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Lamellae deformation and structural evolution in an Al-33%Cu eutectic alloy during equal-channel angular pressing

JINGTAO WANG
School of Metallurgical Engineering, Xi'an University of Architecture and Technology, Xi'an, 710055, People's Republic of China; Department of Materials Engineering, Korea Institute of Machinery and Materials, Changwon 641-010, Korea

SUK-BONG KANG*, HYUNG-WOOK KIM
Department of Materials Engineering, Korea Institute of Machinery and Materials, Changwon 641-010, Korea
E-mail: sbkang@kmail.kimm.re.kr

ZENJI HORITA
Department of Materials Science and Engineering, Kyushu University, Fukuoka 812-8581, Japan

Equal channel angular pressing was successfully applied on a lamellae eutectic alloy of Al-33%Cu at 400°C, up to an equivalent strain of ∼8. A homogeneous fine equiaxed duplex microstructure with an average grain size of 1.1 ± 0.3 μm was obtained. Deformation accommodation is realized in various form of periodical shear banding: periodical bending, periodical shear banding, shear switching, and periodical shear cutting in the eutectic. The shear essence of the strain mode involved in ECAP determines the very different behavior, from that in drawing, of lamellae structural evolution.

1. Introduction

Lamellae structure is of significant importance for material research and development, especially in the case of eutectic or eutectoid. In many cases, however, it is desirable to break the lamellae structure down to form an equiaxed structure. Plastic deformation plays an important role in the processing of various eutectic or eutectoid structure into an equiaxed fine grain duplex structure, which has been a successful practice since the early days in the development of superplasticity [1–3]. Much work has been done on superplasticity of Al-Cu eutectics based alloys through plastic deformation processing [1, 4–6]. Although Al-Cu eutectics based eutectic alloy has fairly good superplasticity, it is basically a laboratory alloy for materials research because of its poor mechanical properties at room temperature [7]. Potentials exist, however, when the alloy grain structure is ultra refined, for a substantially improvement of its properties, through ultrafine grain strengthening, and through the possible improvement from non-equilibrium supersaturation of alloying elements in the alloy phases [8].

Severe plastic deformation, e.g., equal-channel angular pressing (ECAP), is well applied for the processing of various materials to obtain an ultrafine grained microstructure [8–10]. Through ECAP, various ingot metallurgy materials were processed to behave high strain rate superplasticity [11], among which is Zn-22%Al eutectoid alloy [12]. Although high strain rate superplasticity is well obtained in this duplex eutectoid alloy, no detail reports on the structural evolution of this duplex structure during the multi-pass nearly pure shear deformation of ECAP. Although extensive works have been reported on the structural evolution and mechanical property change of lamellae materials of eutectoid pearilite during cold drawing deformation up to a large strain [13–16], there are fewer reports on lamellae deformation behavior in pure shearing deformation.

It is thus desirable and also possible to apply ECAP to the processing of a lamellae structure, such as Al-Cu eutectic lamellar structure, to obtain an ultrafine grained equiaxed duplex alloy. This paper is to investigate the microstructural evolution of a lamellar structure in Al-Cu eutectic alloy during equal channel angular processing. The lamellae structure can in turn act as a special internal grid naturally "inscribed" in the deformation body to help to understand the deformation feature in micro- or mesoscopic scales of this new typical deformation process. This understanding will be a help for the application of ECAP in other lamellae structured materials of engineering importance, such as lamellae TiAl intermetallic compound alloy, pearilite steel, etc. A thermally stable nanostructured bulk materials, free from residual porosities of powder metallurgy process,

*Author to whom all correspondence should be addressed.

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may thus be fabricated through the equal channel angular processing of lamellae materials.

2. Materials and experimental procedures

A chill cast slab with a size of $15 \times 150 \times 120$ mm of Al-33%Cu eutectic alloy was used for the experiment. Machined bars sized $\phi 13 \times 90$ mm from this cast slab were homoginized at 400°C for 3 hr before isothermal ECAP via route Bc carried out at 400°C with a die angle of $\pi/2$ between the two intersecting channels. Here, route Bc denotes repetitive pressings where the sample is rotated by 90° between each pressing [17]. The ECAP die was first heated up to 400°C, and then the sample was loaded for reheating. Ten minutes was given for the sample to be reheated before the first ECAP press. This reheating time was shorten to 2 minutes for the subsequent ECAP passes of the same sample. Reheating of the sample was monitored and recorded with an on-line data acquisition facility, together with pressing load and die temperature during ECAP.

Samples were cut along three orthogonal sections with respect to the pressing direction for microstructure characterization using optical microscope and transmission electron microscope. For optical microscope observation a modified Keller's reagent containing $HF : HCl : HNO_3 : H_2O$ in a proportion of $2:3:5:190$ was used. And for transmission electron microscopy, the final twin-jet electro polishing was carried out in a solution containing $CH_3OH : HNO_3$ in a proportion of $3:1$. The foils were examined using a JEOL-200F electron microscope operating at 200 KV. Grain size was estimated using a VISUS IMAGE ANALYSIS software running on a personal computer.

3. Experimental results

Microstructures were observed of all the samples in as-homoginized state, and after ECAP to 1 through 8 passes via route Bc on three orthogonal sections with respect to the pressing direction. Except for the first and the second ECAP passes, no obvious difference can be observed among different sections. Thus, the following results are given without respects to their section directions. Typical microstructures are shown in the following two subsections: first, the evolution of the overall eutectic structure with ECAP passes; and second, typical deformation features of lamellae during ECAP.

3.1. The evolution of the overall eutectic structure with ECAP passes

Through the severe plastic deformation in equal channel angular processing, lamellae in the eutectic were broken down by shear and multi-shear deformation, the overall structure of the Al-33%Cu eutectic alloy evolved gradually for typical eutectic lamellae to a wholly equiaxed fine duplex structure. Fig. 1 gives typical microstructures from homogenized eutectics, through ECAP for 1, 2, 4, 6 up to 8 passes via route Bc. No obvious change in lamellae interspacing was observed during ECAP. With the increase of ECAP passes and accumulated plastic strain in the material, the lamellae colonies in the eutectic structure were first divided into smaller lamellae regions, through the strong shear banding and breaking described in the following subsection. These small lamellae regions gradually shrink to smaller and smaller islands, and finally, when the ECAP pass reaches 8, a fully homogeneous equiaxed duplex fine structure is obtained.

In addition to the breaking down of the lamellae into equiaxed duplex structure by plastic deformation, the equiaxed duplex structure seemed to be growing during the deformation processing carried out at the experimental temperature 400°C. This is clearly seen from Fig. 1d, through Fig. 1e, to Fig. f, where the equiaxed region dominates in the overall structure. This fact indicates that thermal process is also strongly effective in the high temperature equal channel angular processing, and may give important contribution to the evolution of the structure, in addition to the most strong effect of severe plastic deformation. Further detailed work is necessary to understand the concurrent thermal effect on the speroidization of the lamellae under severe shear deformation.

Although the lamellae eutectic microstructure evolved into a fully homogeneous equiaxed fine duplex structure, in sharp and strong contrast to its ancestor, after 8 passes of repeating equal channel angular processing, the optical microstructure seemed not quite spheroidized, especially the θ phase. It seemed not fully equiaxed, but in irregular connective shape. This can be clearly seen in Fig. 2a. To examine the essence of this irregular connective shaped θ phase, transmission electron microscopic observation was carried out on the same microstructure, and Fig. 2b shows a typical photo. Nearly fully equiaxed θ phase grains are clearly observed scattered on the background of α-aluminum solid solution, with somewhat but not serious aggregation. The average grain size was estimated to be 1.1 ± 0.3 μm. The background α-aluminum solid solution had an equivalent grain size when tilted to proper contrast.

3.2. Typical deformation features of lamellae during ECAP

Typical deformation microstructures of lamellae during the initial passes of ECAP are shown in Figs 3 and 4. Four essential microstructure features of lamellae eutectic aggregates were observed after ECAP:

1. *Periodical bending*. The lamellae in a eutectic colony were bent collectively in a somewhat regular manner, keeping in parallel to each other, into wavy shapes, with repeating or periodical wave peaks (as shown by solid arrows in Fig. 3a) and wave valleys (as shown by hollow arrows in Fig. 3a). These peaks and valleys, penetrating the whole lamellae colony, are in large angle to the general orientation of the lamellae. Both α-aluminum and θ phase lamellae change their direction gradually while being bent at peaks or valleys, and keeping connective in each lamella without bending cracks. This deformation feature is considered as periodical bending, or bend banding, a mild deformation reaction of lamellae to accommodate the severe shear deformation in ECAP.

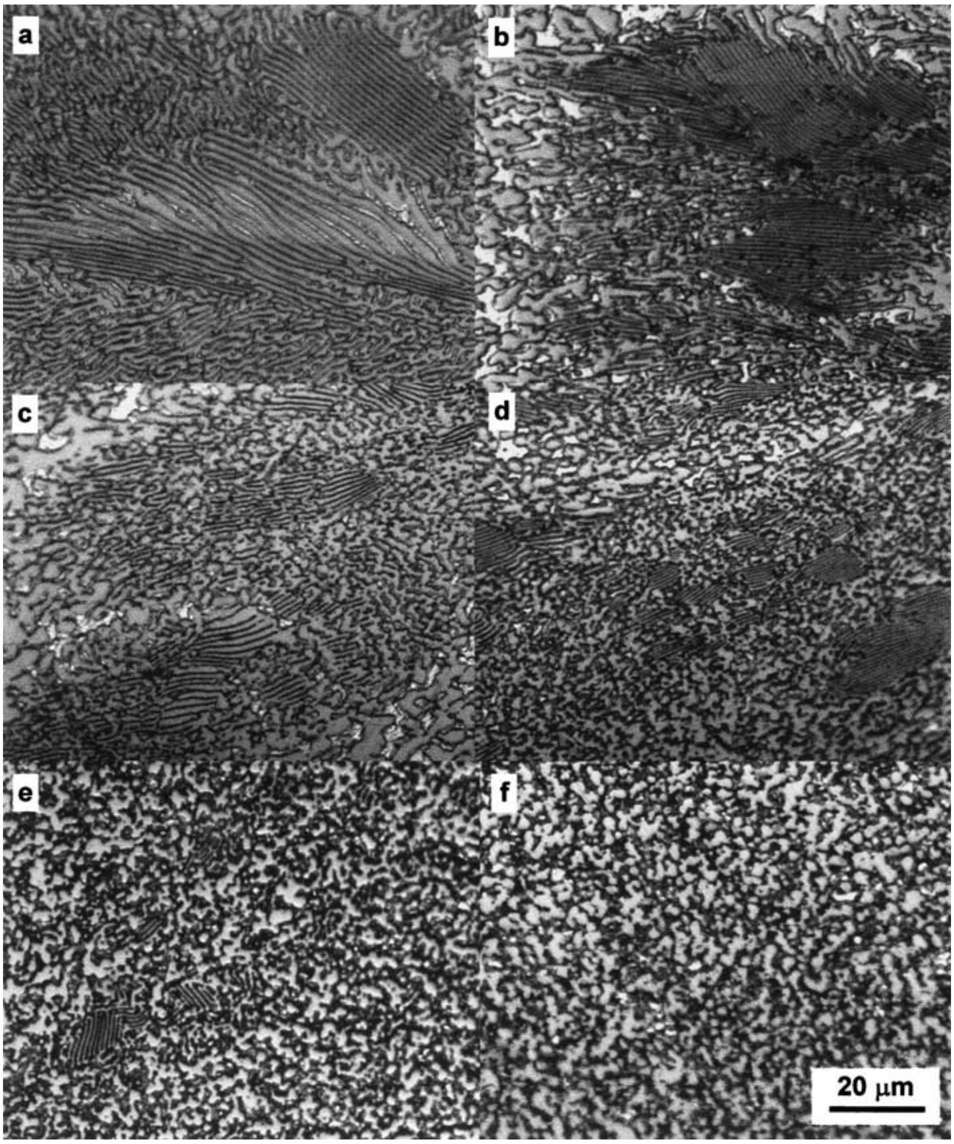

Figure 1 Microstructural evolution in Al-33%Cu eutectics during equal channel angular processing: (a) as-homogenized at 400°C for 3 hrs, (b) 1 pass, (c) 2 passes, (d) 4 passes, (e) 6 passes, and (f) 8 passes ECAP via route Bc.

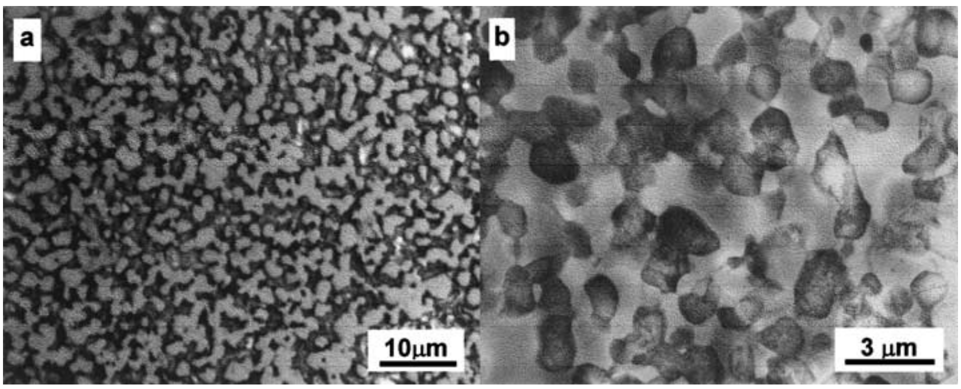

Figure 2 (a) Optical microscopic and (b) transmission electron microscopic microstructure in an Al-33%Cu eutectics after ECAP 8 passes via route Bc.

2. *Periodical shearing*. The lamellae in a eutectic colony were sheared collectively also in a regular manner, also keeping in parallel to each other, having the appearance of repeating or periodical ranks of herringbones (as shown by solid and hollow arrows in Fig. 3b). The ridges of these ranks of herringbones are also in large angle to the general orientation of the lamellae. It differs from bending band that at the vertex point of herringbone, each lamella changes its orientation sharply, often accompanied by lamellae cracks. This deformation feature is considered as periodical shear, or shear banding, a drastic deformation reaction of lamellae to accommodate the severe shear deformation in ECAP.

3. *Shear switching*. A special kind of deformation feature is observed with the appearance of a broad

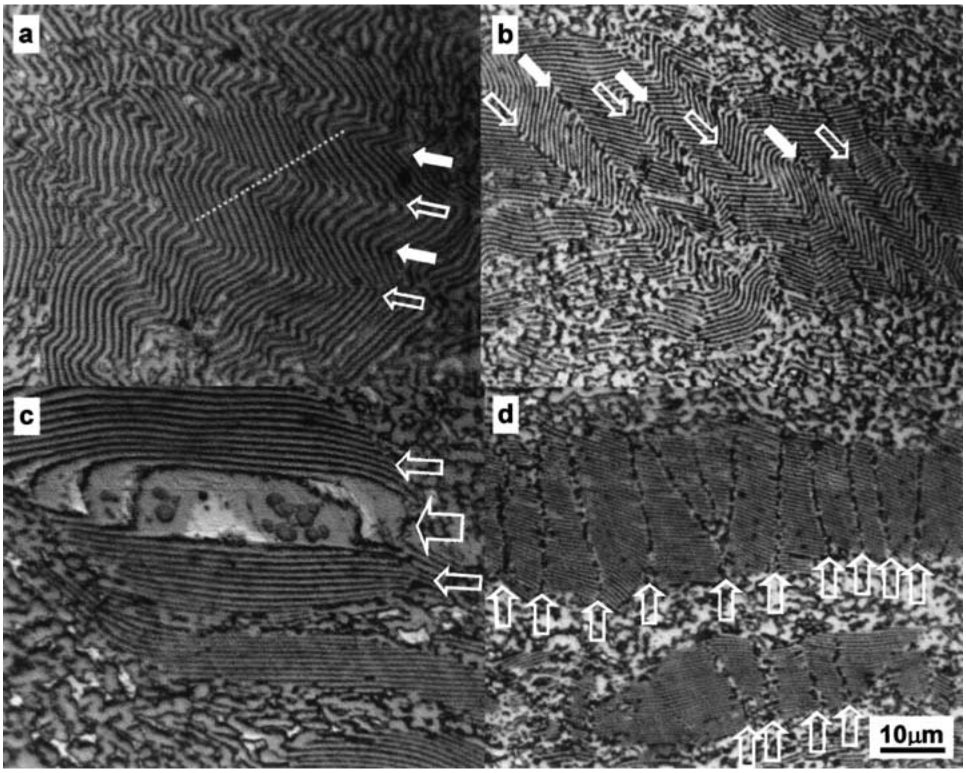

Figure 3 Typical deformation features: (a) periodical bending, (b) periodical shearing, (c) shear switching, and (d) periodical cutting in lamellae Al-33%Cu eutectics during equal channel angular processing.

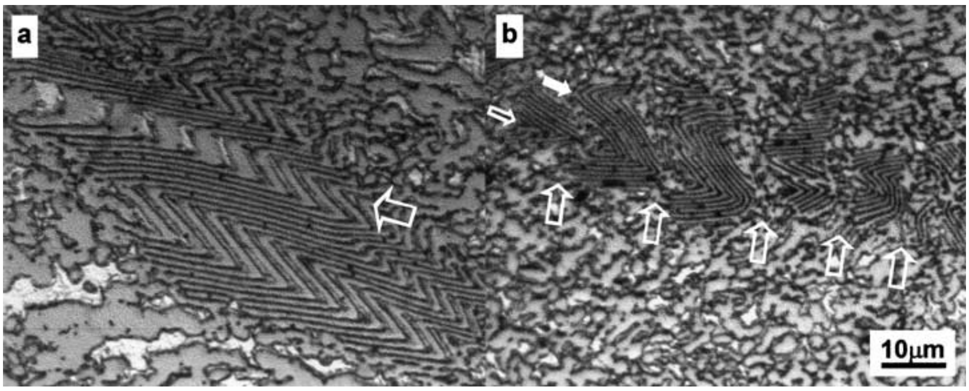

Figure 4 Combination of essential deformation modes: (a) combination of periodical shear banding and shear switching and (b) combination of bend banding and periodical cutting in lamellae Al-33%Cu eutectics during equal channel angular processing.

lamella sandwiched in narrow lamellae, as shown in Fig. 3c. This deformation feature is considered as shear switching of the lamellae, and may also be observed to occur periodically. If the sample were cut and observed along the dashed line in Fig. 3a, the observing section would be cut through the lamellae at one side of the peak, and be parallel to the lamellae on the other side of the same peak, giving the view of broad lamella sandwiched in narrow lamellae, as indicated by broad and narrow arrows in Fig. 3c. Similar view can also be obtained by proper sectioning along the lamella in Fig. 3b. The shear switch observed in Fig. 3c is thus considered not a new deformation accommodation mode of lamellae under severe shear, but resembles that in Fig. 3a or b.

4. Periodical cutting. The lamellae observed in Fig. 3d do not undergo substantial orientation change, but being cut to break periodically, as indicated by the hollow arrows, like bundles of grass cut by a hay cutter. This is quite different from the zigzag orientation of lamellae observed in Fig. 3a or b, and can be considered as a drastic deformation reaction of lamellae to accommodate the severe shear deformation in ECAP.

The essential deformation features described above may combine to form new and further complicate deformation features during multi-pass equal channel angular processing. Fig. 4 shows examples of combinations of periodical shear banding and shear switching (indicated by broad hollow arrow in Fig. 4a), bend banding (indicated by narrow solid and hollow arrows in Fig. 4b) and periodical cutting (indicated by hollow arrows in Fig. 4b) in lamellae Al-33%Cu eutectics during equal channel angular processing.

Both the four essential deformation features and the combination of essential deformation features given above are apparent appearance of shear bandings, primary or primary plus secondary. Bend banding, shear banding and switch banding are apparently forms of shear bandings. Shear cutting or breaking can be considered as a very narrow shear bands. These shear bandings have the following general common characteristics: Periodical, large orientation angle to lamellae direction and penetrating the whole eutectic colony. The lamella which undergoes shear banding is connective in some situation but broken or cut in others.

4. Discussion

Shear characteristics of quasi-single phase materials underwent ECAP has been extensively investigated [17–19]. In this work, microstructure behaviors of lamellae were examined, and strong heterogeneous shear deformation manifested by the periodical shear banding was observed as the most important characteristics of the lamellae underwent ECAP. These shear features must be closely dependent on the straining mode involved in the ECAP process.

In the basic frame of continuum mechanics, there are two essential forms of strain: shear strain and normal strain (tensile or compression) [20]. Conventional metals working like rolling and drawing could be considered as processes having strain modes involving mainly the essential normal strains. Here used in this investigation, ECAP could by considered as a process having the strain modes involving mainly the essential shear strain. These basic differences in essential strain forms involved, determine the different microstructure evolution behaviors of materials during these plastic working processes.

During cold drawing of fully lamella pearlitic steel wire, the main features of the microstructural changes, when observed in the longitudinal cross section, with the drawing strain are a progressive alignment of lamellae along the drawing axis into a fibrous microstructure, a reduction of lamellar interspacing, and a thinning of cementite lamellae. Cementite plates are thinned and, finally, necked down into small fragments during the increasing strain of drawing [21]. A direct proportionality exists between the lamellar interspacing and the diameter of the as-drawn wire [13–16].

During the initial passes of ECAP, the lamellar eutectic Al-Cu undergoes severe heterogeneous shear deformation in various forms of shear bandings. These strong shear bandings subdivided each eutectic colony into smaller lamellar regions. With the increase of ECAP passes and accumulated plastic strain in the material, these subdivided smaller lamellae regions gradually become smaller and smaller lamellae islands, and finally, when the ECAP pass reaches 8, a fully homogeneous fine equiaxed duplex structure is obtained.

In strong contrast to the fibrous microstructure aligning along drawing axis with decreasing lamellar interspacing to the drawing strain, the most impressive structural change of lamellae in ECAP is the strong shear banding and breaking down of the lamellae into homogeneous fine equiaxed duplex structure. No obvious change in lamellar interspacing was observed during ECAP. The differences in essential strain forms involved in drawing and ECAP processes, lead to very different microstructure evolution behaviors of lamellar materials during these plastic working processes.

5. Conclusions

1. ECAP was successfully applied on a lamellae eutectic alloy of Al-33%Cu at 400°C up to an equivalent strain of ∼8. The overall eutectic microstructure evolves gradually from a structure characterized by heterogeneous and lamellar features, into a homogeneous fine duplex structure characterized by equiaxed feature with an average grain size of $1.1 \pm 0.3\ \mu$m.

2. Mechanical breaking down of the lamellae and the mixing effect of the two phase by the severe shear deformation accompanying ECAP is responsible for the spheroidization of the lamellae eutectic structure. Various shear and multishear bandings formed in the sample are responsible for the breaking down of lamellae structure into equiaxed structures.

3. Deformation accommodation is realized in lamellae aggregates by: periodical bending, periodical shear banding, shear switching, and periodical shear cutting in the eutectic Al-33%Cu alloy. These are all the appearances of shear banding accommodating the severe shear deformation in ECAP.

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