Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS) 2 (2): 289-293
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jeteas.scholarlinkresearch.org

Characteristics of an Aluminum Alloy after Generation of Fine Grains Using Equal Channel Angular Extrusion Process

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Abstract

Equal channel angular extrusion (ECAE) was used to generate grains of average size (0.35 μm) in an aluminum alloy at room temperature. Also, it was found that the characteristics of the aluminum alloy 1050 (99.5% pure) after using an x-ray diffractometer equipped with texture goniometer was that of a random microtexture. Therefore, it can be concluded from the results obtained that local grain boundary migration, texture evolution and subdivisions in the grains were possible mechanisms involved in the formation of the grain size developed in this work after equal channel angular extrusion process. The work was carried out at the National High Magnetic Field Laboratory, Tallahassee, Florida, USA.

Keywords: aluminum; equal channel angular extrusion; grain size; plastic deformation

INTRODUCTION

Different methods have been employed in the recent past to impart ultrafine grain sizes (about 1 μm) in bulk materials such as pure aluminum alloy (99.99%), used in this work which is polycrystalline after severe strain deformation at room temperature. These methods include equal channel angular extrusion (ECAE) (Iwahashi et al., 1998) and cyclic extrusion compression (CEC) [2]. Equiaxed fine grains with high angle grain boundaries (HAGB) have resulted after ECAE after ε=4 and production of uniformly distributed equiaxed fine grains with HAGB have also been achieved after ε=60 by using the CEC technique (Richert et al., 1999).

It is very interesting with the mechanisms involved in the creation of the large area of HAGB mentioned above on straining at a relatively low temperature ($\sim 0.3\ T_m$). The microstructure evolution in large strain deformation has been studied quite extensively [Bay et al., 1992a; Bay et al., 1992b and Rosen et al., 1995). Most of these studies have been carried out on specimens deformed in monotonic loading over a strain range up to 4.5. It is unknown whether the known cold deformation mechanism may eventually result in a fine grain structure.

A possible mechanism for the formation of fine grains in aluminum by large deformation at room temperature is static recrystallization (SRX) or dynamic recrystallization (DRX). There are several reports on recrystallization in pure aluminum deformed at room temperature. Some difficulties exist in unambiguously determining whether the recrystallization occurs during deformation or subsequent SRX. Kassner et al., 1994 observed dynamically recrystallized grains in high purity aluminum (99.999%) deformed at room temperature. Ponge et al., 1997 also observed DRX in high purity (99.9995%) Al single crystal but not in less pure (99.995%) Al. On the other hand, one of the studies provided evidences to show that the recrystallization of high purity aluminum (99.999%) during deformation at room temperature was caused by SRX (Choi et al., 1994). The recrystallization of aluminum is very sensitive to the purity, i.e. less pure aluminum recrystallizes much more sluggishly than 99.999% pure aluminum (Haessner and Smith, 1993). There is always doubt as to whether SRX may be involved in the evolution of new grains reported in high purity aluminum deformed at room temperature. The objective of this study is to characterize the submicron grained structure formed in aluminum by ECAE technique in order to understand the mechanism of HAGB formation. To suppress the possible occurrence of SRX in aluminum at room temperature, aluminum of commercial purity was used in this study. The present results will be compared with that of high purity aluminum (Iwahashi et al, 1998).

EXPERIMENTAL

For ECAE, the tool is a block with two intersecting channels of identical cross-section. A well-lubricated billet of almost the same cross-section is placed into one of the channels, and a punch then extrudes it into the second channel. Under these conditions,

deformation is achieved by simple shear in a thin layer at the crossing plane of the channels (the shear plane). Deformed by ECAE, the sample undergoes simple shear but it retains the same cross-sectional area so that it is able to repeat the process to several cycles. Therefore, very large plastic strain could be accumulated in sample deformed by ECAE. In addition, with multiple passages there are a number of ways to develop different structures and textures in the same material through modification of the shear planes and the shear directions during the extrusions (Segal, 1995 and Iwahashi et al., 1996).

The materials used in this work was 1050 Al (99.5% pure) which was homogenized at 893 K for 12 h and slowly cooled. The initial grain size of the material is about 330 μm. Specimens of 12×12×80 mm were subjected to ECAE for various passes at room temperature. The die for ECAE is consisted of two channels with square cross-section meeting in an L-shape configuration at an angle of 90°. The angle defining the arc of the two channels is 20°. The equivalent strain on pressing through the die was calculated to be about 1 (Furukawa et al, 1998). The strain rate applied during ECAE is estimated to be about 10^{-2} s^{-1}. Sample was passed through the die repetitively for eight passages. The sample was rotated counter clockwise about the extrusion axis (*X*-axis) by 90° between each passage. Following Furukawa et al., 1998, this process route is designated as route B_c.

There are two shear planes intersecting at 120° associated with ECAE in the route B_c as shown in Fig. 1. In odd numbered passage (*N*=1, 3, 5, 7), the material is sheared on one plane, while in even numbered passage (*N*=2, 4, 6, 8), it is sheared on the other plane. The shearing direction in *N*=1 and 2 is opposite to that in *N*=3 and 4, respectively. Therefore, a complete cycle of this process route would consist of four passages. Furukawa et al., 1998 have clearly demonstrated that with this process route, the shape of a cubic element will be restored after every four passages

Specimens were cut from both *X*-and *Y*-planes of the extruded material. Thin foils prepared by twin-jet electropolishing were examined by TEM (JEOL 200CX). The grain size was defined as the average of the long and short axes of a grain. Electropolished specimens from both sections were also examined by SEM (JEOL 6400) equipped with electron backscattered pattern (EBSP) measuring system (Opal, Oxford Instrument). The EBSP analysis was obtained with an accelerated voltage of 20 kV, and the grain orientation distribution was analyzed.

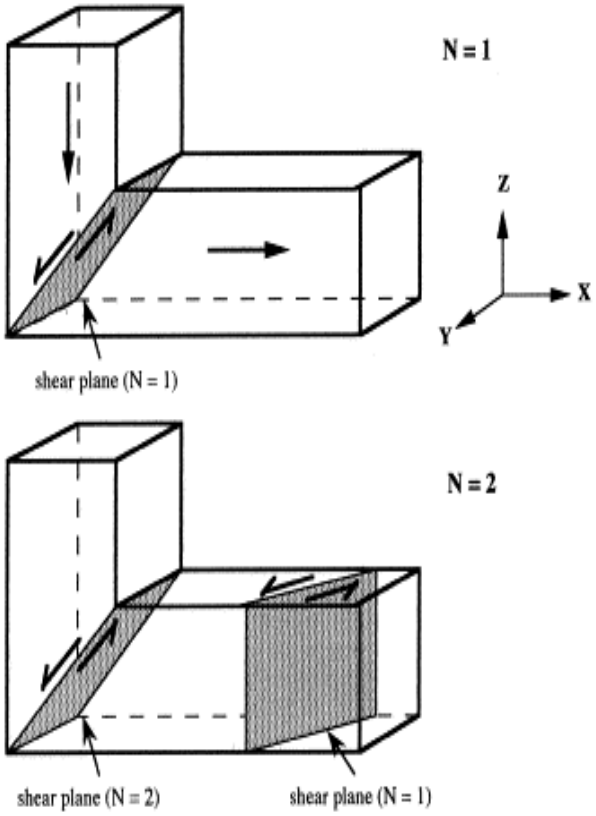

Fig. 1: Schematic illustration of the orientation of the shear plane in a sample processed by ECAE with route B.

RESULTS AND DISCUSSION

For all the specimens examined, there is no indication of SRX. The microstructure of the *Y*-plane is mainly consisted of equiaxed grains delineated by sharp boundaries as shown in Fig. 2a. There may be argument to call these structural unit 'grain'. Because of the following observations, we consider that it is appropriate to use this term. In general, large misorientation was observed among neighbouring units, and dislocations have lost their identity in most of the boundaries, which delineate these structural units. For regions with equiaxed grains, the average grain size is about 0.35 μm. However, there are also some regions with slightly elongated grains which form a band-like structure in the *Y*-plane as shown in Fig. 2b. The average grain size of elongated grains is about 0.45 μm. In general, most of the relatively large grains are elongated and subdivided by dislocation boundaries (Fig. 3), while grains of smaller size are equiaxed and nearly free of dislocations within the grain interior. On the other hand, the microstructure observed on the *X*-plane is quite uniform, consisted of equiaxed grains with an average size about 0.35 μm (Fig. 4).

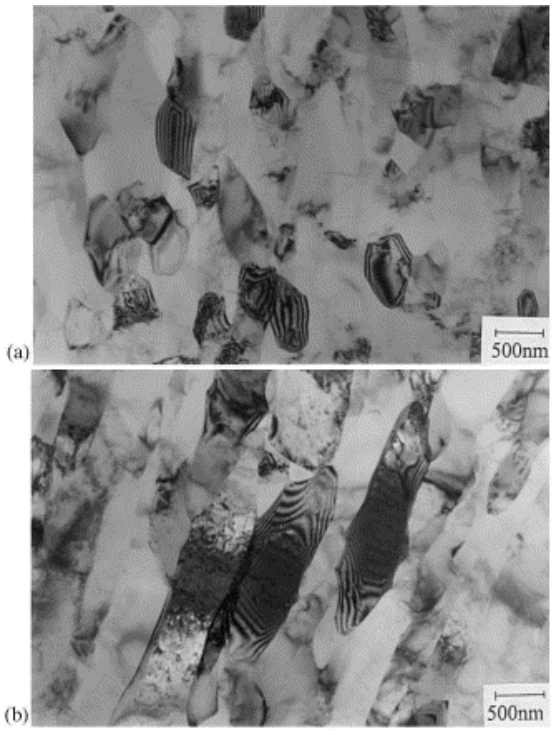

Fig. 2: TEM micrograph of *Y*-plane showing (a) regions with equiaxed grains delineated by sharp boundaries; and (b) regions with mainly elongated grains aligned to form a band structure.

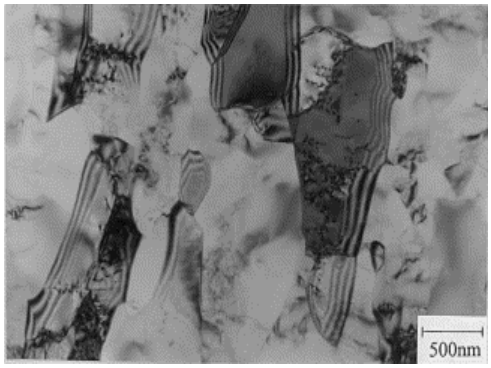

Fig. 3: TEM micrograph of relatively larger grains in *Y*-plane, which are subdivided by polygonized dislocation boundaries

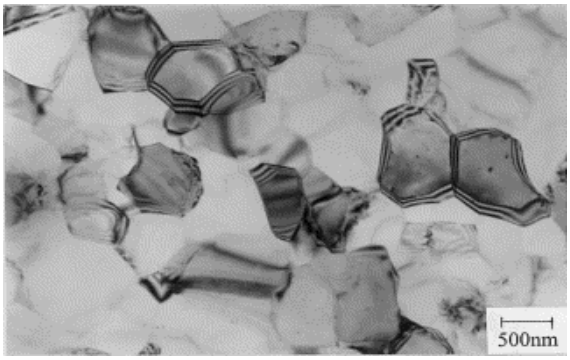

Fig. 4: TEM micrograph of *X*-plane showing equiaxed grains delineated by sharp boundaries.

The local crystallographic orientations of both *X*- and *Y*-planes were investigated using the EBSP technique. An area about 6.6×10 μm was examined. With a scan step of 345 nm, about 530 measurements were made and among which more than 350 measurements were successful. Those patterns, which could not be solved, are apparently caused by the overlap of two Kikuchi patterns diffracting from neighboring grains. Because of the small grain size, the EBSP measurements on neighbouring sampling points certainly can not provide correct information on the misorientation of neighboring grains. However, it does provide information about the distribution of the orientation within the area examined. The distribution of orientation of the sampling points is revealed by the inverse pole figure (Fig. 5), which clearly indicates that a nearly random distribution of orientations on both sections resulted from the severe plastic deformation imposed by ECAE route B_c. This is consistent with the geometrical nature of this processing route, in which shearing direction changes in each pass (Iwahashi et al, 1996).

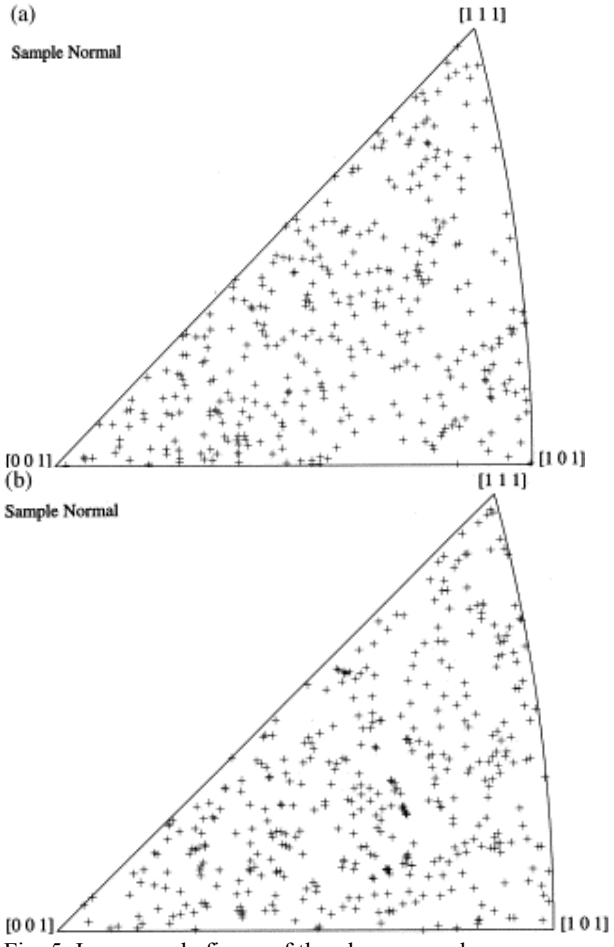

Fig. 5: Inverse pole figure of the plane normal obtained on (a) *X*-plane; and (b) *Y*-plane

The evolution of the microstructure of aluminum deformed to strains up to 2.7 (90% rolling reduction) has been extensively studied (Bay et al., 1992a; Bay et al., 1992b and Rosen et al, 1995). It has been shown that grains break up on a smaller and smaller scale into volume elements within each of which fewer slip systems operate simultaneously than required by the Taylor model. The boundaries between the volume elements accommodate the lattice misorientations arising from the correspondingly different glide. With increasing strain, the microstructure evolves into a lamellar structure with boundaries of small to medium misorientation angles mixed with high angle boundaries. The latter consist of mainly deformation induced high angle boundaries with relatively small fraction of original grain boundaries. Based on grain subdivision processes, the mechanisms leading to formation different texture components within an original grain during deformation were suggested by (Rosen et al, 1995), as follows

1. the rotation of a subdivided grain to different preferred crystal orientations during deformation;
2. ambiguity of slip systems for unstable crystal orientations that lead to diverging rotations within a grain.

If a grain subdivides, the individual crystallites within a grain may rotate to different end orientations. Since the different end orientations may differ by very large misorientations, this process will create very high angle boundaries. The changing shear plane and shear direction in each ECAE passage with this process route should contribute significantly to the formation of random microtexture shown in Fig. 5. On the other hand, considering that most of the grains remain equiaxed and a random texture is resulted in spite of the large plastic strain involved in the last ECAE passage, random grain rotations associated with grain boundary sliding might contribute as well.

Local boundary migration is also vital for the formation of equiaxed grains during deformation. Intense plastic deformation may increase the amount of point defects significantly, which consequently can aid the dynamic process. The boundary misorientations in this structure increase with increasing strain leading to the evolution of high angle boundaries accompanied with their local migration as well as the relaxation of internal stresses as suggested by Kaibyshev et al., 2001b. The energy balance between these boundaries can cause an equilibrium shape of triple junctions promoting local migration of the boundaries. Finally new equiaxed grains with equilibrium boundaries are developed. It is also noted that in high purity aluminum (Iwahashi et al, 1998), ultrafine grained structure can be obtained after only four ECAE passages with the same process route, but the grain size formed in it is 1.3 μm, which is much larger than that observed in 1050 Al in this work. This implies that the grain size formed is significantly affected by the boundary mobility, which is sensitive to the presence of impurity atoms.

SUMMARY

This study has shown that very effective grain refinement can be achieved by applying ECAE to ε =8 at room temperature. In addition, the resulted submicron grained structure is characterized by a random microtexture. Based on the observation, the possible mechanisms of the formation of new grains in aluminum during severe plastic deformation are discussed, and it is suggested that grain subdivision and texture evolution (Rosen et al, 1995), as well as local boundary migration are possible key mechanisms.

ACKNOWLEDGEMENTS

This work was supported by funds provided by Dr Reginald Perry (Associate Dean for Academics and Professor of Electrical Engineering) at the FAMU-FSU College of Engineering, Tallahassee, Florida, USA through the Minority Doctoral Engineering Fellowship funded by Title III of the US Department of Education. Also, thanks to Dr Hamid Garmestani of the Materials Science and Engineering Department, Georgia Institute of Technology, Atlanta, Georgia and Dr Justin Schwartz of the Materials Science and Engineering Department, North Carolina State University, Raleigh, North Carolina for their academic advice.

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