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FABRICATION AND MECHANICAL PROPERTIES OF A NANOSTRUCTURED COMPLEX ALUMINUM ALLOY BY THREE-LAYER STACK ACCUMULATIVE ROLL-BONDING

WYTWARZANIE I WŁAŚCIWOŚCI MECHANICZNE NANOSTRUKTURALNEGO ZŁOŻONEGO STOPU ALUMINIUM WYTWORZONEGO PRZEZ WALCOWANIE PAKIETOWE TRZECH WARSTW

A multi-layered complex aluminum alloy was successfully fabricated by three-layer stack accumulative roll bonding(ARB) process. The ARB using AA1050 and AA5052 alloy sheets was performed up to 7 cycles at ambient temperature without lubrication. The specimen processed by the ARB showed a multi-layer aluminum alloy sheet in which two aluminum alloys are alternately stacked. The grain size of the specimen decreased with the number of ARB cycles, became about 350nm in diameter after 7cycles. The tensile strength increased with the number of ARB cycles, after 6c it reached 281MPa which is about twice higher than that of the starting material. The microstructures and mechanical properties of a three-layer AA1050/AA5052 alloy fabricated by the ARB were compared to those of the conventional ARB-processed material.
Keywords: accumulative roll-bonding (ARB), aluminum alloy, microstructure, mechanical properties

1. Introduction

Accumulative roll-bonding (ARB) process [1-15], a severe plastic deformation technique, has a great advantage that both grain refinement and high strengthening can be attained without any additions of alloying elements or ceramic particles and a change in dimension of the materials. In addition, the ARB process is mostly appropriate for practical applications because it can be performed readily by the conventional rolling process. It has been demonstrated that ultra grain refinement to nanometer order and high strengthening via ARB process can be attained for various metallic materials such as aluminum alloys and copper alloys [8-15]. In the way, we have not necessarily to utilize the same materials in ARB process. The ARB of the dissimilar materials rather than the same ones has been recently studied actively [16-20]. This modified ARB has a merit to be able to fabricate various metal/metal multi-layer composite materials. However, most of the studies were on the ARB of different kinds of metals such as Al and Cu [16, 17], Al and Mg [18], Al and Ni [19, 20]. However, the studies on the ARB of different alloys of the same metal have been seldom done recently [21, 22]. It is expected that such ARB process would let us produce the unique alloys consisting of more complex and various microstructure, resulting in enhancing their mechanical properties [22]. Especially, the complex Al alloys with various mechanical properties can be produced by the ARB, as reported in the previous studies [22, 23]. In the way, if we increase the stacking number per ARB cycle, we would achieve ultra grain refinement and high strengthening very effectively. Therefore, this study is aimed to fabricate the multi-layer nanostructured AA1050/AA5052 aluminum alloy sheets through a three-layer stack ARB using dissimilar aluminum alloys of AA1050 and AA5052 and investigate their microstructure and mechanical properties.

2. Experimental

The materials used in the present study were commercial purity AA1050 and AA5052 sheets with thickness of 1 mm. The chemical compositions of both materials are shown in Table 1.

TABLE 1
Chemical compositions of AA1050 and AA5052 sheets used (mass%)

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
AA1050	0.030	0.29	0.02	0.01	0.01	0.01	0.009	0.03	BAL
AA5052	0.21	0.273	0.028	0.069	2.26	0.162	0.028	0.05	BAL

The as-received AA1050 and AA5052 sheets were annealed at 500° for 1 hour for the ARB process. The Al alloy sheets were cut into dimensions of 50 mm in width and 200 mm in length. The aluminum sheets are then stacked with sandwich structure by three layers after surface treat-

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ment by wire brushing, and roll-bonded to 1 mm in thickness by one-pass rolling at ambient temperature. The roll-bonded AA1050/AA5052/AA1050 complex sheets was then stacked with three layers after cutting and surface treatment again and reduced to 1 mm in thickness by the cold rolling. The same procedure was performed repeatedly up to 7c(c: cycle) at ambient temperature without lubrication. The reduction in thickness per ARB cycle was 67% (equivalent strain $\varepsilon \sim 1.28$).

The microstructure of the ARB-processed samples was revealed by optical microscopy(OM) and transmission electron microscopy(TEM). TEM studies were conducted with a HITACHI H-800 microscope operated at 200 kV. For TEM observation, thin disk-shaped foils were prepared by mechanical machining and twin-jet polishing. The electron back scattering diffraction(EBSD) measurement was carried out using a program TSL OIM Data Collection ver.3.5 in Phillips XL30s SEM with FE-gun operated at 20kV. The EBSD analysis was done using a program TSL OIM Analysis ver. 3.0. The mechanical properties of the ARB-processed samples were determined at ambient temperature by an Instron-type tensile testing machine. The test pieces were spark-machined so that the tensile direction was parallel to the rolling direction. The gauge length was 10 mm and the gauge width was 5 mm. The initial strain rate was $8.3 \times 10^{-4} s^{-1}$.

3. Results and discussion

3.1. Microstructures

Fig. 1 is the variation of optical microstructures of the ARB-processed specimens with the number of ARB cycles. The specimen after 1c shows a sandwich structure that an AA5052 sheet is inserted between two AA1050 sheets. The interface between AA1050 and AA5052 layers is clearly observed in enlarged microstructure. The specimen after 3 cycles consists of complex aluminum sheets of 27 layers that two aluminum alloys are alternately stacked in parallel to each other. The specimen after 5c shows a more complex aluminum sheet that the layers are stacked to each other antiparallely, as shown in Fig. 1(c). In addition, the AA1050 aluminum layers are elongated lengthways along the rolling direction, while the AA5052 aluminum layers is cut in rolling direction and shaped like long islands, as shown in an enlarged microstructure of Fig. 1(c). The specimen after 7c also shows a very complex structure that is similar to that of specimen after 5c, but the size of each layer is smaller than that after 5c, as shown in Fig. 1(d). Fig. 2 is TEM microstructures observed at plane perpendicular to normal direction(ND plane) of AA5052 and AA1050 regions for the specimen after 5c, respectively. In AA5052 region, the ultrafine grains and/or sub-grains with the average diameter of 310nm were developed, as indicated by the arrows. The selected area diffraction(SAD) pattern taken by an aperture size of 1.6μm has lots of extra spots, suggesting that they are not sub-grains but grains surrounded by high angle boundaries. The development of these ultrafine grains is very similar to that of the other ARB-processed aluminum alloys [8, 10]. On the other hand, in AA1050 region, the dislocation density is lower and the grain size is larger, comparing to that of AA5052 region, as shown in Fig. 2(b). This is because the recovery occurred more actively in AA1050 region than in AA5052 region during the ARB process.

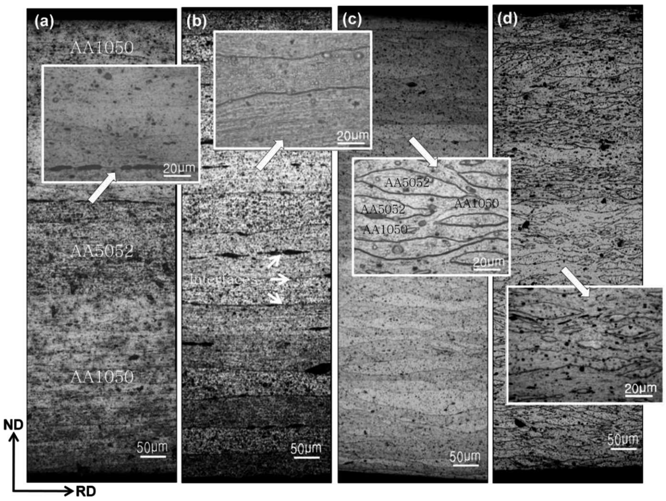

Fig. 1. Optical microstructures of the specimens processed by 1c(a), 3c(b), 5c(c) and 7c(d) of the ARB

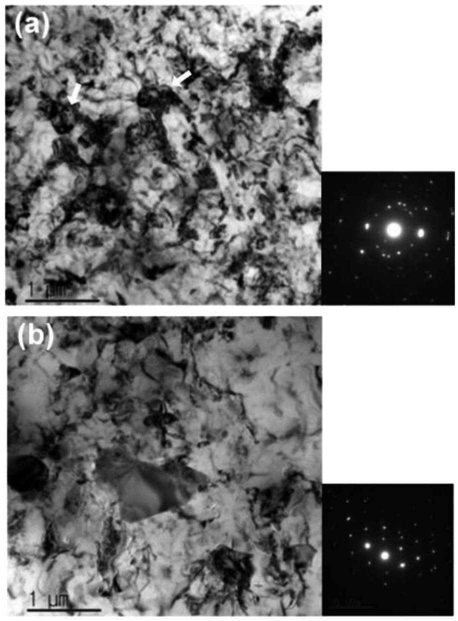

Fig. 2. TEM microstructures observed at AA5052 region(a) and AA1050 region(b) after 5c of the ARB, respectively

Fig. 3 shows the normal direction (ND) map and the rolling direction (RD) map, and the grain boundary (GB) map of the sample after 1c. The color of each point indicates the crystallographic direction parallel to ND and RD of the sample, corresponding to the colored planes. The grains are elongated along the rolling direction at all regions through the thickness. The average grain size of AA1050 region (Fig. 3a) was 18μm, larger than that ($\sim$12μm) of AA5052 region (Fig. 3b). It was also found that the fraction of high angle boundaries above 15° in misorientation was 0.27, smaller than that ($\sim$0.36) of AA5052 region. However, the texture development was not so different between both materials. That is, shear texture components such as {111}<110>and {100}<001>is mainly developed in both AA1050 and AA5052 regions. In general, the shear texture is mainly developed near surface due to high friction coefficient between rolls and workpiece. However, in this study, the shear texture was developed in AA5052 region that is positioned in center in thickness. This is because the shear deformation was introduced near interfaces between two Al layers due to difference in the elongation between both Al alloys during the rolling.

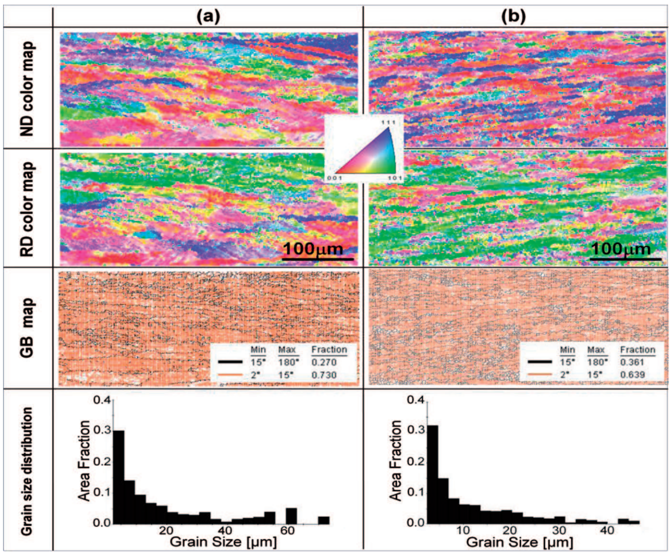

Fig. 3. ND map, RD map, GB map and grain size distribution obtained by EBSD measurement for AA1050 region(a) and AA5052 region(b) after 1c of ARB

Fig. 4 is the ND map(a), RD map(b) and GB map(c) of the sample after 7c. The grains have an equiaxed shape and are greatly smaller than those of sample after 1c. The deviation in grain size was not so large, comparing to that of the sample after 1c, and the average grain size was 350nm. This indicates that the ultragrain refinement and the homogeneity in microstructure can be attained by three-layer stack ARB. As shown in Fig. 4 (a) and (b), the texture was developed very weakly, different from the specimen after 1c. It was also found from Fig. 4(c) that the fraction of the high angle boundaries is 0.67, greatly higher than that of the sample after 1c. This microstructural change is very similar to those of the conventional ARB-processed materials.

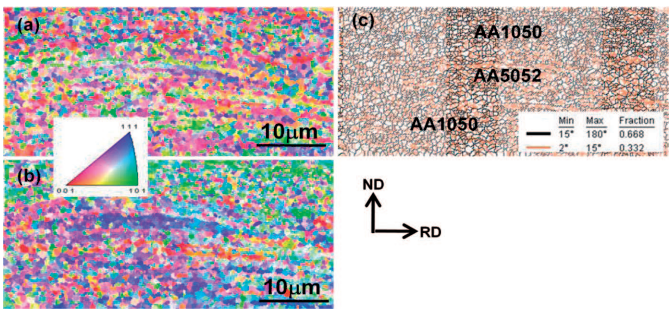

Fig. 4. ND map(a), RD map(b) and GB map(c) obtained by EBSD measurement for the specimen after 7c of ARB

3.2. Mechanical Properties

Fig. 5 shows the variation of mechanical properties with increasing of the number of ARB cycles. The as-received materials of AA1050 and AA5052 show small strength and large elongation because they are the as-annealed states, as shown in Fig. 5(a). The sample after 1c exhibits lower ductility and higher strength due to the work hardening by the cold rolling of 67% reduction. The tensile strength increased with the number of ARB cycles, after 6 cycles it reached a maximum of about 281MPa, which is about twice as large as the starting material. Here, the strength and elongation of the starting material was estimated by the mixture rule. On the other hand, the total elongation of the ARB-processed specimens decreased sharply after 1c, but from 2c it hardly decreased, regardless of increase of the number of ARB cycles. This tendency is also often observed in the other ARB-processed materials. Fig. 6

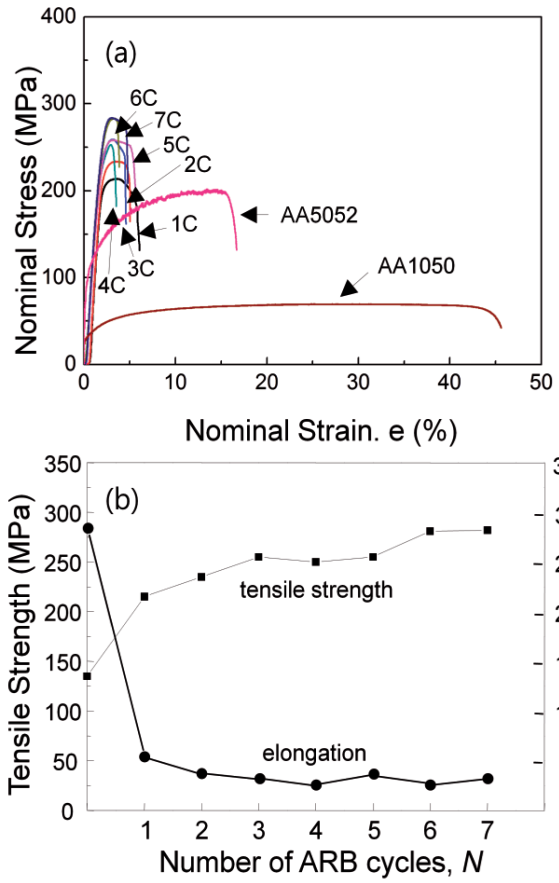

Fig. 5. The variation of stress-strain curves(a) and mechanical properties(b) of the specimen with increasing the number of ARB cycles

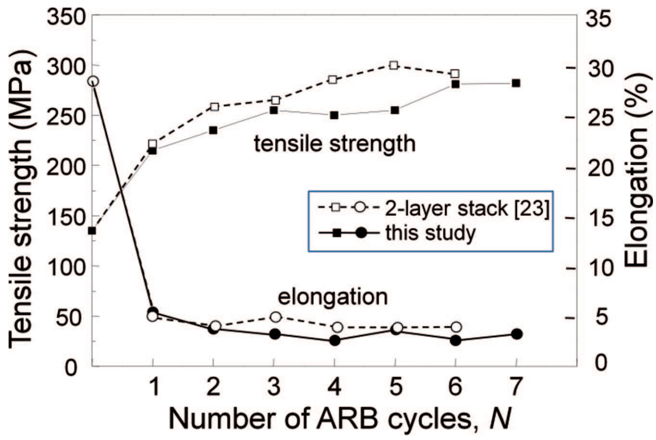

Fig. 6. The comparison of the mechanical properties between the specimens processed by two-layer stack ARB and three-layer stack ARB (this study)

shows a comparison of the mechanical properties between the present study and the previous study of two-layer stack ARB [23]. As shown in the figure, the sample by two-layer stack ARB is superior to that by three-layer stack ARB in the mechanical properties up to 5c. This is probably because that the sample by three-layer stack ARB contains much more AA1050 alloys of relatively low strength than that by two-layer stack ARB. However, the strength of the samples after 6c becomes almost identical in both processes. This is due to the saturation of the mechanical properties at higher cycles of the ARB in both processes. Anyway, it is clear that high strengthening of Al alloys can be attained by three-layer stack ARB as well.

4. Conclusions

A complex nanostructure aluminum alloy in which AA1050 and AA5052 alloys are mechanically mixed to each other could be easily fabricated by three-layer stack ARB process. The tensile strength of the multi-layered AA1050/AA5052/AA1050 alloys increased with increasing the number of ARB cycles, after 6c it reached 281MPa which is about twice that of the initial material. On the other hand, the elongation of the complex alloys showed very low values, regardless of the number of ARB cycles. These mechanical behaviors are very similar to those of the conventional ARB. The strength of the specimen by three-layer stack ARB was lower to that by two-layer stack ARB. Nevertheless, it is clear that high strengthening of Al alloys can be attained by three-layer stack ARB as well. In addition, it was found that the ultra-grain refinement to 350nm in diameter and the homogeneity in microstructure could be also attained by three-layer stack ARB. Furthermore, it is expected that various combination of strength and elongation can be attained by post heat treatment.

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