Effect of Deformation Temperature on Microstructure Evolution in 2219 Aluminum Alloy during ECAP

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The effect of deformation temperature on microstructure evolution during equal channel angular pressing (ECAP) was studied in a coarse grained 2219 Al alloy at temperatures from 250 to 475°C. The structural changes taking place during ECAP up to strains of 12 were investigated. New fine grains with high angle boundaries (HABs) begin to form clearly at strains of around 3 irrespective of deformation temperature. An increase in the pressing temperature leads to decreasing the volume fraction and increasing the size of new grains with HABs. This can be attributed to the relaxation of strain compatibilities between grains due to frequent operation of dynamic recovery at high temperature. The mechanism of grain refinement is discussed in detail

Introduction

Microstructural evolution in pure Al and its alloys during severe plastic deformation (SPD) conditions at various temperatures were studied in previous papers [1-7]. The formation of new grains during equal channel angular pressing (ECAP) of Al-based alloys in a wide temperature interval can results in operation of continuous dynamic recrystallization (cDRX), which generally involves the transformation of low angle boundaries (LABs) formed at early stages of deformation to high angle ones (HABs) with further deformation [1-7, 10-13]. It was found that in Al alloys the average misorientation angle and the fraction of HABs increases faster at lower temperature [1-4, 11]. The rate of transformation of deformation induced LABs to HABs tends to decrease with increasing of deformation temperature [1, 5, 6], while the HABs start to form at a same critical strain at different temperatures. It was also pointed that the characteristics of new grain structures developed at high strains are almost similar irrespective of pressing temperature [5]. The transformation kinetics of new grain formation in Al alloys during ECAP as well as microstructural characteristics, however, was not clear in a wide range of temperature interval and has not been studied in sufficient detail.

This is a main motivation for carrying out the present work. Deformation by ECAP was performed in the temperature interval from 250 to 475°C on 2219 aluminum alloy with an intent to investigate the effect of deformation temperature on microstructure characteristics and new fine grain formation. Special attention was paid to analyze the relationship between deformation temperature and misorientation distribution of deformation induced boundaries. The main factors promoting grain refinement in this alloy under ECAP conditions are considered.

Experimental Procedure

The alloy investigated had the following chemical composition Al–6.4%Cu–0.3%Mn–0.18%Cr–0.19%Zr–0.06%Fe (in mass pct) denoted here as 2219 Al alloy (AA2219). The Al alloy was subjected to solution treatment at 530°C for 6 hours and cooled in a furnace. The average initial grain size before deformation was about ~140 μm. The equal channel angular pressing was performed on the rods with a diameter of 20 mm and a length of around 100 mm which were machined parallel to the ingot axis. ECAP was carried out repeatedly by using route A up to strains 12 with a pass strain of about 1. The samples were quenched in water after each pass of deformation. Microstructures were examined in the central regions of a cross section parallel to the pressing direction, which is marked on the following figures as PD. Optical metallography (OM) was carried out after etching by a standard Dicks-Keller solution by using an optical microscope Olimpus PME3. The orientation imaging microscopy (OIM) pictures were observed by automated indexing of EBSD patterns in Hitachi S3500H scanning electron microscope (SEM) with OIM analysis software provided by TexSem Lab.Inc.

Results

Typical optical and OIM microstructures evolved after deformation to around $\varepsilon=12$ are shown in Fig. 1 and 2, respectively. It can be seen in Figs. 1a and 2a that ECAP at 250°C leads to development of homogeneous grain structure (Fig. 1a). The regions of new fine grains with almost HABs were found to develop fully in the whole material (Fig. 2a). The average size of new grains surrounded by HABs in Fig. 2a was about 1 μm. In contrast, an inhomogeneous structure evolved after ECAP at 475°C consists of fine grained regions with average size of about 15 μm alternated with coarse regions with high density of etched pits (Fig. 1b). It can be seen from the detailed microstructure in Fig. 2b that more equiaxed grains with medium to HABs are developed in several places and coarse subgrains with low angle boundaries still remain in the others regions at $\varepsilon=12$. The volume fraction of new grains developed in material did not exceed 50 pct at 475°C.

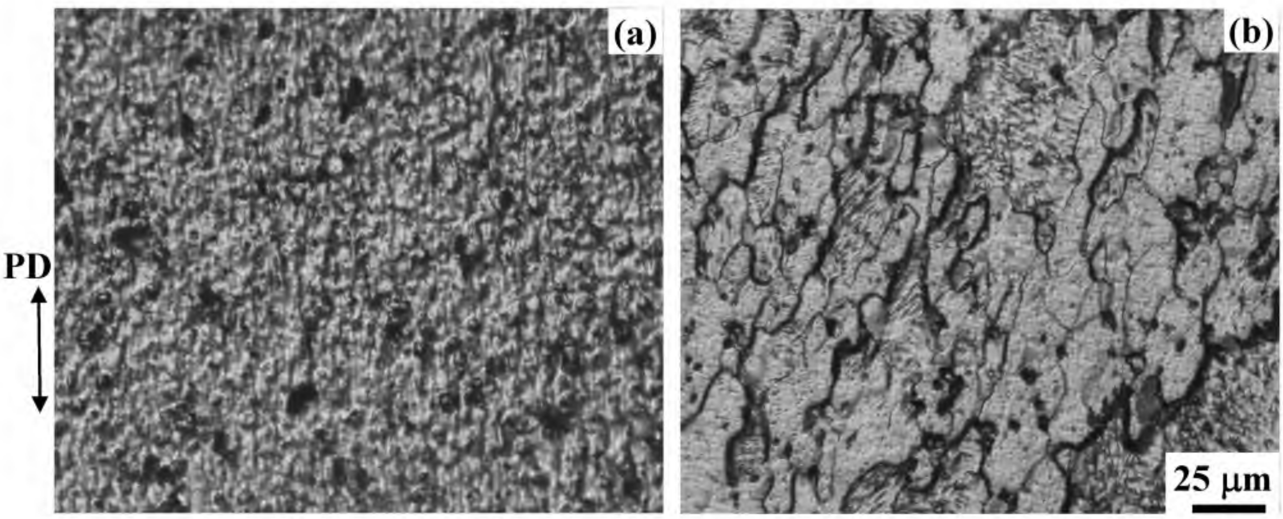

Fig. 1 Optical micrographs for 2219 Al alloy deformed by ECAP to a strain of 12 at temperatures: (a) 250°C and (b) 475°C. PD is the pressing direction

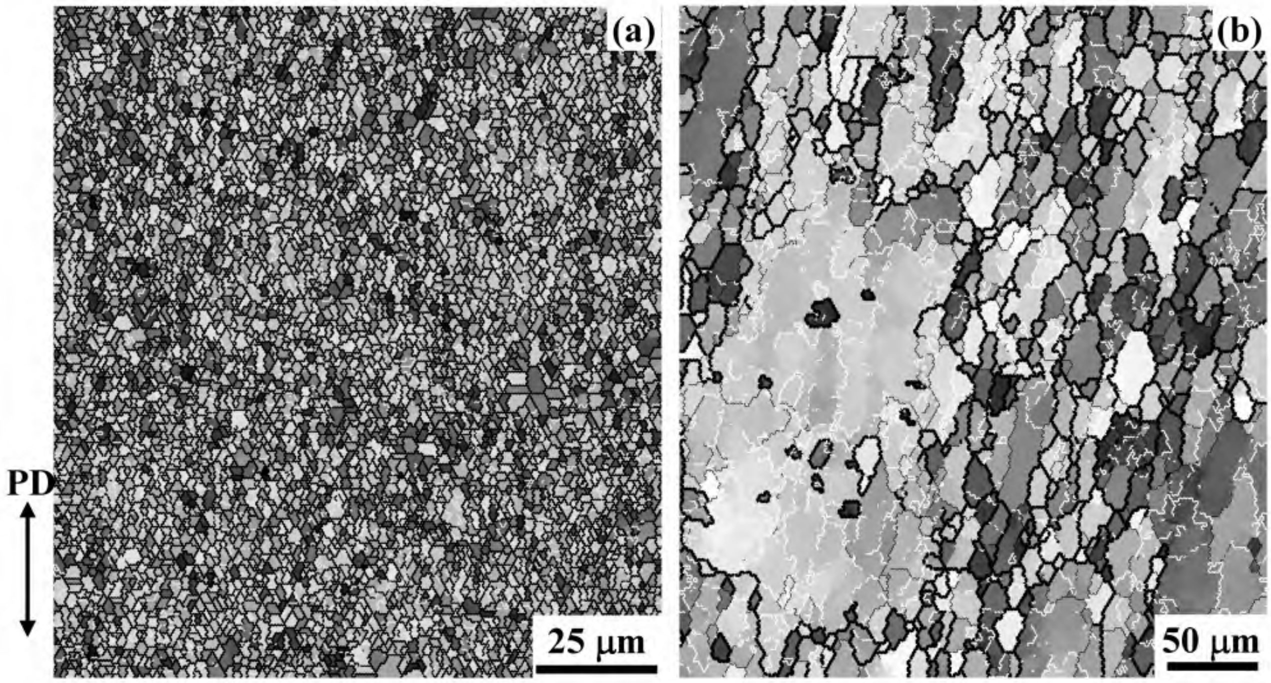

Fig. 2 EBSP maps for 2219 Al alloy deformed by ECAP to a strain of 12 at temperatures of: (a) 250°C and (b) 475°C. Thin white lines correspond to the boundaries of angle misorientation >2°, thin black lines >5° and bold black >15°, respectively. PD is the pressing direction.

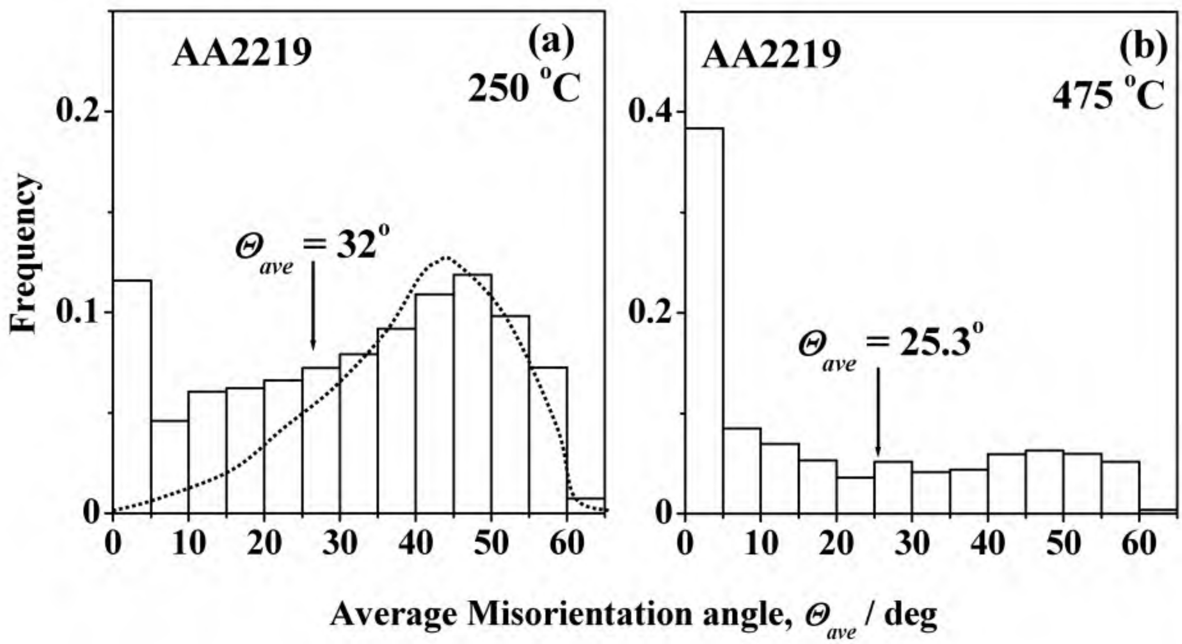

Fig. 3 Distribution of grain boundary misorientations in 2219 Al alloy after deformation by ECAP to a strain of 12 at various temperatures of (a) 250°C and (b) 475°C. The dotted line in (a) indicates the Mackenzie distribution for annealed grains in cubic materials [8].

The distributions of the misorientation angles of strain-induced boundaries Θ_{ave} developed during ECAP at ε=12 are shown in Fig. 3. It is remarkable to see that the distributions at both the temperatures are distinctly bimodal with two peaks at low and high angle misorientation. Average misorientation rapidly decreases from 32 to 25° with increase in temperature. The misorientation distribution developed at 250°C approaches a theoretical distribution for random orientations for fully annealed grains in cubic materials [8], as shown by dotted line in Fig. 3a. Some fraction of low angle misorientations developed is a characteristic in strain-induced microstructure [9]. In contrast, at 475°C the portion of LABs with misorientation less than 5° is about 38%, resulting in decrease in the average misorientation angle (Fig. 3b). This can be resulted from the regions of many coarse original grains, in the interiors of which subgrains with LABs are fully developed (see Figs. 1b and 2b). This suggests that grain refinement process does not take place completely and so the transformation rate to HABs can be reduced with increasing of temperature.

Discussion

Figure 5 represents the changes in the average misorientation angle Θ_{ave} with ECAP at temperatures of 250 and 475°C. The average misorientation angles in the fine grained regions introduced by ECAP and also in the whole areas are represented by solid and broken lines, respectively. It is clearly seen in Fig.5 that the development process of deformation induced boundaries can be categorized into the three stages. At the first stage in the strain interval from the beginning ε = 0 to 2, the misorientation angle increases to a plateau of about 5° at both the investigated temperatures. At the second stage in the strain range from 2 to 4, there is a rapid increase in the average misorientation angle. It is interesting to note that the changes of misorientation angle with ECAP at the early two stages are roughly the same at 250 and 475°C. It can be concluded, therefore, that temperature does not affect the grain refinement process operating in early stages of ECAP for 2219 Al alloy. It should be also noted in Fig. 5 that new grains with HABs were formed at a critical strain between 2 and 3 at both the temperatures.

At the third stage in the region beyond a strain of around 4, in contrast, the development of deformation-induced microstructures during ECAP is clearly affected by temperature, as represented by solid and broken lines. The average misorientation angle for deformation induced boundaries tends to increase continuously with strain and approach the value of about 32° at 250°C and 25° at 475°C at ε =12. The fine grained regions developed at 250°C were found to cover approximately 95% of the whole microstructure, so that the difference of the average misorientation angle is less than 3° and remains constant in this strain interval. In contrast, the average misorientation angle in the whole area at 475°C (Fig. 2b) is roughly constant value and does not exceed 15° at large strains. This lower saturation value of misorientation angle, compared to that in the regions of fine grained structure can be resulted from difference in the volume fraction of new grains developed in the strain interval of 4≤ ε ≤12. The volume fraction of fine grained regions developed after ε =12 at 475°C did not exceed 50 pct (see Fig. 2b). It is concluded, therefore, that temperature effect on the strain-induced microstructural developments appears sensitively in the last stage of ECAP in the strain interval from 4 to 12, while it does not in the early two stages, i.e. 0≤ ε ≤4. Almost similar results have been shown in the previous works on the 7475 Al alloy during hot ECAP [4, 5].

It was emphasized in [5] that evolution in strain-induced boundaries during hot ECAP was directly associated with the formation and evolution of boundaries of deformation bands (DBs).Let us discuss the mechanisms of formation and evolution of such deformation-induced boundaries. The boundaries of DBs start to develop at the early stages of ECAP due to inhomogeneity introduced. Their number and the boundary misorientations increase with further deformation, finally leading to the development of new fine grains surrounded by HABs at large strains. It should be noted in Fig. 5 that regions of new grains with HABs are firstly detected at a critical strain of about 3, after then their volume fraction and misoreintation angle are changed with different rate depending on temperature. The mechanism of gradual increase in the boundary misorientation in the last stage, i.e. $4 \le \varepsilon \le 12$, can be associated with increase in the number of lattice dislocations evolved by usual intrinsic slip and the absorption of accommodation dislocation that originates from incompatibility between neighboring grains. It should be noted that formation of deformation bands are considered to be developed by relaxation of strain gradient resulting from heterogeneous deformation introduced by ECAP [4-7, 10,12,13]. Concurrently, dynamic recovery can operate with lower rate at 250°C rather than at 475°C. As a result, rapid transformation of the deformation induced LABs into HABs occurs much more frequently at 250°C. With increasing the temperature to 475°C, deformation becomes more homogeneous and deformation banding takes place less frequent due to operation of dynamic recovery with higher rate. It leads to some relaxation of grain compatibility and the annihilation of dislocation takes place more frequently, and then the process of transformation into HABs and approaching a saturation value should be retarded at 475°C. Thus, a lower kinetics of increase in the misorientation angle of deformation induced boundaries can be resulted in the operation of dynamic recovery and relaxation of strain gradient between grains in the strain interval $4 \le \varepsilon \le 12$.

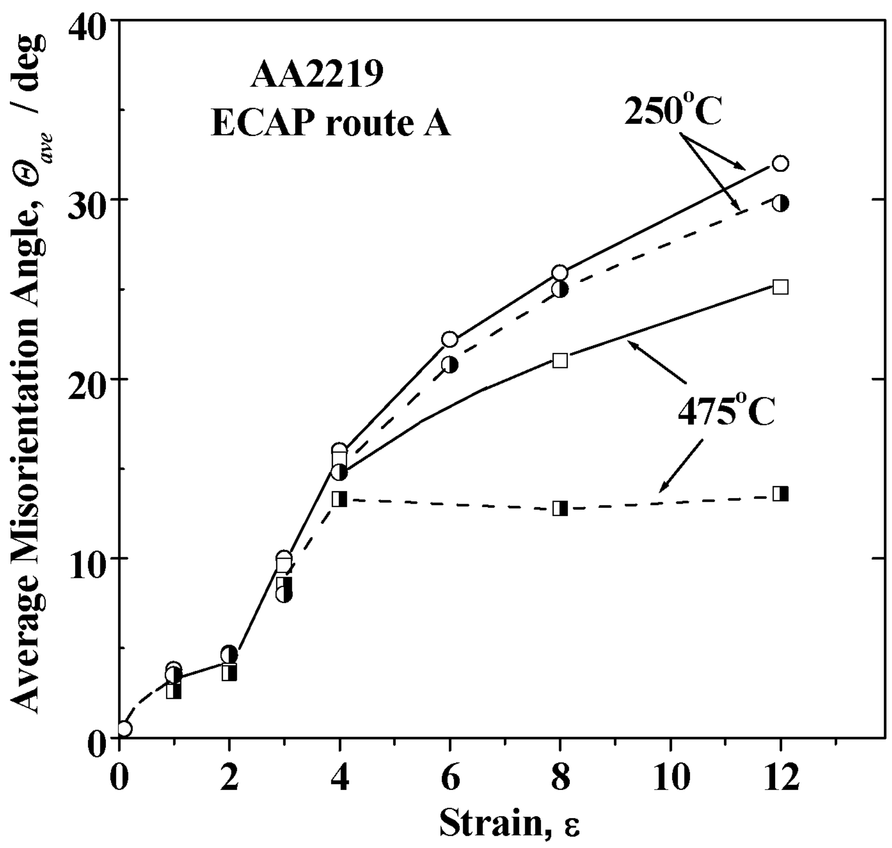

Fig.5 Strain dependence of the average misorientation angle Θ_{ave} of the deformation induced boundaries developed in the regions of new fine grains for 2219 Al alloy at 250 and 475°C (solid lines with open marks). Broken lines indicate the average misorientation angle developed in the whole region.

Summary

Temperature effect on the deformation induced microstructure was studied in 2219 Al alloy deformed by ECAP at temperatures 250 and 475°C. The main results are summarized as follows:

1. ECAP results in grain refinement at all of the pressing temperatures. The average grain size increases from 1 to 15 μm at 250 and 475°C, respectively.
2. Increase in temperature tends to slow down the transformation rate of deformation-induced boundaries into high angle ones in the strain interval from 4 to 12. The misorientation angle of deformation induced new grains decreases in average from 32 to 25° at 250 and 475°C, respectively.
3. Strain dependence of the misorientation angle of deformation-induced boundaries can be categorized in three stages. The significant temperature effect appears clearly in strain range $4 \leq \varepsilon \leq 12$, i.e. the last stage, while it is not observed at the early two stages, i.e. $0 \leq \varepsilon \leq 4$.

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