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Same Area Observations on Recrystallization in Cold-Rolled Al-Mg-Si Alloy by means of EBSD

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Microstructures before and after cold-rolling at 30 and 50 % reduction rates and during annealing at 673 K have been observed on the same area using an SEM-EBSD system. Crystallites for recrystallized grains are dislocation cells which change into subgrains at the early stage of annealing. Subgrains having similar orientations with those of the surrounding subgrains form recovered region, while subgrains having deviated orientations form crystallites. In the case of 30 % reduction rate, SIBM occurs, because there are no isolated subgrains except the areas near grain boundaries. While in the case of 50 % reduction rate, both the crystallites and recovered regions are formed in the interior of the prior grain. As the recovered region contains many small angle boundaries, dislocation density in the region is higher than that in the crystallite, which leads to growth of the crystallite.

Keywords: *Recrystallization, recovery, EBSD, Al-Mg-Si alloy, intermittent observation.*

1. Introduction

The present authors have reported an elemental process of recrystallization in 6061 aluminum alloy after cold-rolling at a reduction rate of 30 % [1-3] through the same area observations during intermittent annealing. Strain induced grain boundary migration (SIBM) was observed. The migrating grain invaded the neighboring grain. The mother grain of the migrating grain was invaded and consumed by other migrating grains, as a result the migrating grain was separated from the mother grain to become a recrystallized grain, and immigrated in the neighboring grain. Orientation of the recrystallized grain was related to that of the mother grain. The orientation of the mother grain was not same as an original orientation but rotated orientation due to cold-rolling. The recrystallized grains have apparently new orientations.

Beck and Sperry [4] reported that the SIBM was predominant in recrystallization in pure aluminum after cold-rolling up to about 40 % reduction rate. In the present study, recrystallization phenomena after cold-rolling at 50 % reduction rate in 6061 aluminum alloy are attempted to be clarified in comparison with those after cold-rolling at 30 % reduction rate.

2. Experimental Procedures

The alloy with a chemical composition of Al-0.38 Si-0.73 Mg-0.20 Cr in mass % was used. Specimens of about 50 x 10 x 2 mm in sizes were cut from the alloy sheet. After solution heat treatment at 813 K for 3.6 ks, one of the surfaces of the specimen was mechanically polished and finished by electropolishing. Microvickers indents were applied to the surface as landmarks for the same area observation. Microstructures were observed by an SEM (Scanning Electron Microscope) - EBSD (Electron BackScattere Diffraction) system. The specimens were cold-rolled at room temperature at reduction rates of 30 % and 50 % through one pass rolling. A small piece including the observed area of about 6 x 6 x 1 mm in sizes was cut from the cold-rolled specimen, and then Ar-ion polished for 10.8 ks under an accelerate voltage of 3 kV. Observation of the same area by SEM-EBSD, annealing at 673 K using a salt bath, and Ar-ion polishing for 180 s were repeated.

3. Results and discussion

Changes in microstructures during annealing at 673 K after cold-rolling at 50 % are shown in Fig. 1. Blank maps with only small angle boundaries and large angle boundaries are shown. Solid lines indicate the former, while fine lines indicate the latter. The view field shown in Fig. 1 was included in one prior grain. The same area observations lead to find out that a "crystallite", which means a small region with low dislocation density and grows into a recrystallized grain, for the recrystallized grain No. 192 is the area indicated by the black arrow in (a). Regions composed of small angle boundaries indicated by "A", spread with annealing as well as recrystallized regions, and finally disappeared (f). These regions are "recovered regions". The recovered regions and the recrystallized regions seem to develop independently and competitively.

Higher magnification images in a part of the area around the crystallite for No. 192 grain after cold-rolling and the early stage of annealing are shown in Fig. 2. Pixels of which confidence index (CI) values are smaller than 0.02 are shown in black area in (a). Bright areas and dark areas in (a) would be dislocation cells and dislocation cell walls, respectively. Most of the pixels in (b), after annealing at 673 K for 6 s, showed higher CI values than 0.02. Recovery with a meaning in narrow sense occurred, that is, decrease in dislocation density and rearrangement of dislocations. Subgrains were formed. Misorientations among the subgrains are larger than 15 degrees. Coalescence of subgrains occurred with annealing as shown in (c) and (d). The bright subgrain indicated by the black arrow in (d) is the crystallite for No. 192 recrystallized grain. In Fig. 3, (001) poles around the crystallite after cold-rolling and at the annealing conditions corresponding to those in Fig. 2 (b), (c)

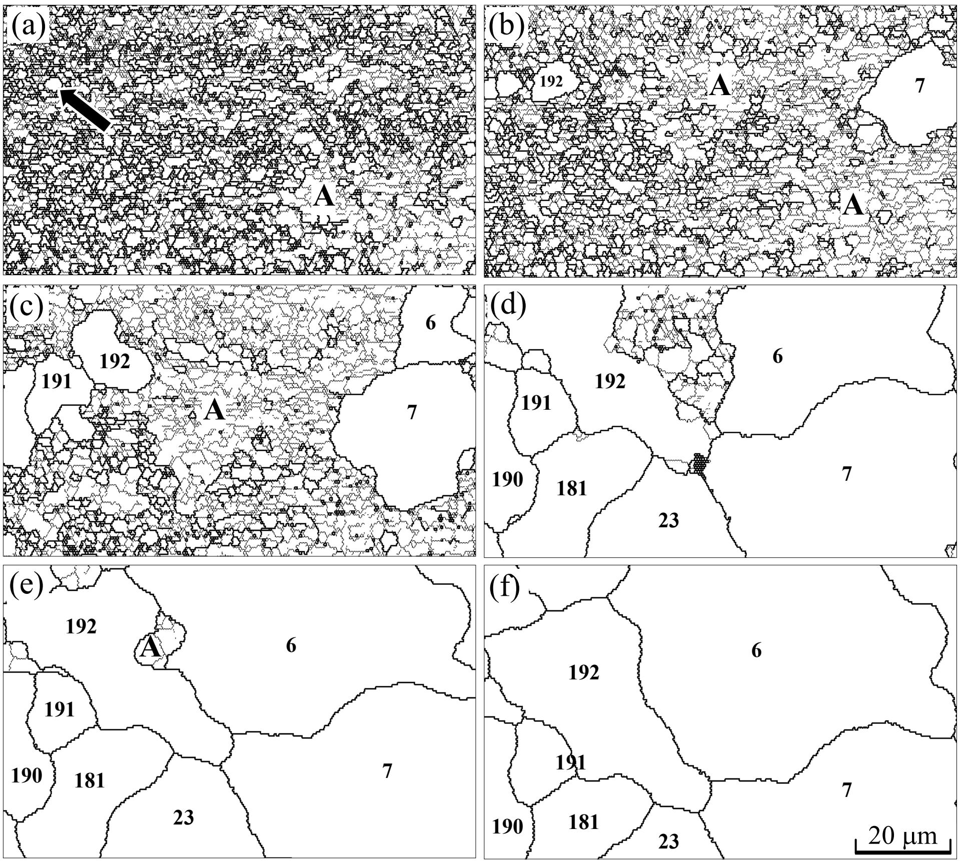


Fig. 1 Changes in microstructures during annealing at 673 K for 20 s, 40 s, 60 s, 120 s, 0.6 ks and 1.8 ks, (a) to (f), respectively after cold-rolled at 50 %. The black arrow in (a) indicates the crystallite for the recrystallized grain No. 192.

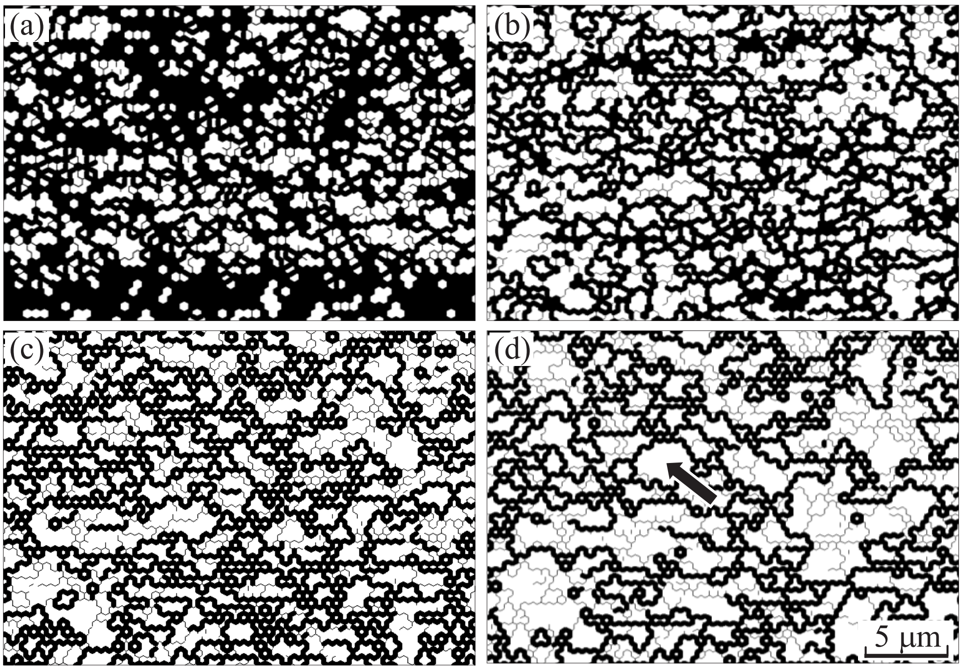


Fig. 2 Microstructures in after cold-rolled at 50 % (a), and changes in microstructures in the early stage of annealing at 673 K for 6 s, 10 s, and 20 s, (b), (c) and (d), respectively. The black arrow in (d) indicates the crystallite for the recrystallized grain No. 192.

and (d) are shown. The (001) poles for the recrystallized grain No. 192 are shown by the black solid circles in (d) and open circles in (a), (b) and (c). Small black dots in (a), (b) and (c) are (001) poles, they would be due to dislocation cells in (a), while due to subgrains in (b) and (c). The (001) poles of the No. 192 grain coincide with those of cells and subgrains. Dislocation cells grow into subgrains with maintaining the crystal orientation, and continuously grow into crystallites to form recrystallized grains.

Dislocation cells also form "recovered regions" by coalescence each other after changing into subgrains, as shown in Fig. 2 (c) and (d). Large angle boundaries would not be obstacles for the coalescence. It should be mentioned that the large angle boundary in the present study is defined as those having larger value than 15 degrees. Such boundaries remain small angle boundaries after coalescence as shown in (d). Both the subgrains for crystallites and subgrains for recovered regions are formed from dislocation cells. It has been shown in Fig. 2 (b) that the orientations of subgrains formed at the early stage of annealing spread in broad range of angle. However, some of the subgrains neighboring each other should occasionally have similar orientations. Coalescence occur among such subgrains to form the recovered region. When there is a subgrain whose orientation is deviated from those of surrounding subgrains, the subgrain can not form a recovered region together with surrounding subgrains but grow into a crystallite for recrystallized grain.

Such a situation is observed in Fig. 4. After annealing at 673 K for 60s, the recrystallized grain No. 192 was surrounded by recovered region as shown in (a). The recovered region is shown with dark contrast in (b). The orientations of the dark area are indicated in (001) pole figure (c) with small black dots. The black solid circles show the (001) poles of the No. 192 grain. The orientation of the No. 192 is deviated from those of the dark area, that is, those of the recovered region. The orientation of the prior grain, before cold-rolling, is indicated by black open circles. Orientations of the recovered region and prior grain are close one another. The role of "recovery", in broad sense, is to recover the original orientation by decreasing dislocation density, and not to prepare the crystallites.

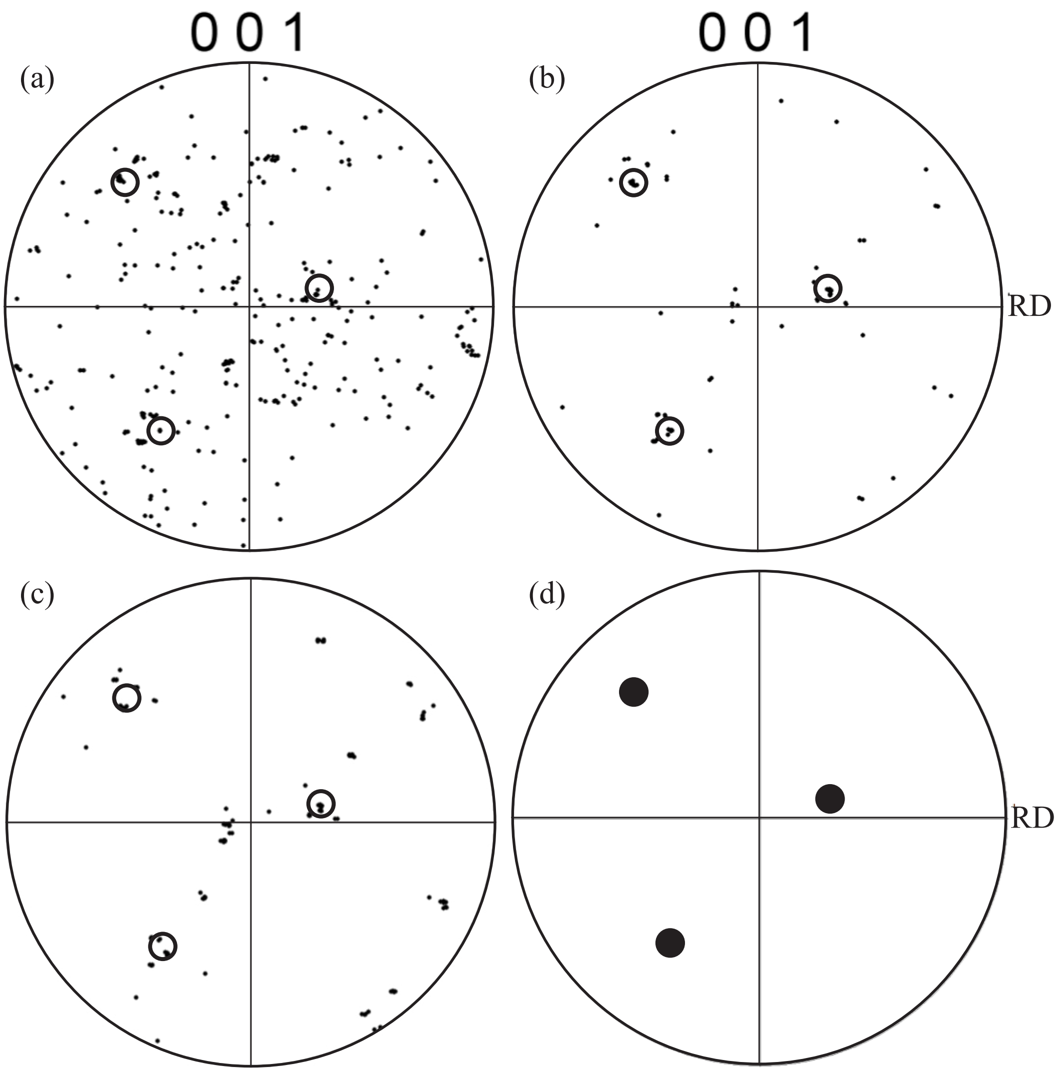
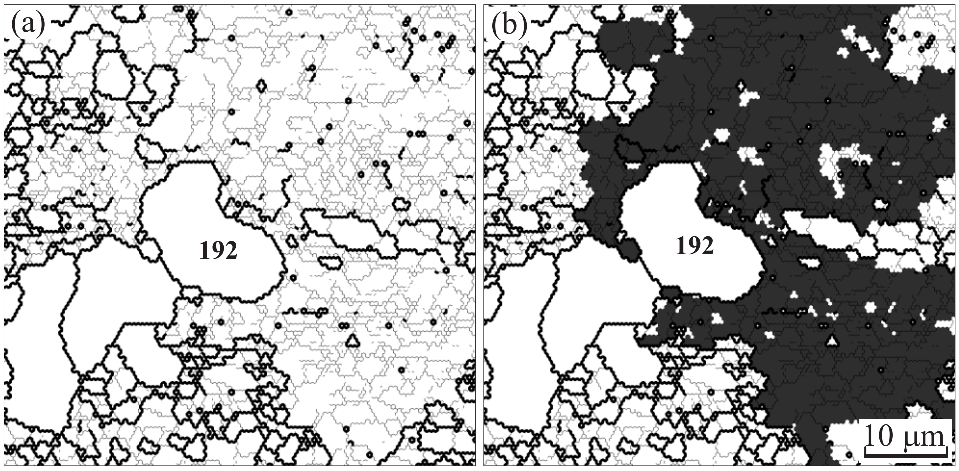


Fig. 3 (001) poles in the area around the crystallite for the recrystallized grain No. 192 indicated in Fig. 2 (d) in the as-rolled condition, annealed at 673 K for 6 s, 10 s and 20 s, (a) to (d), respectively. Black solid circles in (d) and open circles in (a), (b) and (c) indicate the (001) pole of the No. 192 grain.

In the case of recrystallization after cold-rolling at a reduction rate of 30 %, misorientation among dislocation cells are not so large. Microstructure after annealing at 673 K for 60 s is shown in Fig. 5. Large angle grain boundaries are corresponding to prior grain boundaries, before cold-rolling (a). The interiors of prior grains are composed of subgrains with small angle boundaries. Recovered region is easily formed by coalescence of subgrains. Whole of a prior grain is changed into a single recovered region as shown in dark area in (b). The (001) poles for the dark area are shown in small black dots in (c). Open circles in (c) indicate (001) poles of the prior grain, before cold-rolling. Recovered orientation is close to the original orientation. There is no isolated subgrain having a deviated orientation from others. Crystallites for recrystallized grains are not formed in the interior of the prior grains. It is expected that lattice rotation in the area near grain boundaries is larger than those in the interior of the grain, which causes the strain induced grain boundary migration (SIBM) as indicated by the black arrow in (a). Prior grain boundaries are remained after cold-rolling with 30 % reduction rate. Areas with low dislocation density and large angle boundaries seem to be necessary for crystallite formation. The orientation of the crystallite formed by SIBM, indicated by the black



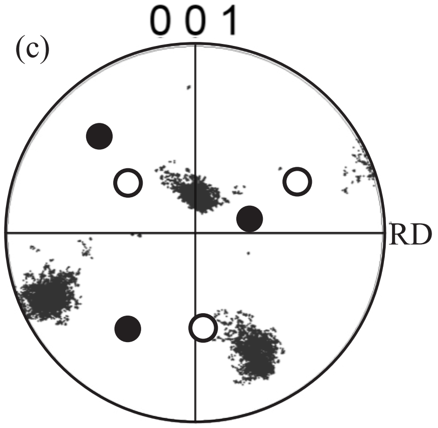


Fig. 4 Higher magnification image on the area surrounding the recrystallized grain No. 192 shown in Fig. 1 (c): (a). The area composed of subgrains with small angle boundaries: (b). Black small dots, solid black circles and open black circles indicate 001 poles in the dark gray area in (b), the recrystallized grain No. 192 and original grain before cold-rolling: (c).

solid circles in (c) is, of course, different from the original orientation of the grain "C" and recovered region. The orientation is related to the deformed orientation of the mother grain as reported in the Ref. [1-3].

As referred above, Beck and Sperry [4] mentioned that the SIBM was a dominant mechanism for recrystallization when the reduction rate was smaller than 40 %. Prior grain boundaries disappeared after cold-rolling at a reduction rate of 50 %, although the microstructure is not shown here. Small angle boundaries also can migrate for developing recrystallized grains, which was reported in the Ref. [2], it plays a minor role in recrystallization. Both the large angle boundary and the region with relatively low dislocation density are necessary for recrystallization. These are corresponding to the prior grain boundary and the interior of the prior grain in the case of 30 % reduction, while these are provided by the recovered region in the case of 50 % reduction.

4. Summary

Elemental process of recrystallization after cold-rolling in 6061 aluminum alloy would be composed of formation of recovered regions and growth of crystallites. Both of them are developed from dislocation cells which are changed into subgrains in the early stage of annealing. In the case of light reduction rate, orientations of the subgrains are similar with each other. The prior grain is covered with a single oriented recovered region, and crystallites are not formed in the interior of the original grain. Concentration of lattice rotation near the prior grain boundary causes the SIBM to form the crystallite. While, in the case of severe reduction rate, prior grain boundaries disappear remaining

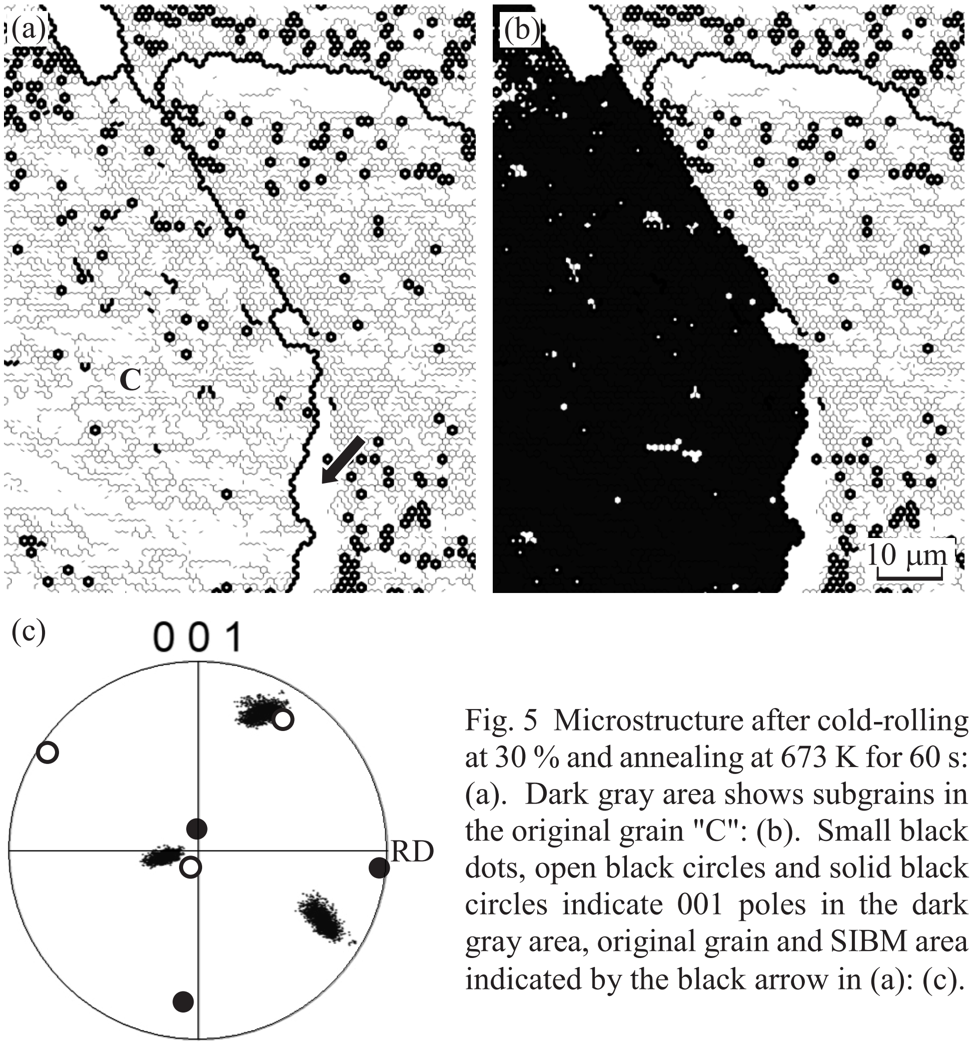


Fig. 5 Microstructure after cold-rolling at 30 % and annealing at 673 K for 60 s: (a). Dark gray area shows subgrains in the original grain "C": (b). Small black dots, open black circles and solid black circles indicate 001 poles in the dark gray area, original grain and SIBM area indicated by the black arrow in (a): (c).

dislocation cells with highly deviated orientation. Some of cells have relatively similar orientation. They form a recovered region. The cells having deviated orientations from surrounding subgrains become crystallites. The recovered region contains many small angle boundaries in it, while the crystallite does not contain the small angle boundaries. Differences in dislocation densities between the recovered region and crystallite lead to growth of the crystallite.

References

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