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Dynamic recrystallization during hot torsion of Al-4Mg alloy

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Abstract: Binary Al-4Mg alloy have been deformed by hot torsion at 300-500℃ and strain rates of 0.006-1.587 s^{-1} to a true strain of 5.5. The specimens were annealed in vacuum for 1.5 h at 500℃ and then water quenched. The study indicates that the dynamic recrystallization occurs during hot torsion of Al-4Mg alloy in a certain range of Z parameter (Zener-Hollmon Parameter), *i.e.* $19.3 \le \ln Z \le 24.8$. Increasing the strain rate at higher deformation temperature or reducing the strain rate at lower deformation temperature accelerates the occurrence of dynamic recrystallization in the alloy.

Key words: Al-4Mg alloy; dynamic recrystallization; hot torsion

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1 Introduction

The occurrence of dynamic recrystallization during the hot deformation of those metals that recover only relatively slow has been established. These metals have low stacking fault energy (such as lead, gold, silver, nickel, copper, γ-iron and alloys based on them). In recent years, it has been found that the dynamic recrystallization can occur in aluminium alloys that have 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 to about 50 $J \cdot m^{-2}$, therefor 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, these values are not considered to be reliable. Shappard *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 modifies the structure and substructure and high solute content Mg hinders the dislocation motion, and the 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 new nuclei in Al-Mg alloys. Dynamic recovery in the solute drag regime gives rise 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 a high SFE deformed to large strains.

Zaidi's [13] experimental results show that the dynamic recrystallization can not occur, as the Mg content is lower in Al-Mg alloy.

The present research examines to dynamic restoration mechanism of Al-4Mg alloy during hot torsion and effect of parameter Z on the dynamic restoration process. The effect of Mg on dynamic restoration mechanism has been discussed.

2 Experimental procedure

The material used was a binary Al-4Mg alloy with the following chemical composition: Mg, 4.0%; Fe, <0.2%; Si, <0.1%; Mn, <0.55%; Zn, <0.15%; Cu, <0.008% (mass fraction).

The cylindrical torsion samples with a gage length L of 30 mm and a gage diameter d of 6 mm were machined. After machining, all of the specimens were annealed in vacuum for 1.5 h at 500℃ and then water quenched.

The 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

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fiber) of 0.006-1.587 s^{-1} to a true strain of 5.5. The shear stress and shear strain at the outer fiber were calculated using the following equations [1]:

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

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

where ε is the equivalent uniaxial strain, γ the radius of gage section, α the twist angle, σ the equivalent uniaxial stress, M the torque, k the strain-hardening exponent, and m the strain rate sensitivity.

The 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 oxdized. The electrolyte consisted of 90% alcohol and 10% perchloric acid. The anodic oxidation liquid consisted of 38% H_2SO_4, 43% H_3PO_4 and H_2O. They were then observed under the polarized light.

The transmission electron microscopy samples were prepared by spark 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.

3 Results and discussion

3.1 Microstructure changes during hot torsion of Al-4Mg alloy

The true stress-true strain curves of Al-4Mg alloy at 500℃ with deferent strain rates are shown in **figure 1**. When the strain rate is equal to and higher than 0.061 s^{-1}, the strain hardening develops rapidly in the early stage of deformation. The stress is increased to a maximum and slowly decreased. It is possible that the stress reduction is caused by dynamic recrystallization. The true stress-true strain curve changes to a typical dynamic recovery curve with no stress peak on it. The microstructures deformed by the torsion of Al-4Mg alloy corresponding with the above true stress-true strain curves are shown in **figure 2**. It can be seen that the partial dynamic recrystallization takes place during the hot torsion at strain rates of 1.587 and 0.529 s^{-1}. There are a lot of deformation bands in the grains where the very fine nuclei of dynamic recrystallization form (see figure 2(a)). The complete dynamic recrystallization takes place during the hot torsion at a strain of 0.061 s^{-1}, as shown in figure 2(c). It is notable that the dynamic recovery occurs as the strain rate reduces to 0.006 s^{-1}. This is a low Z dynamic recovery process [8], *i.e.* the forming subgrain and growth of subgrain.

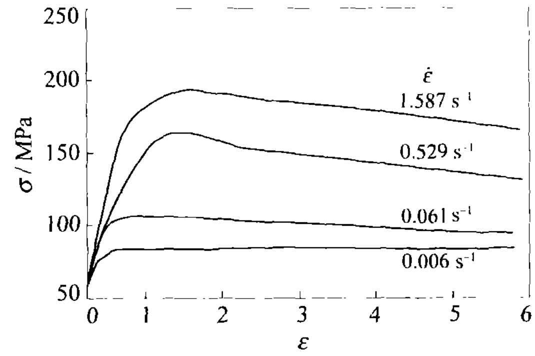

Figure 1 True stress-true strain curves of Al-4Mg alloy deformed by torsion at 500℃ with different strain rate.

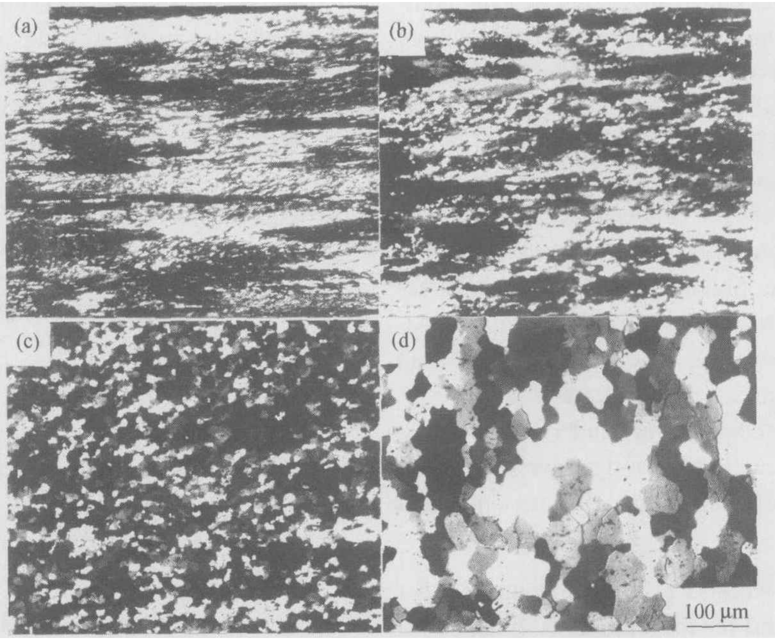

Figure 2 Microstructures of the specimens of chord sections from the 4/5-radius position of Al-4Mg alloy deformed by torsion at 500℃ with strain rates of (a) 1.587, (b) 0.529, (c) 0.061 and (d) 0.006 s^{-1} to outerfiber equivalent uniaxial strain of 5.5.

3.2 The effect of deformation parameter on dynamic recrystallization behaviour

The deformation condition can be summed up by the Zener-Hollomon parameter Z [14]:

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

where $\dot{\varepsilon}$ is the strain rate, T the deformation temperature, Q the activation energy and R the 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 [14]:

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

where A and n are empirical constants. Combining equations (3) and (4):

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

Taking logarithm and deriving equation (5):

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

$$\frac{\partial(\ln\sigma_p^n)}{\partial(1/T)}\Big|_{\ln\dot{\varepsilon}} = Q/Rn \tag{7}$$

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: Q = 142 kJ/mol.

Figure 3 illustrates the dynamic recrystallization diagram of Al-4Mg 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 takes place approximately in a certain range of Z parameter, *i.e.* $19.3 \le \ln Z \le 24.8$. There is an upper region at the left side in the diagram of Al-4Mg, in this region the dynamic recovery at lower Z parameter occurs. So the dynamic recrystallization diagram of Al-4Mg alloy is different from that of the materials having lower SFE. This is a very important feature, which indicates that the dynamic restoration mechanism during hot torsion of Al-4Mg alloy is different from that of the materials having lower SFE.

3.3 Reason of the occurrence of dynamic recrystallization in Al-4Mg alloy

Many investigators have suggested that the addition of Mg to Al hinders the motion of dislocations or reduces the SFE, therefor the discontinuous dynamic recrystallization occurs in Al-Mg alloys. But this hypothesis has not been demonstrated by experiments. **Figure 4** shows the microstructures of the specimen of Al-4Mg alloy deformed by hot torsion at 500℃ and the strain rate of 1.875 s^{-1} to true strain of 2. It can be seen that there are not the stacking faults in the matrix, this means that the addition of Mg can not reduce SFE to the order of magnitude as same as that of the materials having lower SFE. The nuclei of dynamic recrystallization and the region of dynamic recovery coexist in the matrix, this reveals that dynamic recrystallization and dynamic recovery occur simultaneously at the early stage of deformation after the peak stress, because Al alloy with higher SFE is easy to cross-slip. Therefor, the dynamic recrystallization can proceed in Al-4Mg alloy. Increasing the strain rate at higher deformation temperature will restrict the dislocation cross-slip and the occurrence of dynamic recovery, so the dislocation blocks are enhanced, which accelerates the nucleation of dynamic recrystallization. Reducing the strain rate at lower deformation temperature will provide enough time to finish the process of dynamic recrystallization, if the alloy has good plasticity in the deformation condition.

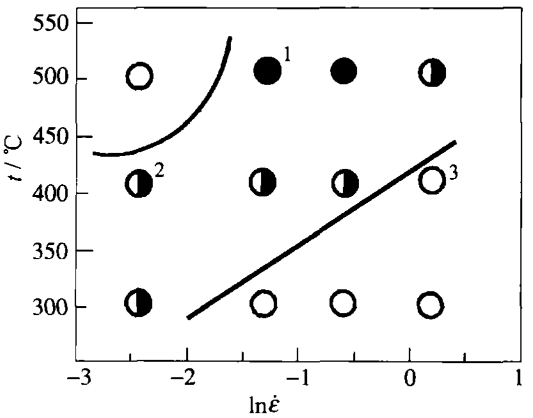

Figure 3 Dynamic recrystallization diagram of Al-4Mg alloy deformed by torsion, 1—complete dynamic recrystallization; 2—partial dynamic recrystallization; 3—dynamic recovery.

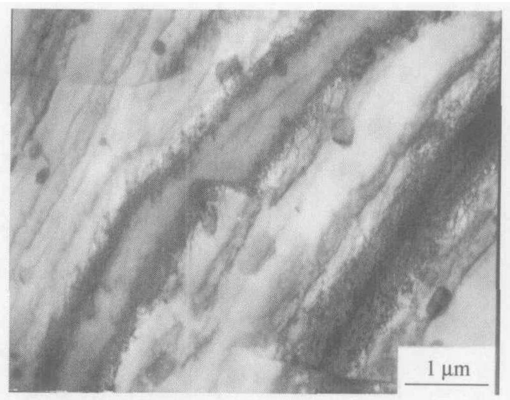

Figure 4 Microstructures of the specimen of Al-4Mg alloy deformed by hot torsion at 500℃ and strain rate of 1.875 s^{-1} to a true strain of 2.

4 Conclusions

(1) The dynamic recrystallization occurs during hot torsion of Al-4Mg alloy in a certain range of Z parameter, *i.e.* $19.3 \leq \ln Z \leq 24.8$.

(2) The Al-4Mg alloy is different from the dynamic recrystallization behaviour to those materials having lower SFE.

(3) Increasing the strain rate at higher deformation temperature or reducing the strain rate at lower deformation temperature accelerates the occurrence of dynamic recrystallization in the alloy.

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