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CHANGE IN MICROSTRUCTURE AND MECHANICAL PROPERTIES OF FOUR-LAYER STACK ARB PROCESSED COMPLEX ALUMINUM SHEET WITH ANNEALING

The four-layer stack accumulative roll bonding (ARB) process using AA1050, AA5052 and AA6061 alloy sheets is performed up to 2 cycles without a lubricant at room temperature. The sample fabricated by the ARB is a multi-layer complex aluminum alloy sheet in which the AA1050, AA5052 and AA6061 alloys are alternately stacked to each other. The changes of microstructure and mechanical properties with annealing for the-ARBed aluminum sheet are investigated in detail. The as-ARBed sheet shows an ultrafine grained structure, however the grain diameter is some different depending on the kind of aluminum alloys. The complex aluminum alloy still shows ultrafine structure up to annealing temperature of 250°C, but above 275°C it exhibits a heterogeneous structure containing both the ultrafine grains and the coarse grains due to an occurrence of discontinuous recrystallization. This change in microstructure with annealing also has an effect on the change of the mechanical properties of the sample. Especially, the specimen annealed at 300°C represents abnormal values for the strength coefficient *K* and work hardening exponent *n* value.

Keywords: accumulative roll bonding, heterogeneous microstructure, aluminum alloy, electron back scatter diffraction, annealing

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.

The ARB [9-17] is well known as an effective process for enhancement in mechanical properties of aluminum. It has been demonstrated that ultra-grain refinement to submicron order by ARB process can be attained for various metallic materials such as aluminum alloys [9-14] and copper alloys [14-17]. In the way, we have not necessarily to utilize the same materials in the ARB process. The ARB of the dissimilar materials rather than the same ones has been recently studying actively because it allows the creation of a variety of functional materials. 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 metallic materials such as Al and Cu [18], Al and Mg [19], Al and Ni [20], and the studies on the ARB of different alloys of same metal have been seldom done [21-22]. However, it is expected that the ARB of different alloys of same metal would let us produce the unique alloys consisting of more complex and various microstructure, resulting in enhancing the mechanical properties of the aluminum alloys. Especially, the complex Al alloys having various mechanical properties can be fabricated by the ARB, as reported in the previous studies [21-22]. In the way, if we increase the stacking number per ARB cycle, we would attain ultra-grain refinement and high strengthening very effectively. Therefore, this study is aimed to fabricate a multi-layer nanostructured AA1050/AA5052/AA6061 /AA1050 aluminum alloy sheet through a four-layer stack ARB using such dissimilar aluminum alloys as AA1050, AA5052 and AA6061 and to investigate the changes in microstructure and mechanical properties with annealing.

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2. Experimental

The materials used in this study were commercial purity AA1050, AA5052 and AA6061 sheets with thickness of 2 mm, of which the compositions are shown in Table 1. The as-received AA1050, AA5052 alloys and AA6061 were annealed at 500°C for 1 hour in order to remove the stored energy retained in the materials. For the ARB process, the Al alloy sheets were cut into dimensions of 50 mm in width and 200 mm in length and alternately stacked by four layers after wire-brushing and then roll-bonded to 2 mm in thickness by multi-pass rolling at ambient temperature, as shown in Fig. 1. The bonded AA1050/AA5052/AA6061/AA1050 complex aluminum sheet was then stacked again and reduced to 2 mm in thickness by the same procedure. This ARB process was performed up to 2c (c: cycle) without lubrication. The as-rolled samples were then annealed for 0.5h from 200 to 400°C. 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 20 kV. The EBSD analysis was done using a program TSL OIM Analysis ver. 3.0. The mechanical properties of the samples 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 initial strain rate of $10^{-3}s^{-1}$.

3. Results and discussion

The ARB process up to 2c was successfully performed without any shape defects. The ARB processed samples showed an alternating lamella structure of AA1050, AA5052 and AA6061. Fig. 2 shows the normal direction (ND) maps of the as-rolled material and samples annealed for 0.5 h at various temperatures from 275 to 400°C. The color of each point indicates the crystallographic direction parallel to ND of the specimens, corresponding to the colored stereographic triangle, respectively. It is found that the ultra-grain refinement to submicron order could be attained over all regions even though the grain diameter is some different depending on the kind of Al alloys, as shown in Fig. 2. The average grain size of the as-rolled complex aluminum alloy was 420 nm in thickness. The sample annealed at 275°C still shows a typical ultrafine grained structure in AA1050 and AA6061 regions, even though the grain size increases slightly due to an occurrence of static recovery. However, for AA5052 region, the various equiaxed coarse grains were observed due to an occurrence of the discontinuous static recrystallization. This static recrystallization occurs more actively at 300°C, so that the AA5052 region shows a complete recrystallization structure covered with the coarse grains in which the deformation structure almost does not exist inside, even if the deformation structure remains in AA1050 and AA6061 regions. The sample annealed at 350°C showed more interesting and various microstructural change in thickness direction; AA6061 region consists of a kind of bimodal structure in which both the ultrafine and the coarse grains by recrystallization coexist, and AA5052 region is covered with coarse grains due to complete recrystallization, and AA1050 region has very coarse grains due to grain growth. Resultantly, the 350°C specimen shows extremely heterogeneous structure in thickness direction. The specimen annealed at 350°C shows a recrystallization structure with equiaxed grains for all regions even though the grain size is different depending on each region.

Fig. 3 shows the misorientation distribution of the grain boundaries obtained from results of EBSD measurement for samples annealed at various temperatures. As shown in Fig. 3,

TABLE 1

Chemical compositions of 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

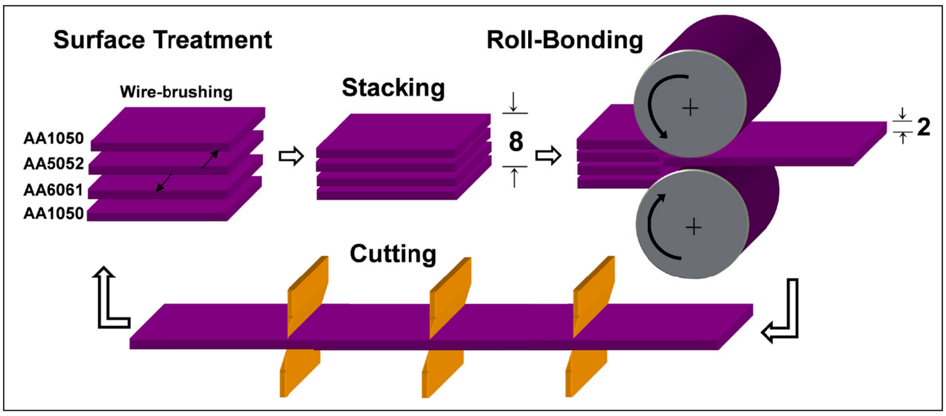

Fig. 1. Schematic illustration of four-layer ARB process using AA1050, AA5052 and AA6061 alloys

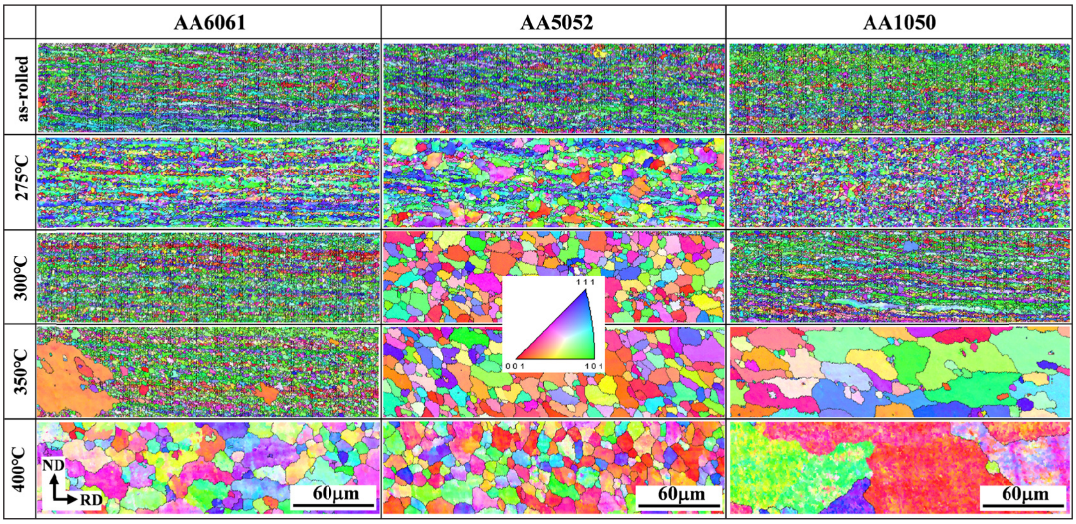

Fig. 2. Normal direction (ND) maps of the as-rolled material and samples annealed for 0.5 h at various temperatures

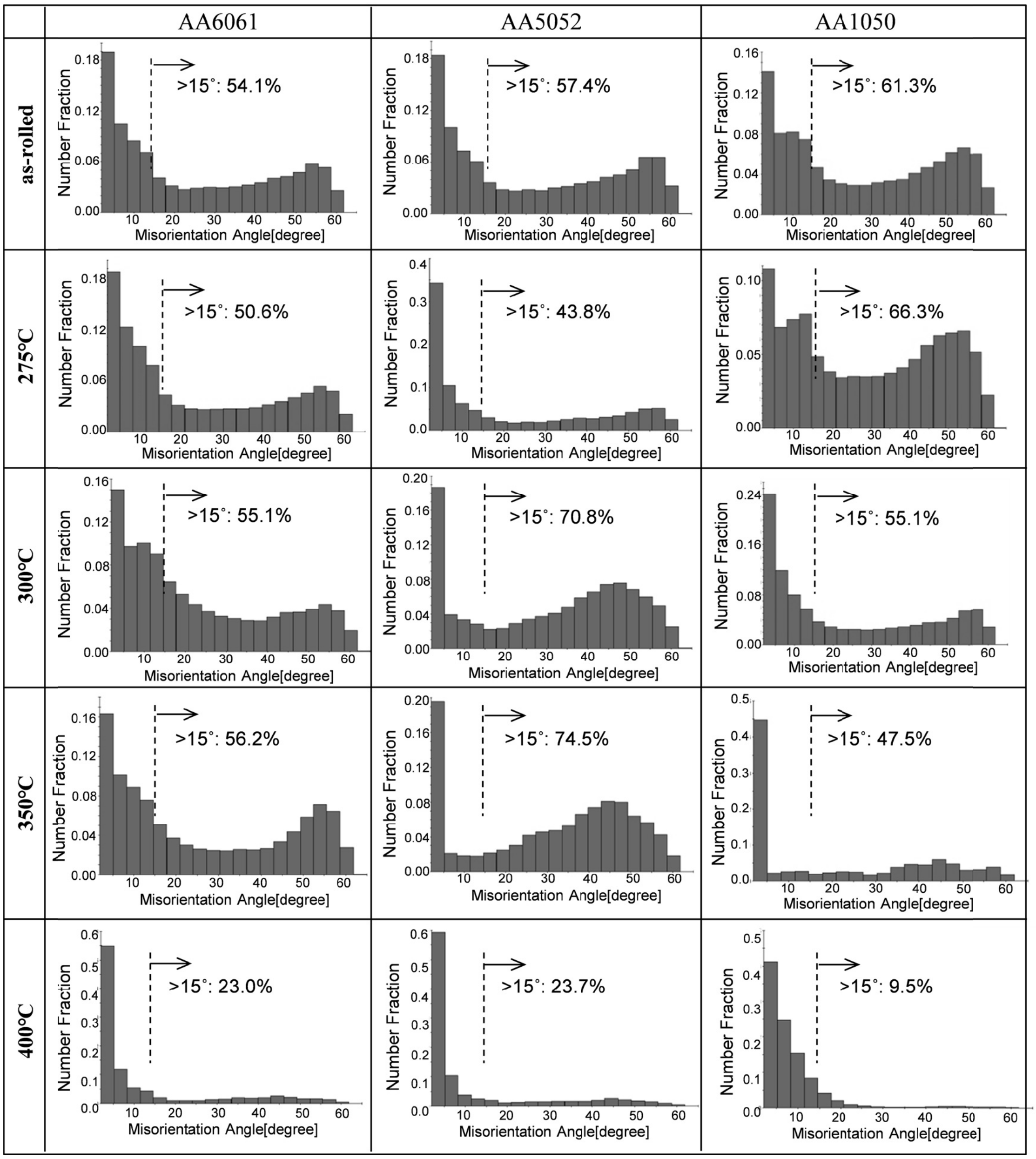

Fig. 3. The variation of misorientation angle distribution with annealing for the ARB processed aluminum sheet

the misorientation distribution is different depending on annealing temperatures and the regions. The samples annealed up to 350℃ tend to exhibit higher number fraction in high angle grain boundaries(HAGB) above 15 degree than that of low angle grain boundaries(LAGB) below 15 degree. In addition, it is found that the difference in distribution of misorientation angle between the regions (or materials) is largest. This result corresponds well to the result of microstructure in Fig. 2. However, the 400℃ annealed sample in which the complete recrystallization occurred in all regions shows very similar misorientation angle distribution in all regions, having far more LAGB than HAGB. This difference is probably due to difference in impurities and thereby stored energy introduced in the specimens during the ARB process. It is also very interesting that the variation of misorientation angle distribution with annealing is different depending on the kind of aluminum alloys. Especially, it is notable that the number fraction of HAGB increased largely with annealing temperature up to 350℃ in only AA5052 region.

It is also interesting for us to investigate the variation of texture development with annealing for the ARB processed material. In general, such rolling texture as {112}//ND, {011}//ND develops mainly after the conventional rolling, and after recrystallization, the recrystallization texture as {100}//ND develops. In the way, in case of this study, the roll bonding was repeated by ARB process using different Al alloys such as AA1050, AA6061 and AA5052. Therefore, it is expected that the texture also develops heterogeneously in thickness direction. Fig. 4 shows the variation of volume fraction of various texture components with annealing temperature for the ARB processed sample. As shown in the figure, the rolling texture developed in the specimens annealed at lower temperatures, however recrystallization texture developed at higher temperatures in every aluminum alloys. Especially, {100}//ND component developed largely in both AA5052 and AA1050 regions after annealing at 400℃.

Fig. 5 shows nominal stress-nominal strain(s-s) curves (Fig. 5a) and the mechanical properties (Fig. 5b) of the as-rolled and the annealed materials. The as-rolled material show relatively high tensile strength and low elongation due to working hardening and grain refinement, as shown in Fig. 5a. However, after annealing, the strength decreased progressively and the elongation increased due to an occurrence of recovery and recrystallization. As shown in Fig. 5b, the strength after the ARB was 324 MPa, however it decreased as annealing temperature increased, became 148 MPa after annealing at 350℃. However, the 300℃ sample shows abnormal behavior; both yield strength and tensile strength are larger than those of 275℃ sample. This result is also considered to be due to the formation of heterogeneous microstructure. On the other hand, the total elongation of 12% after the ARB increased with annealing temperature,

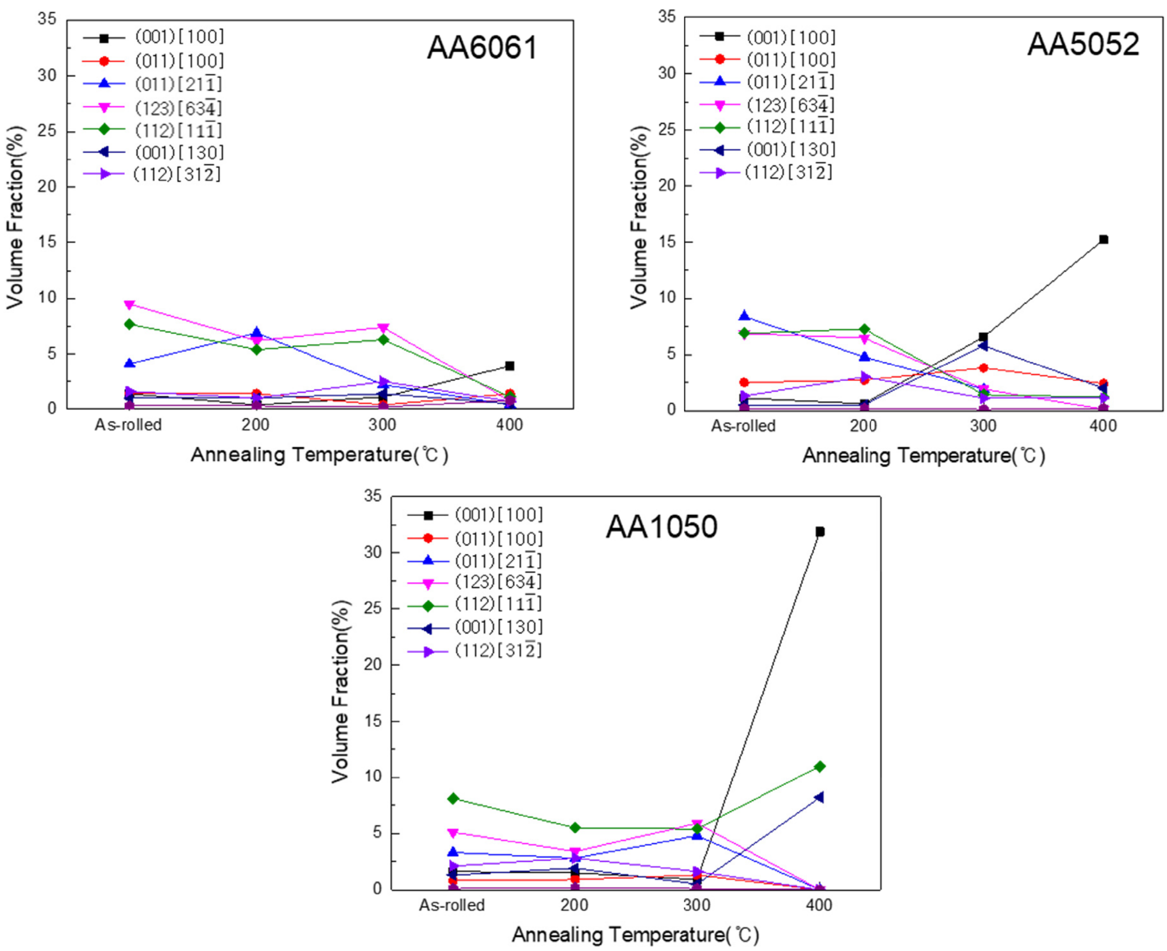

Fig. 4. The variation of texture development in each region with annealing for the ARB processed aluminum sheet

reached 30% after 350°C. The uniform elongation also tends to increase with annealing temperature, but the local elongation did not change so largely. In the way, it is also very interesting to study the work hardening behavior for the ARB processed and annealed materials in which various different aluminum alloys sheets are stacked alternately. That is, the s-s curves of these materials would be different from the conventional aluminum alloys. Fig. 6 shows lnσ-lnε 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, ε is the true strain, and n is the work-hardening exponent [23,24]. In general, as the annealing temperature increases, K decreases and n value increases. However, as shown in Fig. 6, both K and n value represent abnormal behavior in specimen annealed at 300°C. This is probably due to not only multi-layered macrostructure of different aluminum alloy sheets by ARB process but also heterogeneous microstructure developed by annealing. This also suggests that the mechanical properties of aluminum alloys could be controlled through the formation of heterogeneous microstructure by the ARB and subsequent annealing process.

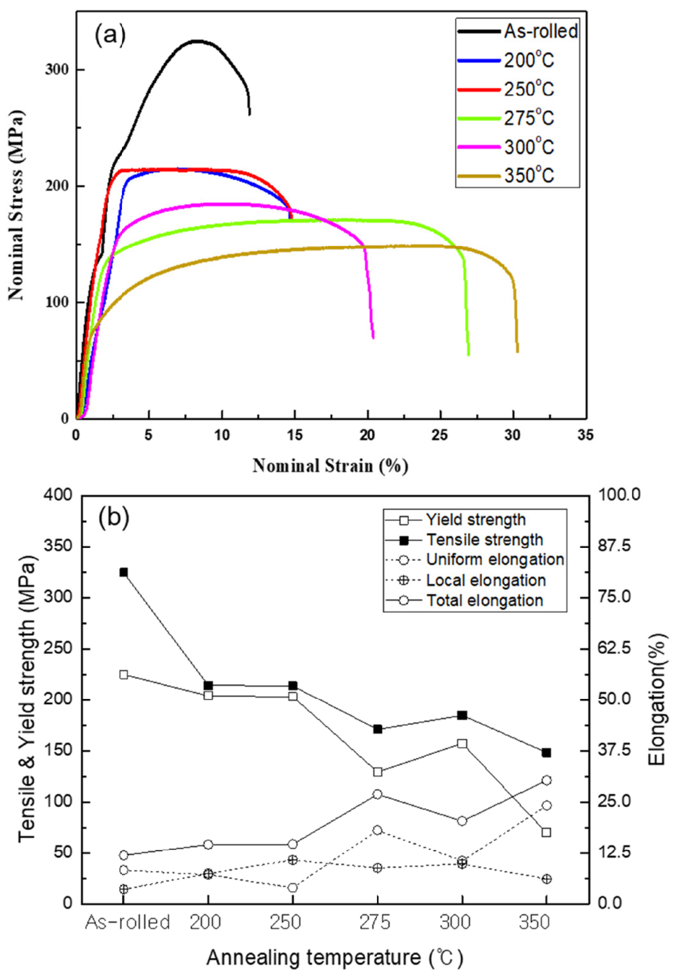

Fig. 5. The changes in nominal stress-nominal strain curves (a) and the tensile properties (b) with annealing for the ARB processed aluminum sheet

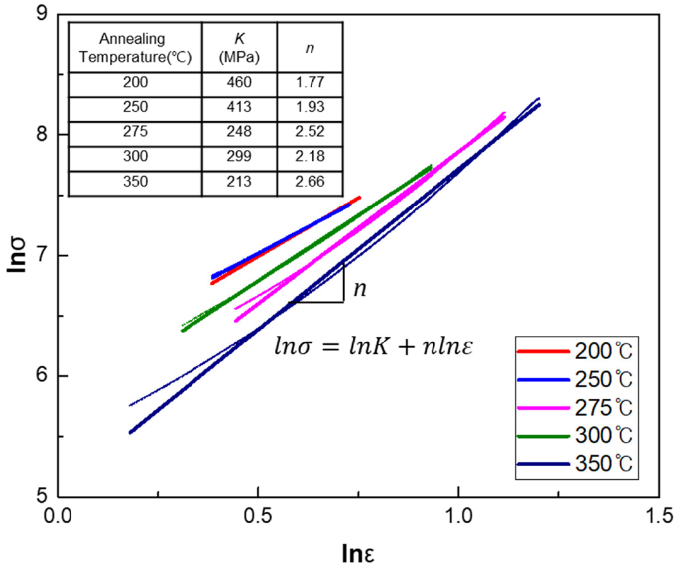

Fig. 6. lnσ-lnε plots of samples annealed at various temperatures for ARB processed aluminum sheet

4. Conclusions

An ultrafine grained complex Al alloy sheet was successfully fabricated by four-layer stack ARB process using different Al alloys such as AA1050, AA5052 and AA6061 and subsequent annealing process. The complex Al alloy still showed ultrafine grained microstructure up to annealing temperature of 250°C, but it showed a heterogeneous structure consisting of both the ultrafine grains and the coarse grains due to an occurrence of discontinuous recrystallization above 275°C. This change in microstructure with annealing also had an effect on the change of the mechanical properties of the sample. Especially, the sample annealed at 300°C represents abnormal values for the strength coefficient K and work hardening exponent n value. Therefore, it is considered that the mechanical properties of Al alloys could be controlled by the ARB process and subsequent annealing.

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