are possible dynamic restoration mechanisms in different conditions. Because Al alloys have high SFE, dislocations can easily cross-slip, so dynamic recovery can easily occur. Only when dynamic recovery is impeded, can dynamic recrystallization take place. For instance, increasing strain rate at higher temperatures or decreasing strain rate at lower temperature can facilitate the occurrence of dynamic recrystallization.

It is not clear how Mg content affects the dynamic restoration processes and what is the operative restoration mechanism during hot deformation as Mg content rises to 9%.

The present research examines dynamic restoration mechanisms of Al-9Mg during hot torsion and effect of parameter Z on the dynamic restoration process. The effect of Mg on dynamic restoration mechanisms has been discussed.

2 EXPERIMENTAL PROCEDURE

The material used is a binary Al-9Mg alloy with the following chemical composition (mass fraction): 9.0% Mg, <0.2% Fe, <0.1% Si, <0.55% Mn, <0.15% Zn, <0.008% Cu, balance Al.

Cylindrical torsion samples with a gage length L, equal to 30 mm, and a gage diameter d, equal to 6 mm, were machined. Following machining, all of the specimens were annealed in vacuum for 1.5 h at 460 ℃ and water quenched.

Torsion testing of specimens with $L/d = 5$ was performed on the torsion machine at 300 ~ 500 ℃ and strain rates (equivalent unaxial strain rate at the outer fiber) of $0.005 \sim 1.587\ s^{-1}$ to true strain of 5.5. The shear strain and shear stress at the outer fiber were calculated using the following equations[14]:

$$\varepsilon = \frac{r}{\sqrt{3}L}\alpha \quad (1)$$

$$\sigma = \sqrt{3}\frac{M}{2\pi r^3}(3 + K + m) \quad (2)$$

where ε is the equivalent uniaxial strain (following is true strain), r is the radius of gage section, α is the twist angle, σ is the equivalent uniaxial stress (following is true stress), M is the torque, K is the strain hardening exponent and m is the strain rate sensitivity.

Optical microscopy was performed on chord sections cut from the 4/5-radius position of the gage section of the water quenched torsion specimens. Then the specimens for optical microscopy were mechanically polished, electrolytically polished and anodically oxidized. The electrolyte consisted of 90% alcohol and 10% perchloric acid. The anodic oxidation consisted of 38% H_2SO_4, 43% H_3PO_4 and H_2O. They were then observed under polarized light.

Transmission electron microscopy samples were prepared by spark erosion cutting disks normal to the radius from the 4/5-radius position of the torsion specimens. The thin foils were prepared with standard twin-jet polishing technique and observed in a CM12 TEM operated at 120 kV. High resolution electron microscopic observation was performed in a Jeol 2000EX(II) electron microscope with $C_S = 0.8$ mm and with a point resolution of 0.21 nm.

3 RESULTS AND DISCUSSION

3.1 Effect of deformation parameters on dynamic restoration processes

The true stress-true strain curves of Al-9Mg alloy at 450 ℃ with different strain rates are shown in Fig. 1. The curves indicate that the

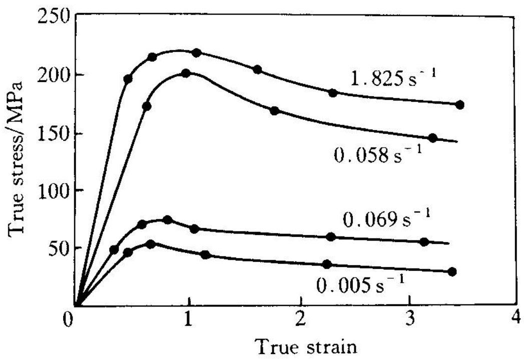

Fig. 1 True stress-true strain curves of Al-9Mg alloy deformed by torsion at 450 ℃ with different strain rates

stresses rise to a peak value followed by a decrease leading to a steady state at higher strains. This shows that the dynamic recrystallization occurs during the deformation. It can be seen that the critical strain needed to initiate dynamic recrystallization decreases with the decrease of strain rate, which reveals that the dynamic recrystallization is accelerated when the strain rate decreases. The microstructures deformed by torsion of Al-9Mg alloy corresponding with the above true stress-true strain curves are shown in Fig.2. It can be seen that the complete dynamic recrystallization takes place, and the grain size is very fine. It can be noted that the grain size of dynamic recrystallization increases with the decrease of strain rate, which is very similar to that in the materials with lower SFE.

Fig.3 shows the microstructural evolution of the specimens of chord sections from the 4/5-radius position of Al-9Mg alloy deformed by torsion at 450 ℃ and strain rate of $0.069\,s^{-1}$ to various strains. The grain size of the original optical

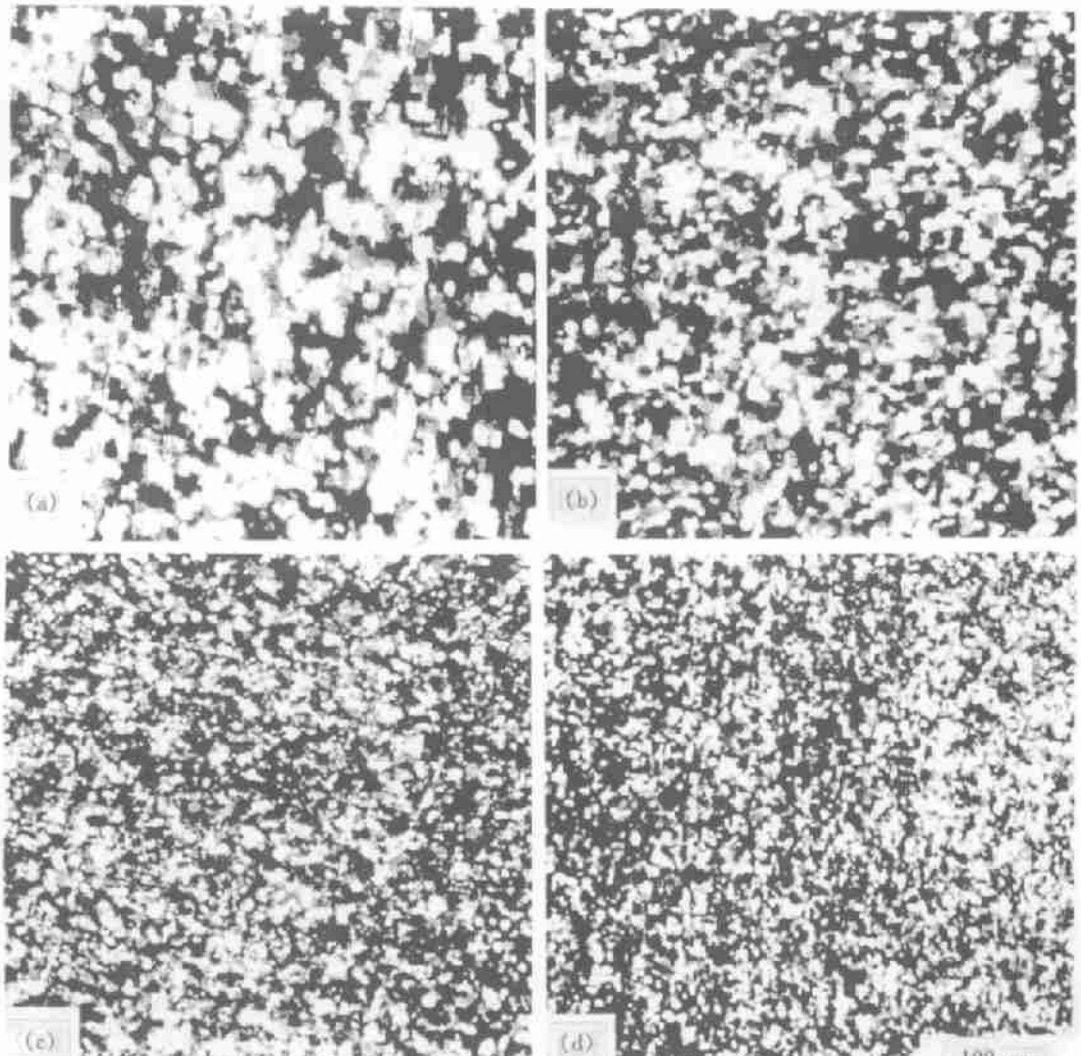

Fig.2 Microstructures of specimens of Al-9Mg alloy deformed by torsion at 450 ℃ with strain rates of $1.587\,s^{-1}$(a), $0.509\,s^{-1}$(b), $0.069\,s^{-1}$(c) and $0.005\,s^{-1}$(d) to strain of 5.5

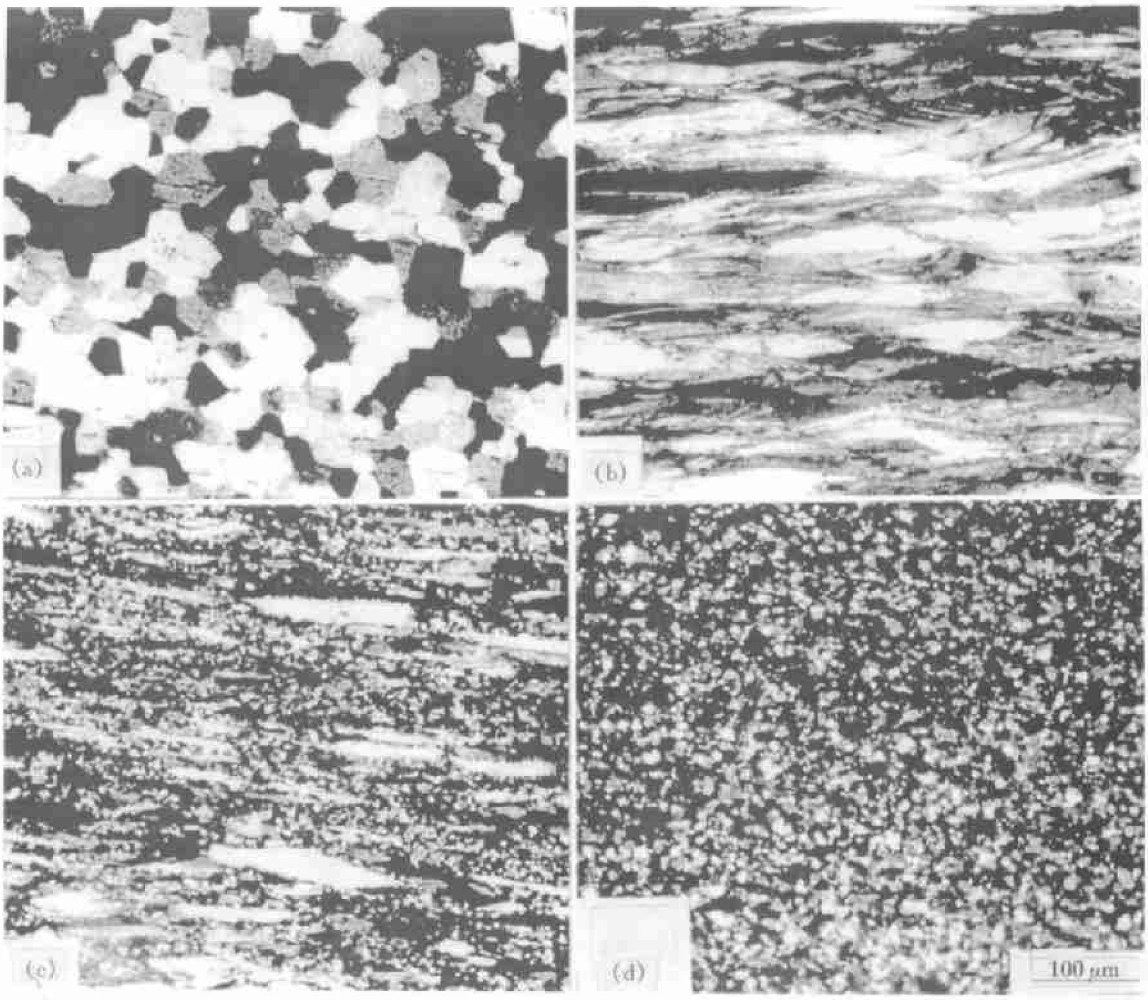

Fig.3 Microstructural evolution of specimens of Al-9Mg alloy deformed by torsion at 450 ℃ and strain rate of $0.069\ s^{-1}$ to various true strains
(a)—ε = 0; (b)—ε = 0.9; (c)—ε = 1.2; (d)—ε = 5.5

microstructure is about 50 μm. At a strain of 0.9, some very fine nuclei of discontinuous dynamic recrystallization were formed mainly at the grain boundaries. As the strain rose to 1.2, the nuclei grew and new nuclei were formed in a lot of regions. The complete dynamic recrystallization occurred at a strain of 5.5.

The deformation condition can be summed up by the Zener-Hollomon parameter Z[15,16]:

$$Z = \dot{\varepsilon}\exp(Q/RT) \tag{3}$$

where $\dot{\varepsilon}$ is strain rate, T is the deformation temperature, Q is activation energy and R is gas constant. The physical meaning of Z is the strain rate compensated by deformation temperature. Parameter Z is dependent upon the peak stress σ_p in the true stress-true strain curves[17]:

$$Z = A\sigma_p{}^n \tag{4}$$

where A and n are empirical constants. Combining Eqs.(3) and (4) yields

$$A\sigma_p{}^n = \dot{\varepsilon}\exp(Q/RT) \tag{5}$$

taking logarithm and deriving Eq. (5) gives

$$\left.\frac{\partial(\ln\sigma_p)}{\partial(\ln\dot{\varepsilon})}\right|_{1/T} = 1/n \tag{6}$$

$$\left.\frac{\partial(\ln\sigma_p)}{\partial(1/T)}\right|_{\ln\dot{\varepsilon}} = Q/Rn \qquad (7)$$

The slope of the line $\ln\sigma_p$—$\ln\dot{\varepsilon}$ is $1/n$ and the slope of the line $\ln\sigma_p$—$1/T$ is Q/Rn. So the activation energy Q can be obtained. It can be known from Fig. 4 that the three lines of $\ln\sigma_p$—$\ln\dot{\varepsilon}$ curve and $\ln\sigma_p$—$1/T$ curve maintained parallel, so that n and Q are constants. We can obtain Q = 136.3 kJ/mol.

It was found that the apparent activation energy of the dynamic recrystallization during hot torsion of Al-9Mg is somewhat less than that of the Al-6Mg alloy (156.7 kJ/mol)[13]. This means that the dynamic recrystallization takes place in Al-9Mg alloy more easily than in Al-6Mg alloy.

Fig. 5 illustrates the dynamic recrystallization diagram of Al-9Mg alloy deformed by torsion. The diagram consists of three regions, i.e. dynamically recovered region, partially dynamically recrystallized region and completely dynamically recrystallized region. It can be seen that the dynamic recrystallization is accelerated with the decrease of Z parameter. There is no upper region at the left side of the recrystallization diagram of Al-9Mg, in this region dynamic recovery at lower Z parameter occurs in Al-2Mg and Al-6Mg alloys[18]. So the dynamic recrystallization diagram of Al-9Mg alloy is different from that of the alloys containing lower Mg content and is similar to the dynamic recrystallization diagram of the materials with lower SFE. This is a very important feature which indicates that the dynamic restoration mechanism during hot torsion of Al-9Mg alloy is similar to that of the materials with lower SFE.

3.2 Effect of Mg on dynamic recrystallization behaviours in Al-9Mg alloy

Many investigators have suggested the addition of Mg to Al hinders the motion of dislocations or reduces the SFE , therefore the discontinuous dynamic recrystallization occurs in Al-Mg alloys. But this hypothesis is not demonstrated by experiments. Up to now, it is not clear how the Mg addition affects the dynamic recrystallization mechanism of Al-Mg alloys. Fig. 6 shows the dislocation structures of hot deformed Al-6Mg alloy and Al-9Mg alloy. It can be seen that the tangles of dislocations were formed after dynamic recrystallization in Al-6Mg alloy (Fig. 6(a)). A large number of dislocations appear in a certain crystallographic orientation after dynamic recrystallization of Al-9Mg alloy (Fig. 6(b)). The morphology of the dislocations

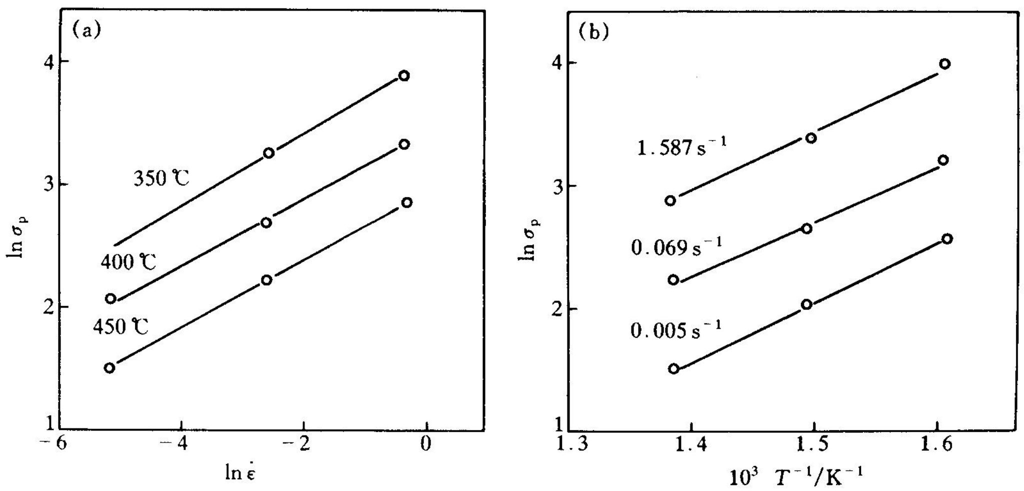

Fig. 4 Relationship between peak stress at true stress-true strain curves and strain rates(a), inverse of deformation temperatures (b) of torsion deformed Al-9Mg alloy

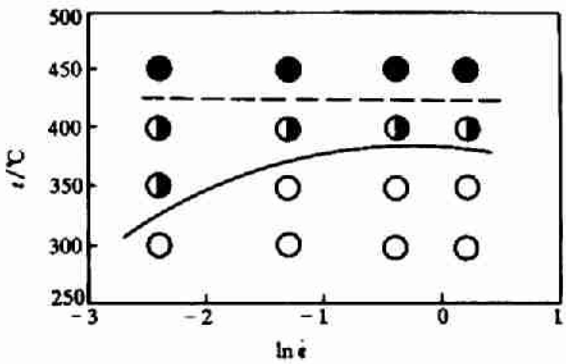

Fig. 5 Dynamic recrystallization diagram of Al-9Mg alloy deformed by torsion
●—Complete dynamic recrystallization;
◑—Partial dynamic recrystallization;
○—Dynamic recovery

in both alloys is different. This means that the mobility of the dislocations reduces and the dynamic recrystallization is accelerated with increasing Mg content. Fig. 7 shows the high resolution streak image on plane of (111) of Al-9Mg alloy. The width of the streak image of 2.37 Å is consistent with the width between (111) planes. It can be seen from Fig. 7 that there are some areas in which the width of streak image is 4.34 Å. It is clear that the regions with the width of streak image of 4.34 Å are the regions of stacking faults. It is the first discovery that the stacking faults exist in aluminum alloys. The regions are very fine, about magnitude of nanometer, therefore the stacking faults were not observed in optical microstructures. The stacking faults reduce the dislocation mobility, so that the process of dynamic recovery becomes more difficult to occur. The migration of the large angle grain boundaries of newly formed grains is impeded by the region of stacking faults. Then the dynamically recrystallized grains become very fine.

4 CONCLUSIONS

(1) The dynamic recrystallization occurs

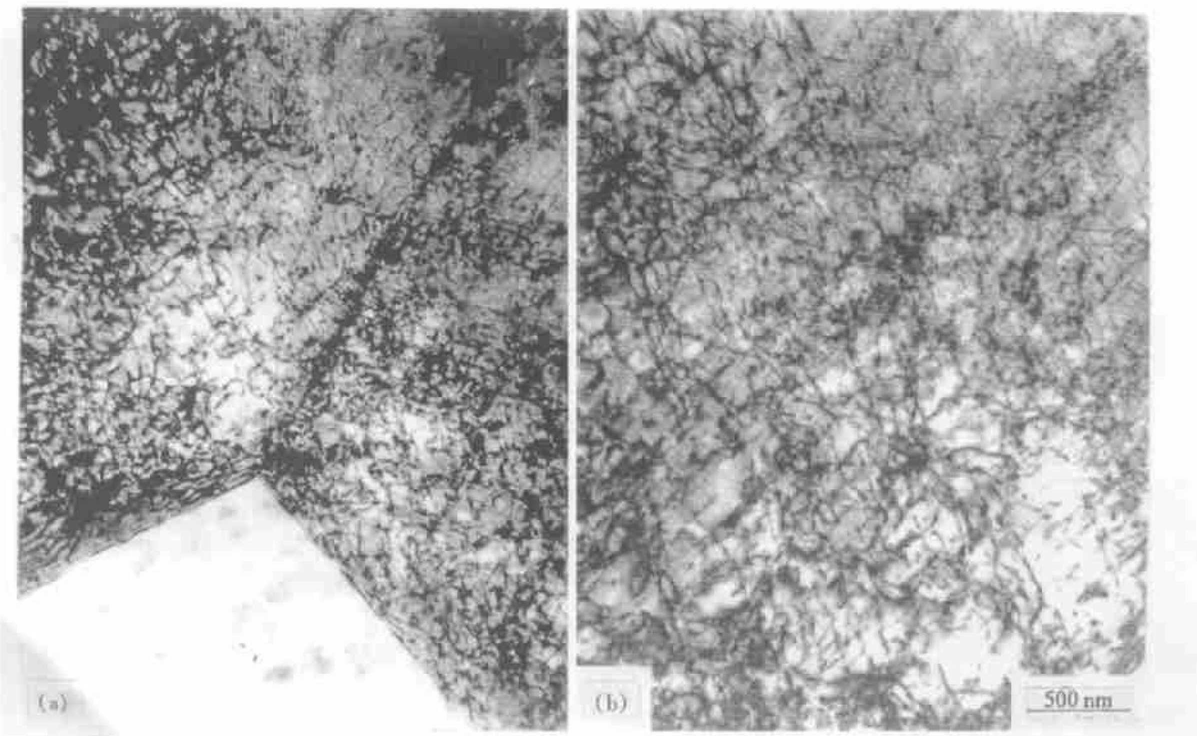

Fig. 6 Dislocation structures after dynamic recrystallication of Al-6Mg alloy (a) and Al-9Mg alloy (b)

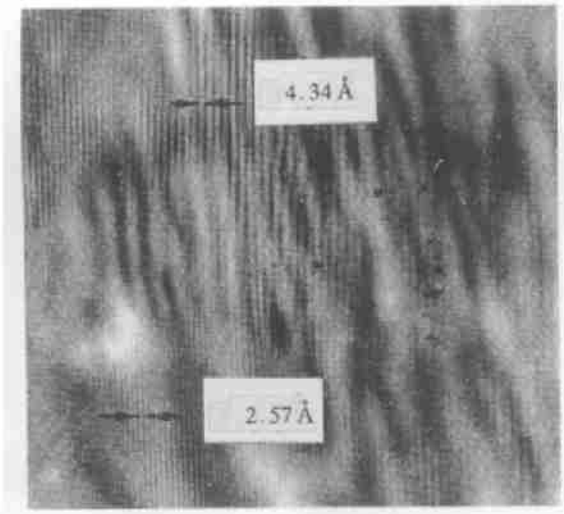

Fig.7 High resolution streak image on (111) plane of Al-9Mg alloy

during hot torsion of Al-9Mg alloy and is accelerated with the decrease of Z parameter.

(2) The Al-9Mg alloy is similar in dynamic recrystallization behaviour to those materials with lower SFE.

(3) Some very fine regions of stacking faults exist in the high resolution streak image of Al-9Mg alloy.

(4) A large number of dislocations appear in a certain crystallographic orientation after dynamic recrystallization. This reveals that the motion of dislocations is impeded by the stacking faults and then dynamic recovery becomes more difficult to occur.

(5) The grain size of dynamic recrystallization of Al-9Mg alloy is finer than those of other Al-Mg alloys containing lower Mg contents.

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