Transactions of the Materials Research Society of Japan 29 [8] 3511-3514 (2004)

Microstructural Changes of Particle Containing AA8011 Alloy Sheets During Accumulative Roll Bonding(ARB) Process

H.W.Kim, S.B.Kang, N.Tsuji *and Y.Minamino*
Korea Institute of Machinery & Materials, 66 Sangnam-Dong, Changwon, Korea 641-010
Fax: 82-55-280-3399, e-mail: hwkim@kmail.kimm.re.kr
*Osaka Univ., Dept. of Adaptive Machining Systems, Japan 565-0871

The changes in microstructure and tensile properties of Al-Fe-Si alloy(AA8011) sheets during accumulative roll bonding(ARB) process were investigated. The effects of microstructure on the mechanical properties were discussed in detail. Generally, severely deformed materials have high tensile strength and low tensile ductility. In case of ARB processed AA8011 alloy sheets, the tensile strength increase up to 3 ARB cycles(the effective strain of 2.4). After 4 ARB cycles it showed constant strength level, meanwhile, total elongation increased with ARB cycles. AA8011 alloy contains large number of intermetallic particles like Al-Fe-Si and Si with the size of 1~5μm, so that equiaxed grain structures and high fraction of high angle grain boundaries were obtained by lattice rotation near large no-shearable particles. A mechanism on the increase of tensile elongation was suggested in the view point of dynamic recovery and plastic instability in ultra fine grain structures.

Keywords: Accumulative Roll Bonding(ARB), Ultra Fine Grain(UFG), Intermetallic particles, Dynamic recovery, In-situ recrystallization

1. INTRODUCTION

Recently, many severe plastic deformation processes (SPD) have been developed like Accumulative Roll Bonding (ARB), Equal Channel Angular Pressing (ECAP), Torsion Straining and Cryogenic Working etc. It is well known that the severe plastic deformation (SPD) processes enable introducing sub-micron grain structures in various metals. Among those processes, ARB process is most probable to manufacture large bulky type ultra-fine grain materials. The ARB process [1] has been successfully applied to pure aluminum (AA1100) [2], Al-Mg alloy (AA5083) [3] and Ti-added interstitial free steel [4]. Most of ARB processed materials had microstructure with sub-micron grains and showed very high tensile strength at ambient temperature [1-4]. The commercial AA8011 alloy is Al-Fe-Si alloy, Al-Fe-Si alloys has large number of second particles due to high content of Si and Fe element comparing with pure aluminum. In casting process of Al-Fe-Si ternary alloys, the formation of second particles was affected by casting temperature, cooling rate and subsequent homogenization temperature. Also the size and type of particles are various according to the chemical composition (especially Fe/Si ratio) and heat treatment. [5,6,7] These alloys have a wide variety of applications owing to the possibility to control the microstructure and mechanical properties by means of specific thermo- mechanical treatment [8,9].

In the previous reports [10,11], we observed very unique microstructures and mechanical properties in heavily deformed AA8011 alloy sheets manufactured by accumulative roll bonding.(ARB) The ultra-fine grains with size less than 1μm were formed by the ARB processes, but its strength at ambient temperature did not increase after several cycles. Meanwhile, the elongation was greatly increased. In order to analyze the unique tensile behavior of AA8011 alloy sheets manufactured by ARB processes, the microstructures and mechanical properties at each ARB cycles were investigated. The elongation increase in these materials was discussed in the view points of plastic instability and dynamic recovery. Also, A mechanism was suggested in this article.

2. EXPERIMETAL PROCEDURES

The material used in this study was commercial hot rolled AA8011 alloy plate whose chemical compositions is Al-0.725wt%Fe-0.625wt%Si. The initial dimension of the materials was 4.0 mm in thickness, In order to get fully recrystallized microstructure, the initial materials were cold rolled to the thickness of 1 mm and annealed at 400°C for 1hr.

The sheets were cut to the dimension of 1x 30x300mm^3. One surface of these sheets were degreased by acetone and wire-brushed. Those two sheets were layered to make brushed surface in contact and fixed to each other closely by stainless steel wires of 0.5mm in diameter. Roll

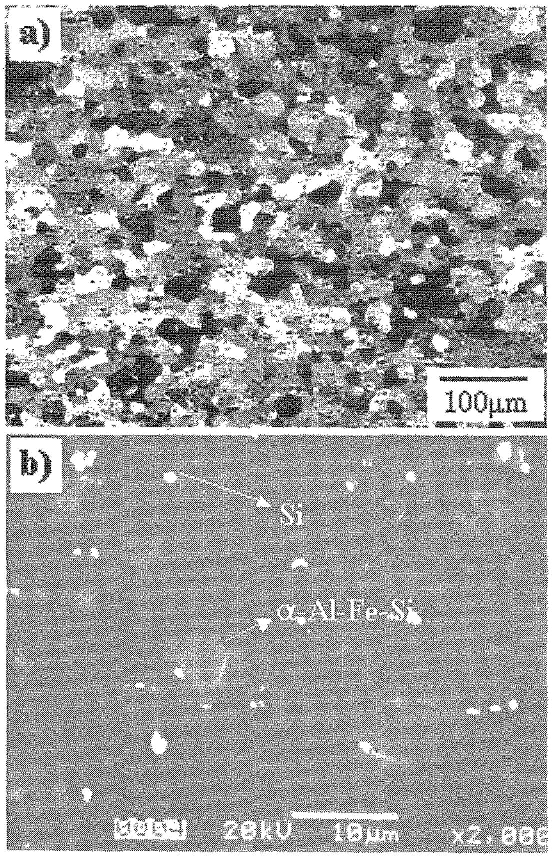

Fig.1 The initial microstructures of AA8011 alloy sheets after 75% cold rolling and annealing.

bonding was conducted under no lubrication condition at ambient temperature, the rolling reduction in thickness per cycle was 50%(effective strain, ε_{eff}=0.8/cycle)[1]. The roll diameter was 175 mm and the rolling speed was about 1m/min. The procedures were repeated up to 15 cycles. (Total effective strain, ε_{eff} of 12, total cold rolling reduction in thickness of 99.99%)

Tensile tests at ambient temperature were conducted on standard universal testing machine (Instron 4206) at the initial strain rate from $1.6\times10^{-4}s^{-1}$ to $1.6\times10^{-2}s^{-1}$. By reference of ASTM-E8M, ARB processed sheets were machined to subsize tensile specimens, whose size was 1mm in thickness and 6mm in width, the gage length of samples is 25mm along rolling direction.

The distribution of intermetallic particles and the morphology of grains were observed by JEOL-5800 scanning electron microscope operated at 15KV and Hitach-800 transmission electron microscope operated at 200KV. Thin foil for TEM observation were prepared by twin-jet electro-polishing in 300ml HNO_3 + 600ml CH_3OH solution at 253K. The grain boundaries characteristics of ARB processed samples also observed by Philips FEG-SEM equipped with TSL-OIM system.

3. RESULTS AND DISCUSSION

3.1 Microstructures

Fig.1 shows the initial microstructures of AA8011 alloy sheet. The microstructures of full annealed 8011 alloy sheets consist of fully recrystallized equi-axed grains with the mean size of 25μm.(Fig.1 (a)) In commercial pure aluminum alloy, it was well known that Al_6Fe or Al_3Fe inclusions were formed during solidification process due to solubility limit of Fe in solid Al[7,12], but only a few particle existed. Meanwhile, AA8011 alloy in this experiment contained much Si and Fe elements, so that it had large number of second particles, whose sizes were smaller than 5μm as shown in Fig.1(b) There were two kinds of particles, some particles were gray one, the others were white one. From EDS analysis and several literatures [5,6,7,13], it was proven that the white particles were Si precipitates and gray ones were α-AlFeSi (Al_8Fe_2Si) inclusions.

From those full recrystallized starting materials, ARB processes were repeated up to 15cycles. The microstructures of AA8011 alloy sheets at each ARB cycle were observed from transverse direction(TD). In the first ARB cycle

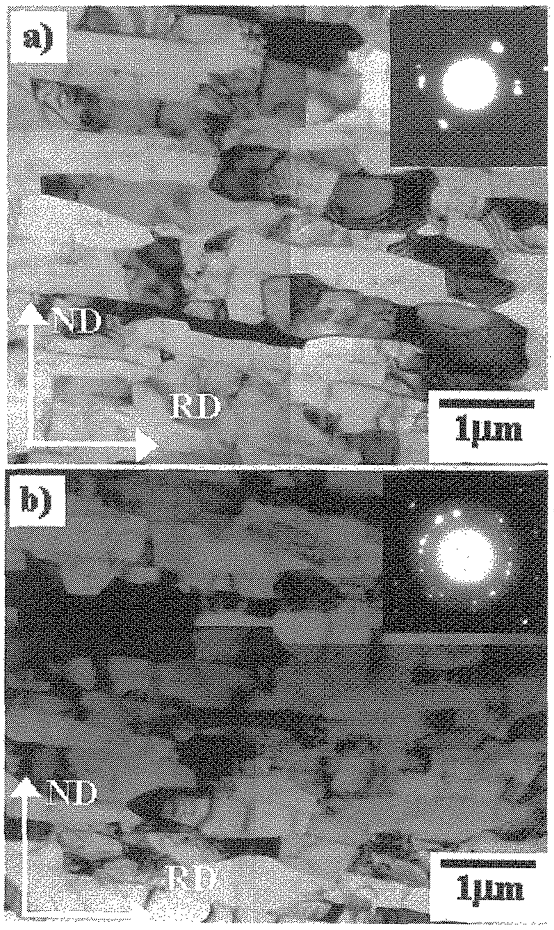

Fig.2 Grain morphology of ARB processed AA8011 alloy sheets at different ARB cycles observed by transverse direction; (a) 4 cycles (b) 8 cycles

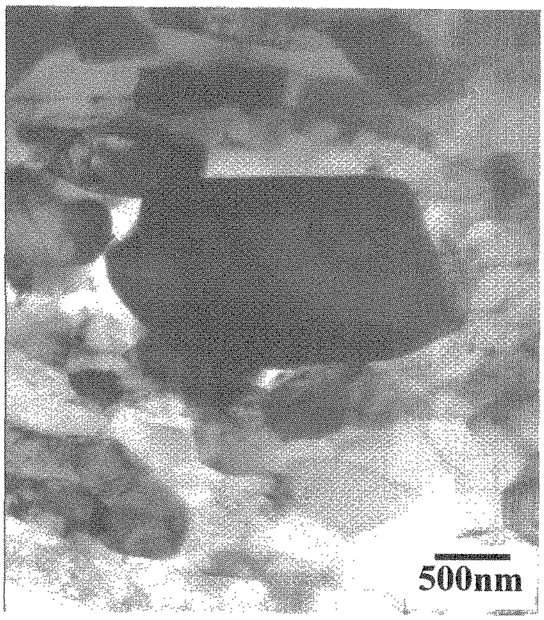

Fig. 3 Grain morphology near intermetallic particle in 8 cycles ARB processed AA8011 alloy sheets.

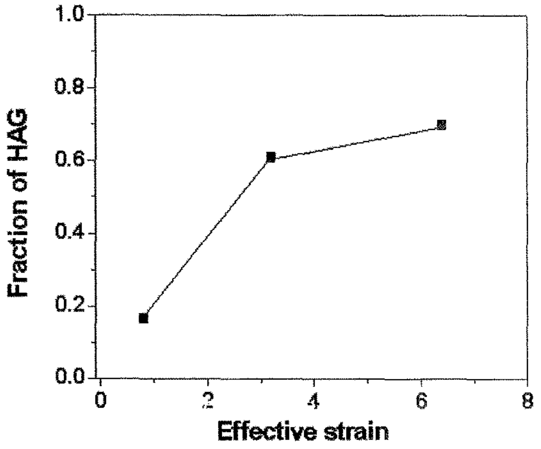

Fig. 4 The fraction of High angle grain boundaries(θ_{mis} >15°) in ARB processed AA8011 alloy sheets at different cycles.

sample, large number of dislocations were generated in original grains and it made dislocation tangles and cell structures. In the specimen after 4 ARB cycles,(Fig.2(a)) a lamellar structure composed of the ultra fine grains elongated along the rolling direction (RD) were observed. The mean size of the elongated grains was smaller than 1μm. Some grains showed high dislocation density inside. The selected area diffraction pattern (SADP) taken by use of an aperture 1.5μm in diameter did not show single net spot pattern but ring-like one, which implied that ultra fine grain structure with high angle grain boundaries was generated after the 4 ARB cycles. In the specimen of 8 ARB cycles, the grain thickness became slightly small and dislocation density in grain interior was lower than that of specimen after 4 ARB cycles. Comparing to other ARB processed materials, however, the shape of grains in ARB processed 8011 alloy sheets was more equiaxed and the dislocation density in grain was not so much. Also the mean thickness of grain was not reduced much more after 4 cycles. In several report about Al-Fe-Si alloy [10,11,14,15], it was reported that Al matrix was more pure because Si element reduced the solubility of Fe element due to formation of AlFeSi intermetallic particles, thus static or dynamic recovery could be easy to occur even if at ambient temperature. Also, dynamic recovery could be occured more severely near particle because of high stress concentration and lattice rotation during ARB process.

Fig.3 show the grain shapes around Al-Fe-Si intermetallic particle. The lattice rotation and dynamic recovery near particles resulted in low dislocation density and equiaxed grains (Fig. 3), which were seems to be recrystallization microstructures.

By EBSP analysis, the fractions of high angle grain boundaries (θ_{mis} >15°) were measured as shown in Fig.4. As the ARB cycles increased, the fraction of high angle grain boundaries increased remarkably. As mentioned above, the 8011 aluminum alloys contained a number of second particles. The deformation behavior might be complex near the second particles during ARB process. Therefore, the fraction of high angle grain boundaries was high at high ARB cycles.

3.2 Mechanical properties

Tensile strain-stress curves of ARB processed AA8011 alloy sheets at different ARB cycles are shown in Fig. 5. The initial strain rate is 8.3x10^{-4}/sec. At 1 cycle ARB processed sheets (ε_{eff} =0.8), it shows early yield drop and fracture within a few strain. But after 2cycles(ε_{eff} =1.6), flow stress increases up to peak stress and then the stress holds constant value. Also, the range of steady states in flow stress increase with number of the ARB cycles, so that total elongation increases. It is a very unique behavior in the

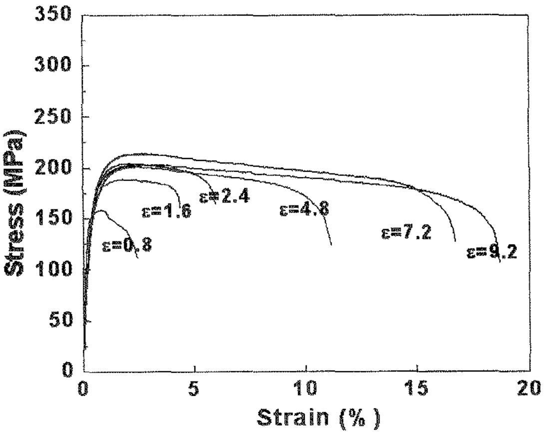

Fig. 5 Engineering strain-stress curves of ARB processed AA8011 alloy sheets.

materials severely deformed by ARB process. Most of ultra fine grain materials manufactured by severe plastic working showed very high strength and low tensile ductility [1-4]. Those low tensile ductility have been explained by low strain hardening, which leads to early stress drop(necking) and low uniform elongation.

However, total elongation of severely plastic deformed AA8011 alloy sheets increased with ARB cycles. After flow stress reached at maximum stress, the stress level was not change and slightly softened. Those kinds of strain-stress curves could be seen commonly in dynamic recovery at elevated temperature. Dynamic recovery in very pure aluminum at ambient temperature was well known. As mentioned above, the AA8011 alloy has pure matrix due to formation of AlFeSi intermetallic compound, so that dynamic recovery may be easy to occur. Furthermore, lots of high angle grain boundaries existed in high cycle ARB processed AA8011 alloy sheets. Those high angle grain boundaries might be served as source of vacancy. It could increase the diffusivity of atoms. That is, dynamic recovery is easy in the ultra-fine grained AA8011 alloys. Fig.6 shows the tensile strain-stress curves of 8 cycle ARB sheets at different initial strain rates. At the high strain rate, the stress increase rapidly and reach at fracture within a few percent of elongation. Meanwhile, at the low strain rate, the flow stress is comparatively low and total elongation is large. In other word, ultra fine-grained AA8011 alloy sheets showed dynamic recovery behavior during tensile deformation at ambient temperature, especially at low strain rate. The increase of total elongation can be explained by plastic instability. The necking would be initiated on a surface of sample at a few percent strains due to low strain hardening, but strain rate around local necking area would be increased, thus the strength of necking area will be higher than other area. As a result, necking is difficult to grow into whole specimen. Therefore, this local strain rate hardening around necking area could result in the increasing of tensile elongation. The strain rate hardening of AA8011 alloy sheets were increased with ARB cycles, therefore, tensile fracture strain increased with ARB cycle in AA8011 alloy sheets. It seemed to be affected by dynamic recovery, which has close relationship with the fraction of high angle grain boundaries and purity of matrix. But, more detail study on dynamic recovery during tensile deformation at low strain rate should be done in detail.

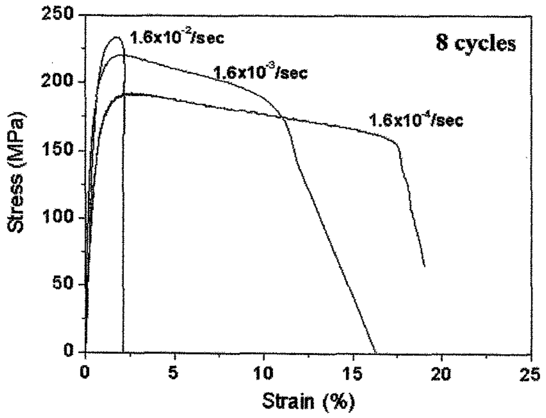

Fig. 6 Tensile strain-stress curves of 8 cycles ARB processed AA8011 sheets at different strain rate.

4. CONCLUSIONS

1) In AA8011 alloys, ultra-fine grains with the size of less than 1μm were obtained by the Accumulative Roll Bonding (ARB) process.
2) The tensile strength of AA8011 alloy sheets increased up to 3cycles. After that, the material showed constant strength level, but total elongation increased with increasing ARB cycles.
3) During ARB process, large number of high angle grain boundaries were generated and grain morphology was more equiaxed. The increase of high angle grain boundary fraction brought about increase of strain rate hardening at local area(neck). As a result, fracture strain was increased by retardation of growth of neck.

REFERENCES

1. Saito Y, Utsunomiya H, Tsuji N, Sakai T.: Acta Mater., 47 (1999) 579
2. Saito Y, Tsuji N, Utsunomiya H, Sakai T, Hong R G.: Scripta Mater., 39 (1998) 1221
3. N.Tsuji, K.Shiotsuki and Y.Saito : Mater. Trans. JIM, 40 (1999) 765
4. N.Tsuji, Y.Saito, H.Utsunomiya and S.Tanigawa : Scripta Mater., 40 (1999) 795
5. O.Engler : Materials Science forum, 273-275 (1998) 483
6. R.K.Davis, V.Randle and G.T.Marshall : Acta Mater. 46 (1998) 6021
7. K.Lucke and O.Engler : Mater. Sci. Tech., 6 (1990) 1113
8. H.W.Kim, S.B.Kang, N.Tsuji and Y.Minamino : Proceedings of the 101th conference of Japan Institutes of Light Metals, Chiba, Japan, (2001) 139
9. M.Murayama, Z.Horita and K.Hono: Acta mater., 49(2001)21-29
10. H.Takei, K.sato and M.Yokota : aluminum, 50 (1981) 33
11. L.F.Mondolf : Aluminum alloys, structure and properties, London, Butterworths, (1976) 534
12. Z.P.Xing, S.B.Kang and H.W.Kim : Scripta Mater., 45 (2001) 597
13. Humphreys, F.J. and Hirsh, P.B. (1976), phil. Mag. 34, 373
14. Lloyd, D.J. and Kenny, D. : Acta Metall. 28 (1980) 639
15. Humphreys, F.J. ; Acta Metall. 27 (1980) 1801

(Received December 1, 2003; Accepted July 27, 2004)