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Continuous dynamic recrystallization and discontinuous dynamic recrystallization in 99.99% polycrystalline aluminum during hot compression①

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Abstract: The dynamic restoration behavior of 99.99% polycrystalline aluminum was investigated. The deformation was carried out by compression test at 533-773 K and initial strain rate of 0.002-2 s^{-1} to a true strain of 1.0 followed by water quench. Polarized optical microscopy and transmission electron microscopy were applied to observe the deformation microstructure. It's found that discontinuous dynamic recrystallization, which is commonly observed in lower stacking fault energy metals or ultra-high purity aluminum(≥99.999%), occurs when Zenner-Hollomon parameter(Z parameter) is low, but the true stress—strain curve doesn't accompany stress oscillation. Continuous dynamic recrystallization occurs when Z parameter is intermediate, and only dynamic recovery takes place if Z parameter is high.

Key words: hot deformation; continuous dynamic recrystallization; discontinuous dynamic recrystallization; Zenner-Hollomon parameter

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1 INTRODUCTION

It's commonly believed that the mechanism of dynamic restoration in aluminum during hot deformation is essentially dynamic recovery (DRV). This is because that the high stacking fault energy of aluminum makes dislocation climb and cross slip easy, and therefore the stored energy is too low to cause dynamic recrystallization (DRX). However, many recent reports show that DRX may take place in Al and its alloys under certain conditions[1-7]. A comparison of different materials that undergo DRX proves that DRX is set off at a lower stored energy with increasing stacking fault energy[6], so Al could recrystallize at very small stored energies.

Two types of DRX[8] are likely to occur in aluminum during hot deformation. 1) Discontinuous dynamic recrystallization(DDRX), i.e. the classical recrystallization, which is operated by nucleation and grain growth. The dynamically recrystallized grains after DDRX are coarse and distribute heterogeneously throughout the deformation matrix[9-11]. True stress—strain curves of DDRX usually exhibit strong oscillation. 2) Continuous dynamic recrystallization(CDRX), which is proceeded by the progressive accumulation of dislocations in low angle boundaries, leading to an increase of their misorientation and the formation of high angle boundaries. The microstructure after CDRX consists of small grains, which distribute uniformly[9-11] in the materials. The stress—strain curve of CDRX does not show stress oscillation. The main purpose of this work is to investigate whether DDRX, which is commonly observed in lower stacking fault energy metals or ultra-high purity aluminum(≥99.999 %), can occur in 99.99% aluminum. The relationship between Z parameter and the type of DRX was also studied. Aluminum with an average grain size of about 6 mm was used in this work. The advantage of the use of coarse grain aluminum lies in that it makes it easier to distinguish the original grain boundaries from the new grain boundaries, therefore it is easier to analyze the dynamic restoration behavior of aluminum.

2 EXPERIMENTAL

The material used for this study was 99.99 % polycrystalline aluminum. The initial structures were fully recrystallized, consisting of coarse grains with a grain size of about 6 mm. The amounts of impurities were (in mass fraction,

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10^{-6}) 10 Si, 9 Fe, 28 Cu, 1 Mn, 10 Mg, 6 Cr, 2 Ni, 10 Zn, 2 Ti and 2 Zr.

Compressive specimens with a diameter of 10 mm and a height of 15 mm were used. The hot compression tests were carried out in Gleeble-1500 thermal simulator. A graphite type lubricant was utilized to reduce the friction between the specimen and the loading platen. Compression tests were performed at various strain rates of 0.002, 0.02, 0.2, and 2 s^{-1}, and the temperatures were selected as 533, 673, 723 and 773K. All the specimens were compressed to a true strain of 1.0. The true stress—strain curves were drawn immediately by computer with signals received by a strain-sensor during hot compression. For microscopic observation, the specimens were rapidly cooled to room temperature by water within 1 s after termination of the compression tests. The compressed and then quenched specimens were electro-polished and subsequently anodically oxidized to observe the microstructure under polarized optical microscope (POM). The plane vertical to the compressive axis was observed. For TEM examination, the thin foils were prepared with standard twin-jet polishing technique.

3 RESULTS AND DISCUSSION

3.1 Dynamic restoration behavior of 99.99% aluminum during compression

Fig. 1(a) shows the true stress—strain curves of the specimens compressed to a true strain of 1.0 at various temperatures with a strain rate of 0.02 s^{-1}. When the temperature is 533 K, only gradual work hardening is observable, showing a typical DRV curve. Fig. 2(a) also proved that no DRX occurs during hot compression at 533 K with a strain rate of 0.02 s^{-1}. When the temperature is above 533 K, stress reduction appears. The stress reduction is possibly caused by DRX. The deformation microstructures containing new equiaxed grains shown in Figs. 2(a) and (b) and Fig. 3(b) confirm the occurrence of DRX. As the temperature increases, the peak stress and the critical strain to initiate DRX are decreased in the true stress—strain curves of 99.99% aluminum. It's obvious that the increase of temperature will favor the occurrence of DRX. Fig. 1(b) shows the true stress—strain curves of specimens compressed to a true strain of 1.0 at 723 K with various strain rates. The significant features of all the curves are the rapid initial rise to the peak stress and the following slow stress reduction. These are typical DRX curves. New equiaxed grains in Fig. 3 confirm the occurrence of DRX in specimens. The lower the strain rate, the smaller the peak stress and the critical strain. This demonstrates that DRX is enhanced with the decrease of strain rate.

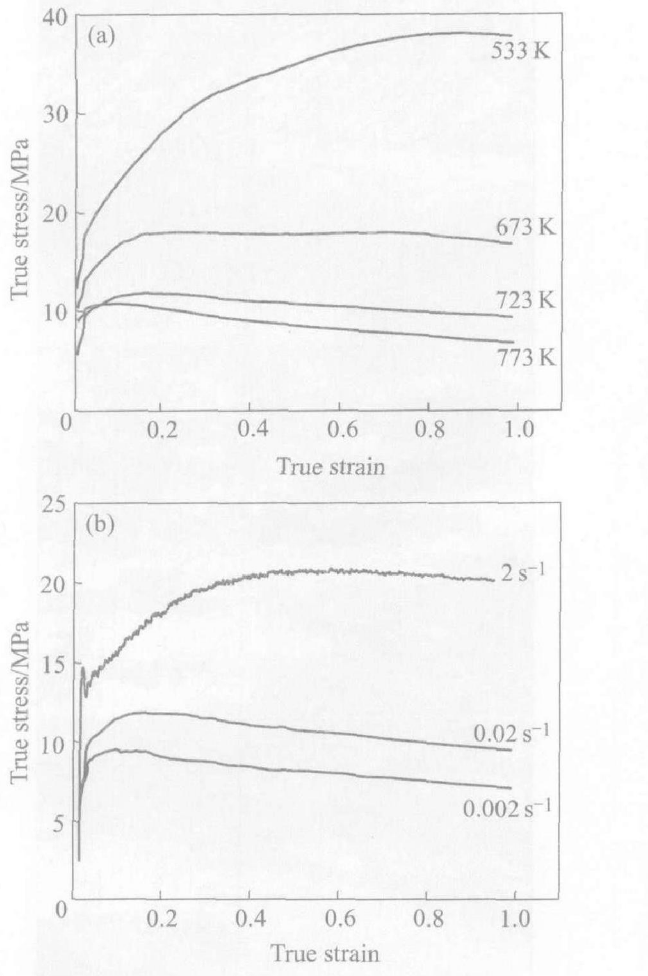

Fig. 1 True stress—strain curves of specimens compressed at various temperatures and strain rates
(a) —0.02 s^{-1}; (b) —723 K

The substructures of specimens observed under TEM are shown in Fig. 4. A recovered structure of polygonization is seen in Fig. 4(a), but no DRX grains are observed. In the dynamically recrystallized microstructure (Figs. 4(b) and (c)), DRX grains exist and the grain boundaries are sharp. Grain A in Fig. 4(b) has a strong contrast with the other grains around it and is almost free of dislocations. So it's likely that grain A is a nucleus of DRX. In Fig. 4(c), pile-ups or tangles of dislocations still exit in the recrystallized grains because of continuous deformation.

Two types of microstructural characteristic can be seen. In Fig. 2(b) and Fig. 3(a), deformation bands and small equiaxed new grains can be seen, and the new grains distribute uniformly throughout the deformation matrix. These are typical CDRX microstructures[11, 12]. In Fig. 2(c), Figs. 3(b) and (c), deformation bands are rather weak or invisible and several coarse equiaxed new grains appear. The distribution of those new grains is heterogeneous with most of them existing near the original grain boundaries (indicated by ar-

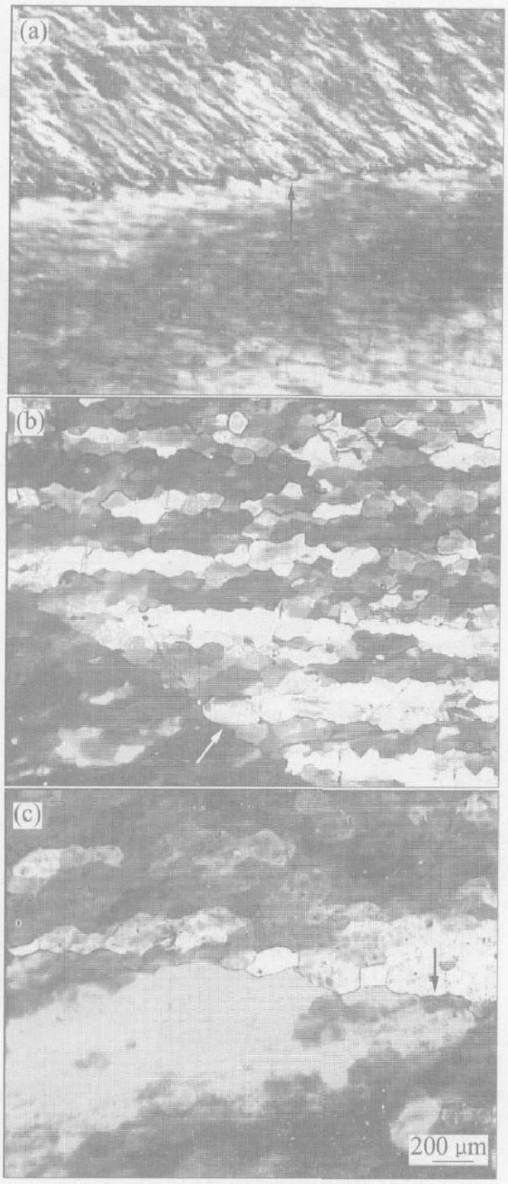

Fig. 2 Microstructures of specimens compressed at strain rate of 0.02 s^{-1}
(original grain boundaries are indicated by arrows)
(a) —533 K; (b) —673 K; (c) —773 K

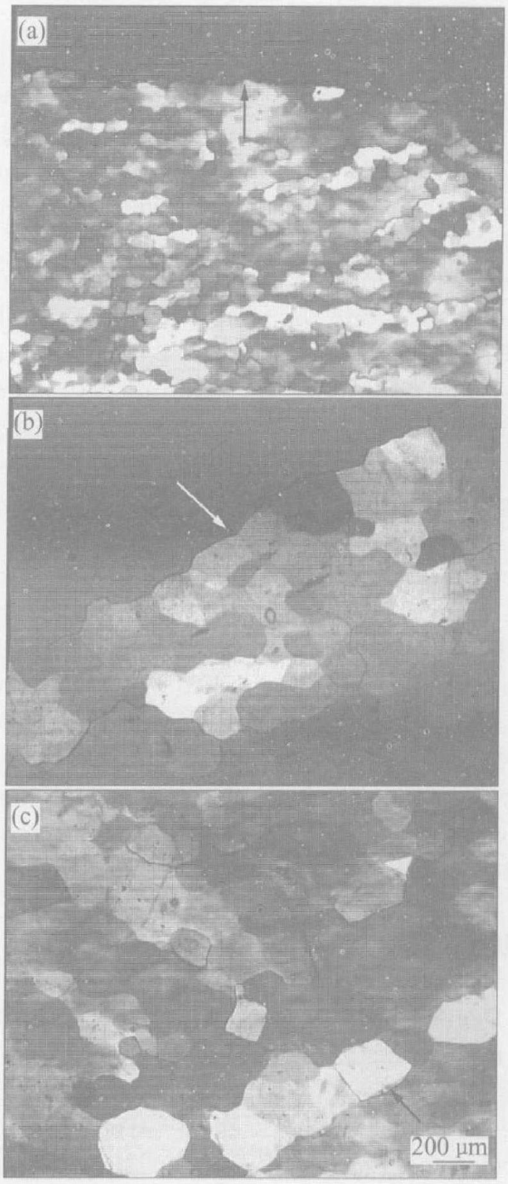

Fig. 3 Microstructures of specimens compressed at 723 K
(original grain boundaries are indicated by arrows)
(a) —2 s^{-1}; (b) —0.02 s^{-1}; (c) —0.002 s^{-1}

rows). The feature of the microstructures in Fig. 2 (c), Figs. 3(b) and (c) coincides with the reported DDRX characteristics[11]. These results show that both CDRX and DDRX can occur in 99.99% polycrystalline aluminum.

However, some comments have been given about the explanation of DRX in aluminum. McQueen and coworkers[13, 14] suggested a different mechanism termed geometric dynamic recrystallization (GDRX), which explains that, during deformation, the original grains are thinned, and their boundaries become progressively serrated while subgrains form. Ultimately, when the original grain thickness is reduced to about two subgrain sizes, GDRX will occur by recombination of opposite boundaries of the thinned grain or by pinching off of the serration. The resultant microstructure of GDRX has equiaxed grains and high-angle subgrain boundaries, which are very similar to those produced by DRX. Since there's no formation of new high-angle subgrain boundaries during this process, GDRX is essentially a kind of DRV. So it's important to examine carefully the microstructure and substructure to confirm the mechanism involved during hot deformation.

In this work, polycrystalline aluminum with coarse grain (≥6 mm) is used. Since the grain boundaries of coarse grain are very long, it's easy to distinguish the original grain boundaries from the new ones. As shown by arrows in Fig. 2 and Fig. 3, only one original boundary is observed in each image, and the original boundaries are relatively flat. Therefore the possibility of GDRX which occurs by recombination of opposite bounda-

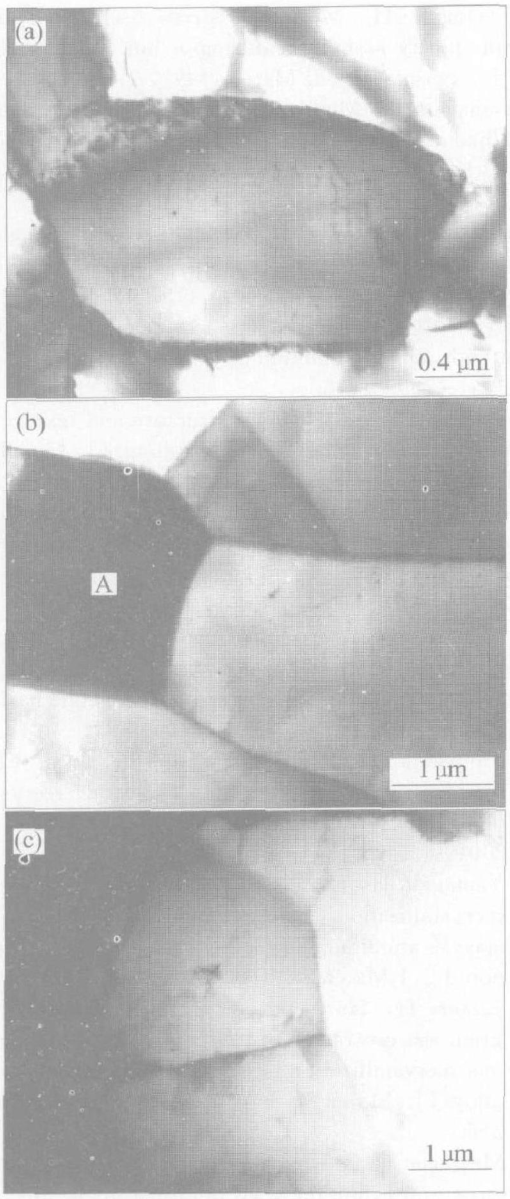

Fig. 4 TEM microstructures of pecimens compressed at strain rate of 0.02 s^{-1}
(a) —533 K; (b) —673 K; (c) —723 K

ries of the thinned grain or pinching off of the serrations is excluded.

3.2 Effects of deformation parameter on dynamic recrystallization

The deformation condition can be summed up by the Zenner-Hollomon parameter (*Z* parameter)[15]:

$$Z = \dot{\varepsilon}\exp(Q/RT) \quad (1)$$

where $\dot{\varepsilon}$ is the strain rate, *T* the deformation temperature, *Q* the activation energy and *R* the gas constant.

Z parameter is dependent on the peak stress σ_p in the true stress—strain curves:

$$Z = A\sigma_p^n \quad (2)$$

where *A* and *n* are empirical constants. Combining Eqns. (1) and (2) yields:

$$A\sigma_p^n = \dot{\varepsilon}\exp(Q/RT) \quad (3)$$

Then the value of *Q* (142 kJ/mol) can be obtained.

Z parameter at various temperature and strain rates can be calculated according to Eqn. (1). The value of *Z* parameter under various conditions is listed in Table 1.

Combining the value of *Z* parameter listed in Table 1 and the type of dynamic restoration under different deformation conditions, we can get that there is a relationship between *Z* parameter and the dynamic restoration behavior in 99.99% polycrystalline aluminum: when $\ln Z > 28$ (Fig. 2(a)), only DRV takes place; CDRX occurs when *Z* parameter is intermediate, i.e., $20 < \ln Z < 28$ (Fig. 2(b) and Fig. 3(a)), and DDRX takes place when *Z* parameter is low, i.e., $\ln Z < 20$ (Fig. 2(c), Figs. 3(b) and (c)).

3.3 Relationship between CDRX and DDRX in aluminum

According to some previous investigations, a lower purity aluminum of 99.99% grade always shows CDRX as a restoration mode instead of DDRX[8,10]. This does not accompany stress oscillation on stress—strain curves.

By contrast, a zone refined 99.999% aluminum shows DDRX during deformation[3-5]. Typical multi-peak stress oscillation occurs in the stress—strain curves.

It was reported that the CDRX process results from the combination of three elementary mechanisms[8]. 1) The formation of subgrain boundaries. These boundaries are created with a very low misorientation angle ($\leqslant 1°$), as a result of dynamic recovery. 2) The transformation of subgrain boundaries into grain boundaries. The increase in misorientation of the subgrain boundaries is more or less rapid, according to the materials and the experimental conditions. 3) The elimination of subgrain and grain boundaries through grain boundary migration. The nucleation mechanism of DDRX was not clear through previous experimental studies. Chovet et al[16] suggested that the

Table 1 Value of ln*Z* under different deformation conditions

Parameter	Deformation condition					
	0.02/s, 533 K	0.02/s, 673 K	0.02/s, 773 K	2/s, 723 K	0.02/s, 723 K	0.002/s, 723 K
Ln*Z*	28.1	21.5	18.2	24.3	19.7	17.4

mechanism of CDRX is related to that of DDRX. Recent OIM (orientation imaging microscopy) observation has confirmed that the nucleation mechanism of DDRX is the same as CDRX[17]. CDRX works as a nucleation process for the DDRX. The difference between CDRX and DDRX in microstructure and stress—strain behavior is mainly induced from the grain growth process after nucleation of high angle boundaries (HAGBs): if the generated HAGBs can migrate rapidly, DDRX occurs; CDRX takes place when the mobility of HAGBs is low.

Since the boundary mobility increases with increasing deformation temperature, it's possible that a low purity aluminum of 99.99% grade can also show DDRX if the deformation temperature is high enough. The present result and those of Yamagata et al[10,11] indicate the occurrence of DDRX in 99.99% aluminum at high temperatures. However, no stress oscillation on stress—strain curves is observed in 99.99% aluminum when DDRX occurs. This is different from that of 99.999% aluminum. The reason is that although the mobility of HAGBs in 99.99% aluminum at high temperature is high enough to cause DDRX, it's still not high enough to cause the stress oscillation. As for the strain rate, it has two opposite effects: on one hand, the boundaries have more time to migrate for a given strain increases at low strain rates, which favors DDRX; on the other hand, it inhibits DDRX since the available driving force is less because of the lower dislocation density[18]. Experimental results demonstrate that the former effect prevails over the latter.

4 CONCLUSIONS

1) Both DDRX and CDRX can take place in 99.99% polycrystalline aluminum during hot deformation.

2) There is a relationship between Z parameter and the dynamic restoration behavior in 99.99% polycrystalline aluminum: when Z parameter is high, only DRV takes place; CDRX occurs when Z parameter is intermediate and DDRX takes place when Z parameter is low.

3) The stress—strain curves of 99.99% aluminum do not accompany stress oscillation when DDRX takes place.

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