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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF LAYERED ALUMINUM ALLOY SHEETS FABRICATED BY MULTI-STACK ARB PROCESS

A layered Al sheet was fabricated by three cycles (c) of multi-stack accumulative roll-bonding (ARB) using commercial AA1050, AA5052, and AA6061 alloy sheets, and then annealed. The as-ARBed Al sheet showed ultrafine grained (UFG) structure, with average grain diameter of 1.07 μm. Through up to 250°C, the annealed sheets still showed UFG structure, above 300°C, they exhibited heterogeneous structure, in which due to static recrystallization, both ultrafine and coarse grains coexisted. As the number of ARB cycles increased, the tensile strength increased, after 3c, they reached 390 MPa, 2.4 times the average value of the starting materials. The changes in microstructure and mechanical properties of the multi-layered Al sheet with annealing are discussed in detail, and compared to those of the 2c ARBed materials by the previous study.

Keywords: Accumulative roll-bonding; aluminum alloy; annealing; heterogeneous microstructure; mechanical properties

1. Introduction

Aluminum alloys have recently been extensively studied for automotive body panels because of their benefits of medium strength, good formability and lightweight [1-3]. It is anticipated that the substitution of such aluminum alloys for steels will result in great improvements in energy economy, recyclability, and life-cycle cost. To expand the application area of the Al alloys as materials for transportation equipment, studies to improve their mechanical properties, like strength and ductility, are needed.

Accumulative roll-bonding (ARB) [4-15] is known to be an effective process to enhance the mechanical properties of aluminum. Ultra-grain refinement by the ARB process has been demonstrated for various metallic materials such as aluminum alloys [4-12], and copper alloys [9-15]. In this way, it is not necessary to use the same materials in the ARB process. The ARB of dissimilar materials can potentially create various kinds of structural and functional materials. However, most of the studies were on the ARB of different kinds of metallic materials such as Al and Cu [16], Al and Mg [17], and Al and Ni [18], while studies on the ARB of different alloys of the same metal have seldom been performed [19,20]. It is expected that the ARB of different alloys of the same metal would allow the production of unique alloys consisting of more complex and various microstructures, enhancing the mechanical properties of the Al alloys. In particular, the ARB can be used to fabricate multi-layer Al sheets having various mechanical properties, as reported in previous studies [19-21]. In this way, increasing the stacking number per ARB cycle could very effectively attain ultrafine grain (UFG) and high strengthening. In the previous study, the authors have reported the microstructure and mechanical properties of the AA1050/AA6061/AA5052/AA1050 layered sheet fabricated by 2 cycles (c) of the multi-stack ARB [21]. That previous study found that the formation of UFG and heterogeneous microstructure by the multi-stack ARB could improve the mechanical properties of Al alloys. This study further conducted the multi-stack ARB up to 3 cycles. The changes in microstructure and mechanical properties of the ARBed materials with annealing were investigated in detail, and compared to those of the previous study [21].

2. Experimental

TABLE 1 shows the compositions of the materials used in this study, which were commercial AA1050, AA5052 and AA6061 sheets. The AA1050, AA6061 and AA5052 sheets have recrystallization structure consisting of equiaxial grains with the average grain diameter of (72, 29, and 39) μm, respectively. For the multi-stack ARB process, the sheets were cut into dimensions of 2 mm × 50 mm × 200 mm thickness × width × length, and

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TABLE 1

Chemical compositions of the AA1050, AA5052, and AA6061 alloys used in this study.

Materials	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Each	Al
AA1050	0.03	0.29	0.02	0.01	0.01	—	0.01	0.009	0.03	RE
AA6061	0.6	0.7	0.3	0.15	1.0	0.155	0.25	0.15	0.05	RE
AA5052	0.21	0.273	0.028	0.069	2.26	0.162	0.028	—	0.05	RE

after degreasing and wire-brushing, alternately stacked on each other to four layers, then roll-bonded to 2 mm thickness by multi-pass rolling at ambient temperature. The roll-bonded AA1050/AA5052/AA6061/AA1050 layered sheet was then stacked again, and by the same procedure, reduced to thickness of 2 mm. The ARB process was performed up to 3c, without lubrication. To calculate the amount of equivalent strain introduced by 3c of the four-stack ARB, the equivalent strain ($\bar{\varepsilon}$) introduced by four-stack ARB is calculated by the following equation if the rolling deformation is uniform compressive deformation [22]:

$$\bar{\varepsilon} = \left(\frac{2}{\sqrt{3}}\right) n \ln k \tag{1}$$

where, n is the number of ARB cycles, and k is the stacking number. Therefore, according to the above equation, the equivalent strain introduced by 3 cycles of the four-stack ARB is 4.8. This is a huge strain, equivalent to 6 cycles of the conventional two-stack ARB. The severely deformed specimens were then annealed for 0.5 h at temperatures ranging (200 to 500)°C. The electron back scattering diffraction (EBSD) measurement was conducted using the software TSL OIM Data Collection ver. 3.5 in Phillips XL30s SEM with FE-gun operated at 20 kV. The EBSD analysis was performed using the software TSL OIM Analysis ver. 3.0. The mechanical properties of the specimens were examined at ambient temperature by an Instron-type tensile testing machine. The test pieces were machined so that the tensile direction was parallel to the rolling direction. The gauge length and width were (32 and 6) mm, respectively. The tensile test was conducted with an initial strain rate of 10^{-3} s^{-1}.

3. Results and discussion

3.1. Microstructure

The ARB process up to 3 cycles was successfully performed without shape defects. The ARBed specimens showed an alternating layered structure of AA1050, AA5052, and AA6061 sheets. Fig. 1 shows the changes in microstructure with increasing the number of ARB cycles. The color of each point indicates the crystallographic direction parallel to the normal direction (ND) of the specimens, corresponding to the colored stereographic triangle, respectively. The grain size decreased with increasing number of ARB cycles in all regions of the AA1050, AA6061, and AA5052; after 3c, it became so ultrafine that it was difficult to distinguish one from another, as shown in Fig. 1. The grain diameter decreased greatly with increasing number of ARB cycles, in all regions. The decrease in grain diameter was the greatest in the AA1050 region. Eventually, after 3c, the specimen showed microstructure consisting of UFGs with average grain diameter of 1.07 μm over all regions.

Fig. 2 shows the change in microstructure of the layered sheet with increasing annealing temperature. The specimens annealed up to 250°C still showed the UFG structures in all regions,

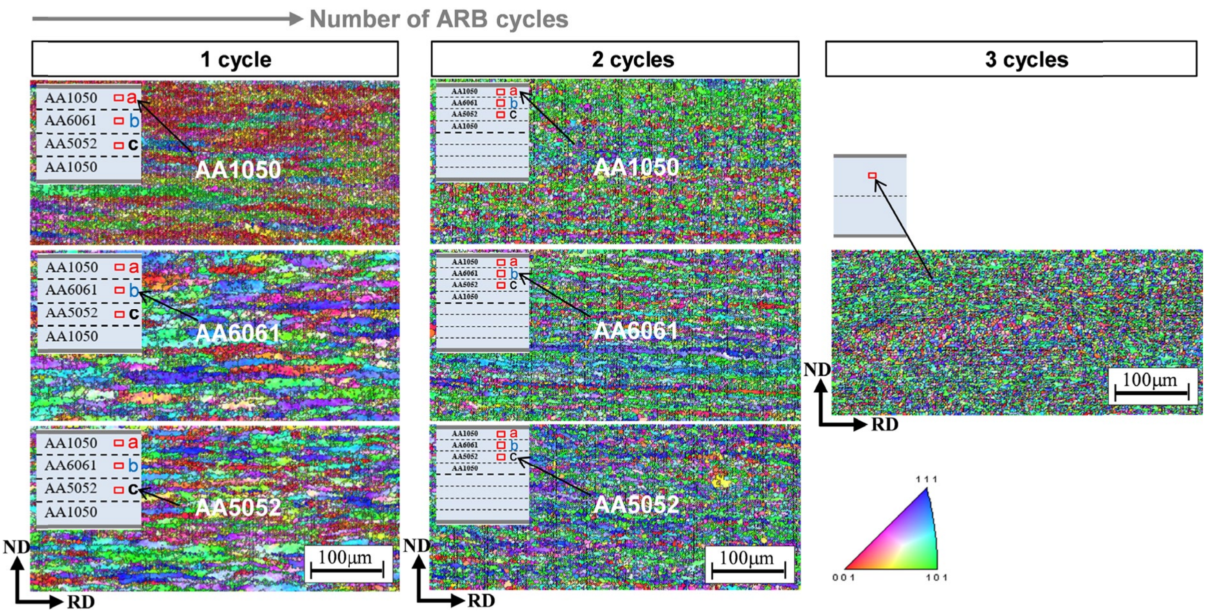

Fig. 1. The change in microstructure of the specimens with increasing number of ARB cycles

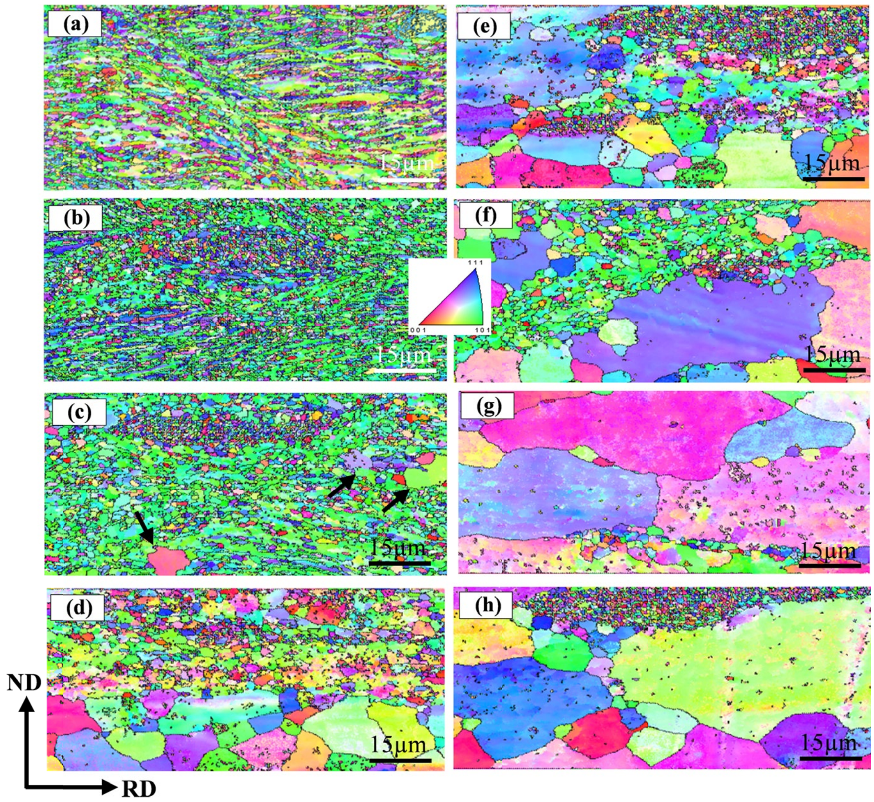

Fig. 2. The change in microstructure of the 3c ARBed specimen with increasing annealing temperature of (a) 200°C, (b) 250°C, (c) 300°C, (d) 350°C, (e) 375°C, (f) 400°C, (g) 450°C and (h) 500°C

even though due to the occurrence of recovery, the grain size slightly increased. The specimen annealed at 300°C still showed UFG structure; however, the equiaxial coarse grains formed due to discontinuous static recrystallization were observed in part, as indicated by the arrows in Fig. 4. At 350°C, static recrystallization occurred more actively, so that all regions showed a complete recrystallization structure in which the coarse and fine grains coexist by division of the area. At temperatures greater than 400°C, the heterogeneous microstructure was still observed even in the specimens annealed, even though the grain size increased with increasing annealing temperature in all areas. The formation of heterogeneous microstructure in the present study is mainly because Al alloys with different recrystallization temperatures were used for the starting materials. With increasing annealing temperature, the average grain diameter increased gradually, while above 400°C, it increased significantly.

3.2 Mechanical Properties

Fig. 3 shows the nominal stress-nominal strain (s - s) curves of the ARBed specimens (Fig. 3a) and the annealed specimens (Fig. 3b). As shown in Fig. 3a, as the number of ARB cycles increased, the tensile strength increased; after 3c, it reached 390 MPa, 2.4 times the average value (162 MPa) of the starting materials. After 3 cycles, however, the elongation decreased from (19 to 8). After annealing, however, the strength decreased greatly while the elongation increased, due to the occurrence of

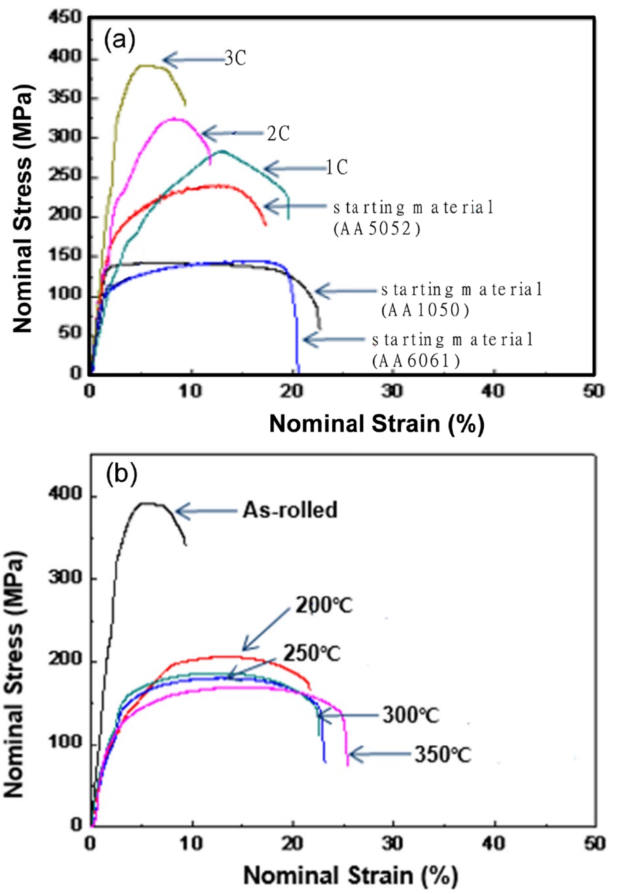

Fig. 3. The nominal stress – nominal strain curves of (a) the ARBed specimens and (b) the annealed specimens

recovery and/or recrystallization. The tensile strength of the 3c ARBed material was 390 MPa; but after annealing at 350°C, it decreased to 170 MPa. On the other hand, with increasing annealing temperature, the elongation increased; and after 350°C, it increased from (8 to 25) %.

Fig. 4 shows the relation of tensile strength and elongation of the 3c ARBed and subsequently annealed specimens to those of the starting materials and the 2c ARBed materials in the previous study for reference [21]. It was found from the figure that the tensile strength of the 3c ARBed materials was slightly higher than that of the 2c ARB specimens. The tensile strengths of the annealed specimens were higher than those of the AA1050 and AA6061 starting materials; however, they were slightly lower than that of the AA5052 starting material. In conclusion, it was found that the multi-stack ARB process could produce layered Al sheets having various combinations of tensile strength and elongation, even though the effect of strengthening by 3c ARB in the present study was not as significant, compared to that of the 2c ARB.

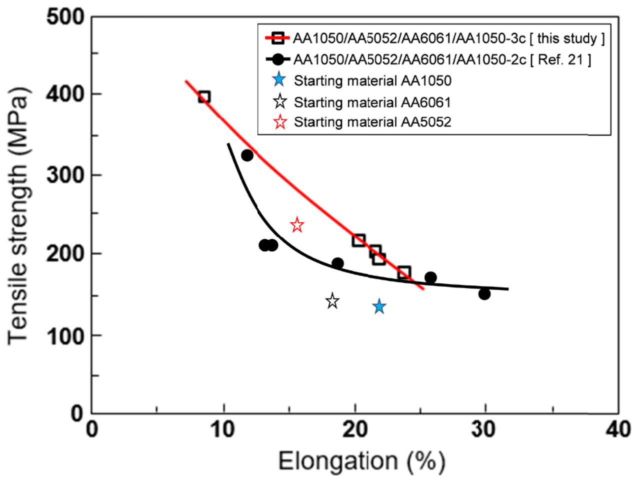

Fig. 4. The relation between the tensile strength and elongation of the multi-stack ARBed and subsequently annealed specimens

4. Conclusions

A multi-layer Al sheet was successfully fabricated by 3 cycles of four-layer stack ARB using AA1050, AA5052, and AA6061 alloys, and subsequently annealed. The grain diameter of the sheet decreased with increasing number of ARB cycles in all regions of the AA1050, AA6061 and AA5052; and after 3c, it became 1.07 μm. The specimens annealed up to 250°C still showed the UFG structure in all regions; however, above 300°C, they exhibited heterogeneous microstructure consisting of both ultrafine and coarse grains. As the number of ARB cycles increased, the tensile strength increased; after 3c, it reached 390MPa, 2.4 times the average value of the starting materials. As the annealing temperature increased, the strength decreased greatly, while the elongation increased, due to the occurrence of recovery and/or recrystallization. The tensile strengths of the Al sheets in the present study were slightly higher than those of the 2c ARBed Al sheets produced in the previous study.

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