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SEONG-HEE LEE[1*]

# FABRICATION AND EVALUATION OF AA6061/AA5052/AA6061/AA5052 MULTI-LAYER COMPLEX SHEET BY COLD-ROLL BONDING PROCESS

A cold roll bonding process is applied to fabricate an AA6061/AA5052/AA6061/AA5052 multi-layer sheet. Two AA6061 and two AA5052 sheets with 2mm thickness are stacked alternately to each other, and reduced to a thickness of 2 mm by multi-pass cold rolling. The roll bonded multi-layer sheet is then hardened by natural aging (T4) and artificial aging (T6) treatments. The as roll-bonded sheet shows a typical deformation structure that the grains are elongated to the rolling direction. However, after T4 and T6 aging treatments, it has a recrystallization structure consisting of the coarse equiaxed grains in both AA5052 and AA6061 sheets. The as rolled material shows a lamella structure in which AA5052 and AA6061 sheets are stacked alternately to each other, having higher hardness in AA5052 than in AA6061. However, T4 and T6 aging treated materials show a different lamella structure in which the hardness of the AA6061 layers is higher than that of the AA5052 layers. The strengths of the T4 and T6 age-treated specimens are found to increase by 1.3 and 1.5 times respectively, compared to that of the starting material.

*Keywords:* aluminum alloy, cold roll-bonding, aging treatment, mechanical properties, microstructure

## 1. Introduction

Recently, lots of studies on lightweight of automobile have been done because of importance of the energy saving and green environment [1-5]. Especially, the aluminum alloys for automotive body panel have been studied extensively because of their benefits such as medium strength, good formability and lightweight [6-8]. It is also expected that the substitution of such aluminum alloys for steels will result in great improvements in energy economy, recyclability and life-cycle cost. Therefore, the studies on development of newly designed Al alloys to satisfy both strength and plastic workability are needed for their wide applications to automotive industry.

In the way, the cold roll bonding (CRB) which has been widely used in manufacturing large sheets can be one way to design various layered materials to have the promising mechanical properties [9-13]. Compared to other processes, CRB is very effective because it is easy to be automated and simple to set up continuous process system. Further, CRB has a great merit to fabricate various clad materials through various combination of metallic sheets. Therefore, many researches have been carried out on the fabrication and evaluation of layered materials processed by CRB. However, there are only a few studies on multi-layer aluminum alloys by the CRB process, even though they have great potential in mechanical properties. The authors have studied on fabrication of multi-layer complex aluminum alloy sheets through CRB [12,13]. Through the CRB by various aluminum alloys, the possibility for fabrication of aluminum clad showing excellent mechanical properties of was confirmed in previous studies [12,13]. However, there are no studies using combination of AA5052 and AA6061 even though they have great potential in mechanical properties. Therefore, this study also aims to fabricate and to evaluate AA5052/AA6061/AA5052/AA6061 multi-layer stack aluminum alloys by the CRB process.

## 2. Experimental

The materials used in present study are commercial AA6061 and AA5052 alloys with chemical compositions as Table 1. The as-received materials of 2 mm thickness, 40 mm width, and 300 mm length are annealed for 0.5 h at 400°C to remove the residual stress for the starting materials. As shown in Fig. 1, a cold rolling was performed for four-layer sheets in which AA5052 and AA6061 sheets are stacked alternately after surface

[1] MOKPO NATIONAL UNIVERSITY, ADVANCED MATERIALS SCIENCE AND ENGINEERING, 1666 YOUNGSAN-RO, CHUNGGYE-MYEON, MUAN-GUN, JEONNAM 58554, KOREA

* Corresponding author: shlee@mokpo.ac.kr

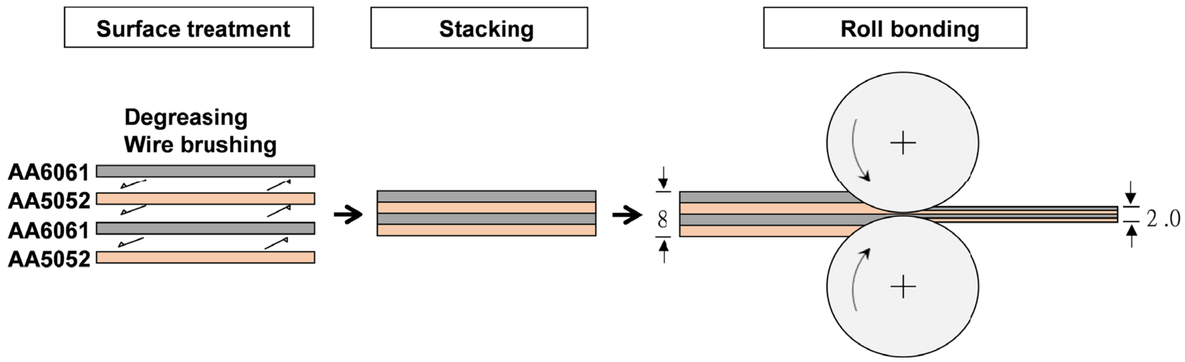


Fig. 1. Schematic illustration of four-layer roll-bonding process of AA5052 and AA6061 alloys

treatment such as degreasing and wire brushing. The rolling was done at a speed of 5.0 m/s by a two-high mill with a diameter of 210 mm without lubricant at ambient temperature. Resultantly, the four-layer sheets of 8 mm thickness were roll-bonded to 2 mm thickness by the rolling at total rolling reduction of 75%. The as-rolled AA5052/AA6061/AA5052/AA6061 multi-layer materials was then processed by natural aging (T4) and artificial aging (T6) treatments, as shown in Fig. 2.

TABLE 1

Chemical compositions of AA5052 and AA6061 used in this study

| | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti | Each | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| AA6061 | 0.6 | 0.7 | 0.3 | 0.15 | 1.0 | 0.15 | 0.25 | 0.15 | 0.05 | RE |
| AA5052 | 0.25 | 0.40 | 0.10 | 0.10 | 2.5 | 0.2 | 0.1 | — | 0.03 | RE |

Microstructures of the multi-layer aluminum materials were revealed by scanning electron microscopy (SEM) observation. 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 mm and 6 mm, respectively. The initial strain rate was $10^{-3}s^{-1}$. The variation of Vickers hardness through the thickness of the specimens was also measured with the load of 0.98 N.

## 3. Results and discussion

Fig. 3 shows the hardness distribution in thickness direction of the starting materials of AA5052 and AA6061 and the as-roll bonded four-layer material. As shown in Fig. 3, the both starting materials show relatively homogeneous hardness distribution through thickness due to the as-annealed state, even though the hardness of the AA5052 is higher than that of AA6061. However, the as roll-bonded material is a lamella structure in which the AA5052 and AA6061 sheets are stacked alternately to each other, with higher hardness in AA5052 than in AA6061. The hardness after roll-bonded material increased comparing with those of the starting materials of as-annealed state because of work hardening. It is also found that an increase in hardness by work hardening is larger in AA5052 regions than in AA6061 regions. Resultantly, the roll-bonded material has a heterogeneous hardness distribution in thickness direction in which the hardness value in AA5052 region is larger by about 15 Hv than that in AA6061 region. Fig. 4 shows the variations of hardness distribution through thickness after T4 (Fig. 4a) and T6 (Fig. 4b) treatments for the rolled materials. As shown in Fig 4a, the hardness is decreased more largely in AA5052 region than in AA6061 region after T4 treatment. The decrease in hardness is due to the recrystallization occurred during solution treatment. The decrease in hardness in AA6061 regions was not

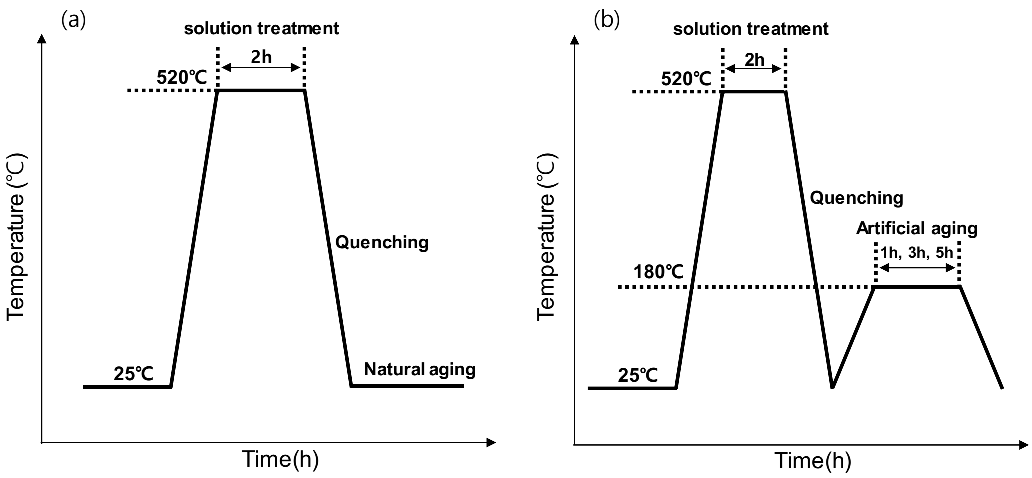


Fig. 2. Schematic illustration showing T4(a) and T6(b) aging treatments

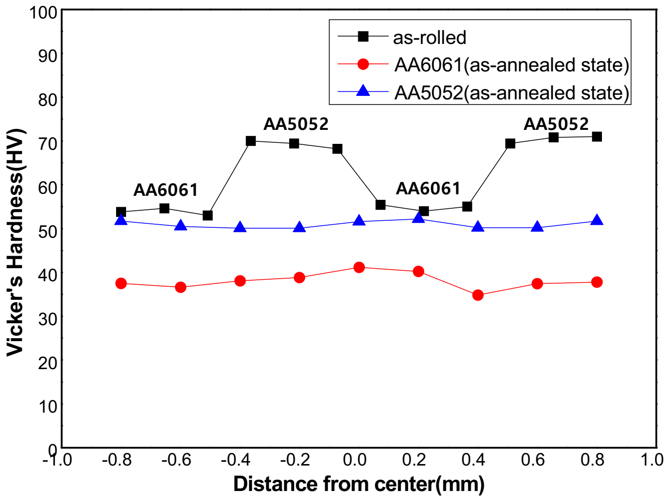


Fig. 3. Hardness distribution through thickness of starting materials of AA5052 and AA6061 and as-rolled material

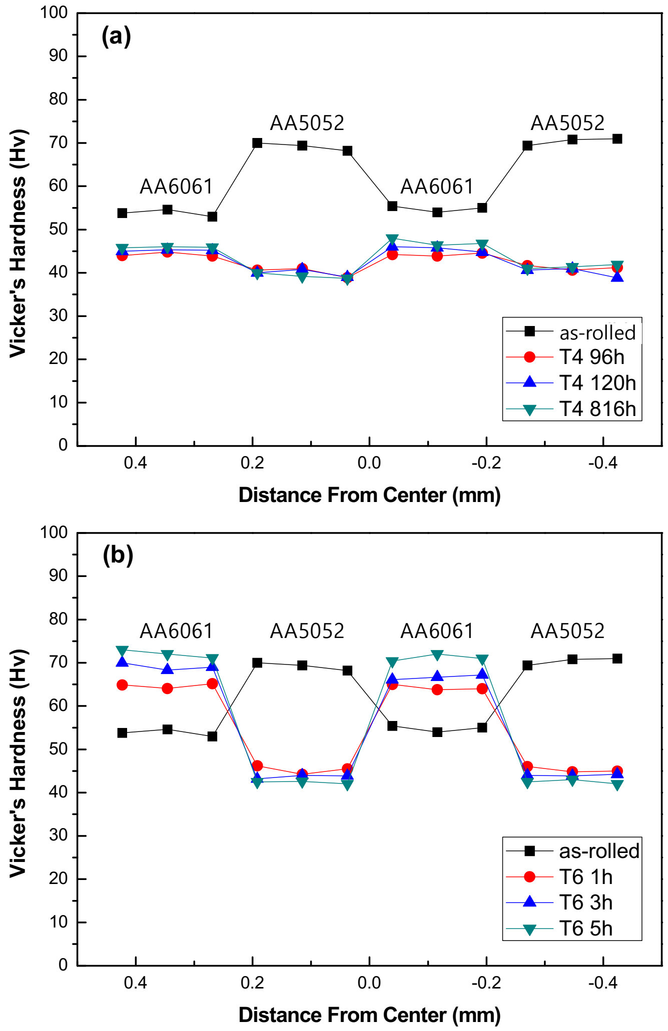


Fig. 4. Hardness distribution through thickness of T4(a) and T6(b) treated materials after roll-bonding

such large as AA5052 regions because of the age hardening by T4 treatment. Resultantly, the difference in hardness between AA5052 and AA6061 regions was decreased largely after T4 treatment. The variations in hardness with increasing of the aging time appeared hardly, as well. However, T6 treated material shows different hardness distribution from those of T4 treated ones, as shown in Fig. 4b. There is, the hardness rather increased largely in AA6061 region, even if it decreased in AA5052 region. This is due to significant increase in hardness by artificial age hardening. It is very interesting that the hardness distribution is reversed to each other by aging treatment. It is also notable that the hardness increases with increasing of the aging time in AA6061 regions, different from T4 treated ones.

Fig. 5 is SEM micrographs observed at TD plane of T4 aging treated material after roll-bonding. As shown in the figure, A and C belong to AA6061 and AA5052 areas, respectively. And B is the roll-bonded boundary region of AA5052 and AA6061. The T4 treated specimen showed a recrystallization structure consisted with the equiaxed grains in all regions of AA5052 and AA6061. The average grain size of AA6061 region is 15.4 μm, some larger than that (11.0 μm) of AA5052 region. The sound bonding is recognized even though the trace of the bonded boundary as B region in Fig. 5 is partially observed. Fig. 6 is SEM micrographs observed at TD plane of T6 aging treated material after roll-bonding. After T6 treatment, the specimen also has a recrystallization structure in all regions, similar to that of T4 treated one. However, the grain size was larger than those of T4 specimen in both AA5052 and AA6061. That is, the average grain size in AA6061 and AA5052 regions was

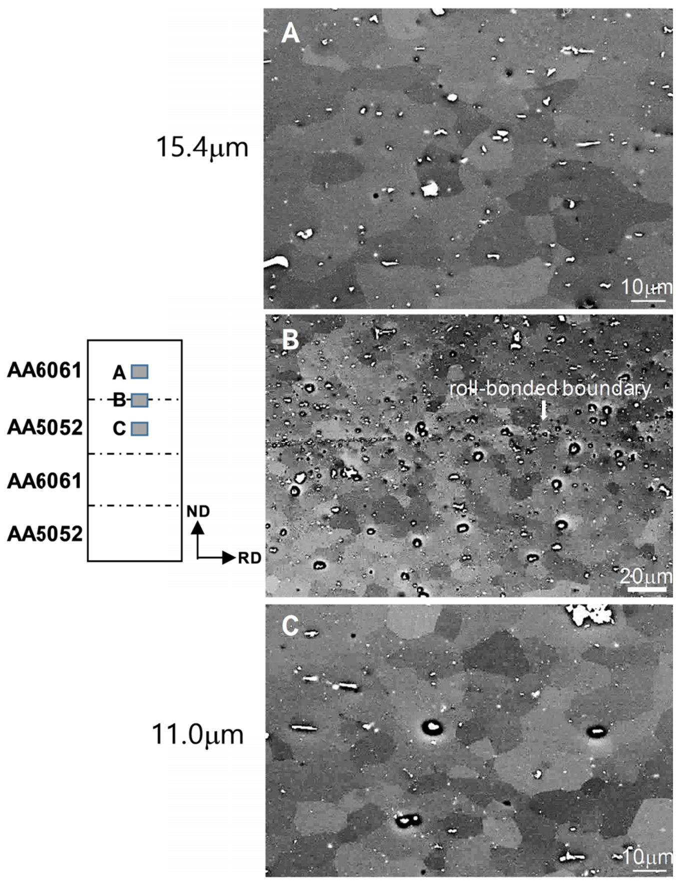


Fig. 5. SEM micrographs observed at TD plane of T4 aging treated material after roll-bonding

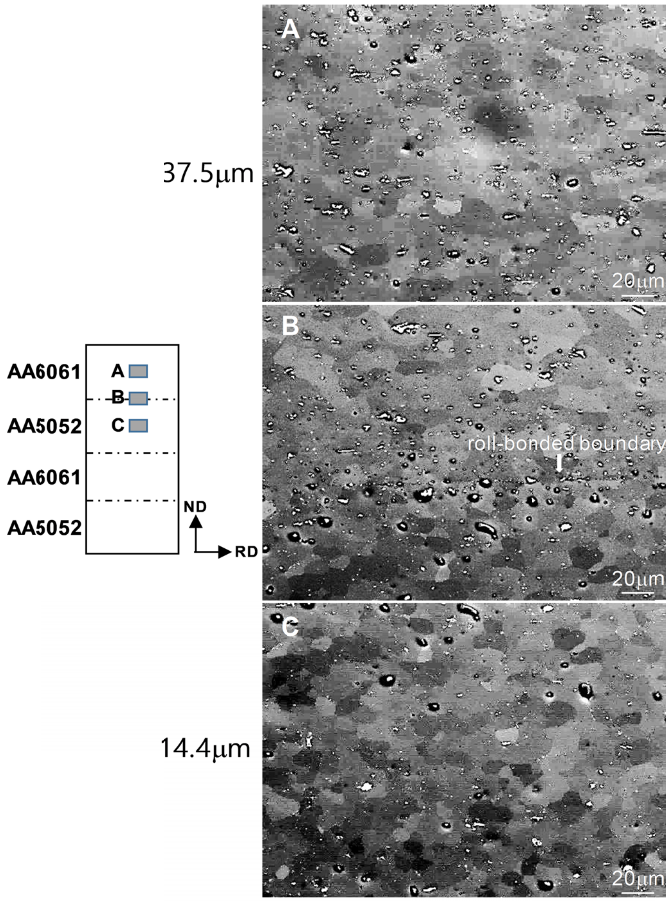


Fig. 6. SEM micrographs observed at TD plane of T6 aging treated material after roll-bonding

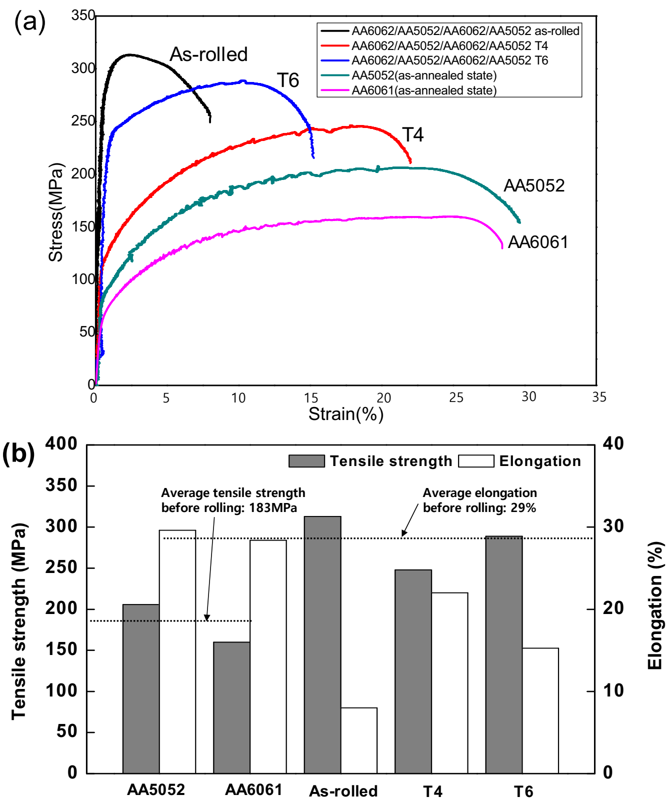


Fig. 7. Nominal stress-nominal strain curves(a) and the mechanical properties(b) of as-rolled and aging treated materials

37.5 μm and 14.5 μm, respectively. The grain size in AA6061 region for T6 specimen is larger by above two times than that for T4 one.

Fig. 7 shows nominal stress-nominal strain(s-s) curves (Fig. 7a) and the mechanical properties (Fig. 7b) of the as-rolled and the age-treated materials. The starting materials of AA5052 and AA6061 sheets show relatively low tensile strength and high elongation due to fully annealed state, as shown in Fig. 7(a). However, after the rolling, the strength was highly increased and the elongation was significantly decreased, because of work hardening. The strength after rolling was 312 MPa that is raised by 1.7 times comparing with that (183 MPa) before rolling, as shown in Fig. 7(b). On the other hand, the elongation of 29% was reduced to 8% after rolling. Here, the strength and the elongation before rolling were calculated by the mixture rule, respectively. The strength decreased and the elongation increased after the aging treatments of T4 and T6, comparing with the as-rolled material. It is also found that the strength is higher in T6 treated specimen (280 MPa) than in T4 specimen (248 MPa). Resultantly, the tensile strengths after T4 and T6 treatments were increased by 1.3 and 1.5 times, comparing to that of the starting material. In the way, it is also very interesting to study the work hardening behavior for these layered materials. That is, the s-s curves of the layered material would be different from the conventional aluminum alloys. Fig. 8 shows *ln*σ-*ln*ε relation plots of the specimens derived from a power law

$$\sigma = K\varepsilon^n$$

where σ is the true stress, $K$ is the strength coefficient, $\varepsilon$ is the true strain, and $n$ is the work-hardening exponent [14,15]. As shown in Fig. 8, $n$-value of T6 treated specimen (0.13) is smaller than that of T6 treated one (0.28), but much larger than that ($n = 0.05$) of the commercial AA6061-T6 material [15]. This is probably due to existence of AA5052 layer, suggesting very definitely that the $n$-value, associated with uniform elongation, would be increased through the fabrication of layered materials through cold roll bonding process.

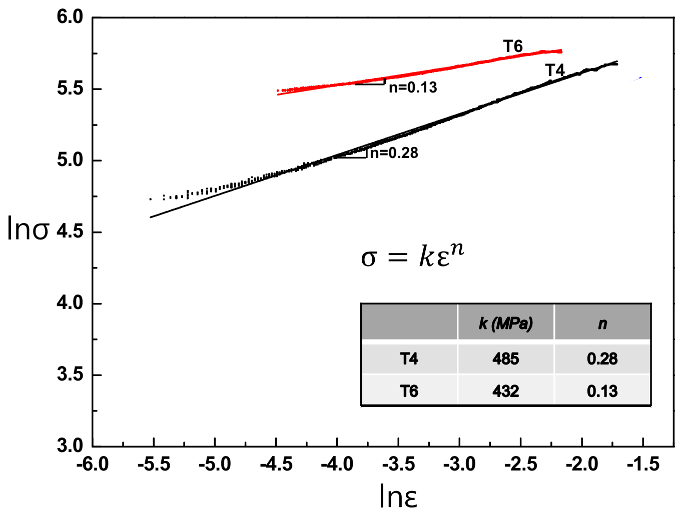


Fig. 8. Relations between true stress and true strain of the materials T4 and T6 aging-treated after roll-bonding

## 4. Conclusions

A cold roll bonding process was applied to fabricate an AA5052/AA6061/AA5052/AA6061 multi-layer sheet, and then treated by natural aging (T4) and artificial aging (T6). The as roll-bonded sheet showed a typical deformation structure that the grains are elongated to the rolling direction, but it had a recrystallization structure consisting of the coarse equiaxed grains in both AA5052 and AA6061 sheets after T4 and T6 aging treatments. The as roll-bonded material showed a lamella structure having higher hardness in AA5052 than in AA6061, but T4 and T6 treated materials had a different lamella structure in which the hardness is much higher in the AA6061 layers. The strengths of the T4 and T6 age-treated samples were found to increase by 1.3 and 1.5 times, compared to those of the starting materials, respectively.

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