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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF AA6061 LAYERED SHEET FABRICATED BY FOUR-LAYER STACK COLD ROLL-BONDING

Four-layer stack cold roll-bonding (4L-CRB) process is applied to enhance the mechanical properties of AA6061 sheet. Commercial AA6061 sheets having thickness of 1 mm, width 0f 40 mm and length of 300 mm were stacked to four layers, and roll-bonded by two-pass cold rolling. The as roll-bonded Al sheet was then annealed for 1h at temperatures from 200 to 500°C. The conventional rolling (CR) was also proceeded at ambient temperature for AA6061 sheet for comparison. For both CR and 4L-CRB, the as roll-bonded Al sheets showed a typical deformation structure, where the grains are elongated in the rolling direction. However, they exhibited different recrystallization behaviors between the CR and the 4L-CRB. The grain diameter of the specimens annealed at higher temperatures than 350°C was smaller and more homogeneous in 4L-CRB than in CR. In addition, the mechanical properties of the specimens processed by 4L-CRB were more superior, comparing with those of the CR. The microstructures and mechanical properties of the specimens by 4L-CRB are compared with those by the CR in detail.

Keywords: Cold roll-bonding; AA6061 alloy; mechanical properties; microstructure; annealing

1. Introduction

Recently, the metallic materials such as aluminum and magnesium are attracting a lot of attention for the lightweight of transport machines [1-8]. From viewpoint of just lightweight, magnesium alloys are very attractive because they have a specific gravity of 1/4 of iron, but they are more expensive than aluminum alloys, and are very disadvantageous in terms of plasticity and corrosion resistance. Therefore, aluminum alloys have long been widely used as structural materials in various fields including transport machines, and the scope of application is also expanding. However, in order for aluminum alloys to expand the scope of application to transport machines, the studies to improve the mechanical properties such as strength and ductility should be proceeded more actively [9-11]. In this study, the CRB process is tried to improve the mechanical properties of Al sheets. In general, it is very important to optimize the rolling conditions as rolling reduction and temperature for CRB process, because it requires the sound bonding between Al sheets simultaneously with plastic deformation [12-17]. In previous studies, the authors fabricated various different aluminum layered materials consisting of 2 to 4 layers through the CRB, and identified the possibility to obtain the various mechanical properties [15,16]. In particular, it was conformed that the CRB of AA1050 and AA6061 sheets enables various combinations of strength and ductility depending on the number of layers [15,16]. In addition, it was found that the difference in the number of stacks affects the mechanical properties for the CRB of the AA5052 [18]. However, no studies have so far improved the mechanical properties using the same material in the CRB. Therefore, this study aims to improve the mechanical properties of the AA6061 sheet through the 4L-CRB.

2. Experimental

2.1. CRB and annealing

Material used in this study is commercial AA6061 sheet, and its chemical composition is shown in TABLE 1. The as-received Al sheet had thickness of 1 mm, width of 40 mm, and length of 300 mm, and were annealed for 0.5h at 400°C to remove the residual stress of the starting materials. The tensile strength, yield strength, and fracture elongation of the starting materials were 160 MPa, 70 MPa, and 28%, respectively. Four Al sheets are laminated after surface treatments such as degreasing and wire-brushing. The 4L-CRB process was then performed at ambient temperature without lubrication. The rolling was

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proceeded by two-pass at a roll speed of 5.0 m/s using a four-high mill with a working roll diameter of 370 mm, so that the thickness of 4 mm became 1 mm. The conventional rolling (CR) was also performed for the Al sheet from 2 to 0.5 mm in thickness at the same rolling conditions. Therefore, the total reduction was the same for both CR and 4L-CRB at 75%. The CR and 4L-CRB processed AA6061 sheets were then annealed at 200 to 500°C for 1 h.

TABLE 1

Chemical compositions of AA6061 sheet used in this study (wt.%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Each	Al
0.6	0.7	0.3	0.15	1.0	0.15	0.25	0.15	0.05	RE

2.2. Characterization

Microstructures of the roll-boned Al sheets were revealed by optical microscopy (OM) observation. The mechanical properties were examined at ambient temperature by an Instron-type tensile testing machine. The tensile 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, and the initial strain rate was $10^{-3}s^{-1}$. The variation in Vickers hardness in the thickness direction of the specimens was also measured with a load of 0.98 N.

3. Results and discussion

3.1. Microstructure

The specimens annealed up to 300°C showed a typical deformation structure that the grains are greatly elongated in the rolling direction. The specimens annealed at temperatures more than 350°C showed typical complete recrystallization structure. Fig. 1 shows the morphologies of the grains observed at surface and center of the specimens annealed at 300~500°C. The 300°C specimen showed the large average aspect ratios (AR) of 4.2 and 6.8 in surface and center regions, respectively. The 400°C specimen showed the average AR of 2.2 and 2.3 in surface and center regions, respectively. That is, the AR was smaller than that of the 300°C specimen due to the occurrence of complete recrystallization.

Fig. 2 shows the change in OM microstructure with the increase of annealing temperature for the 4L-CRB specimens. As shown in the figure, the bonding interfaces were observed at 1/4, 1/2, and 3/4 positions from the surface, as indicated by the arrow. The as-rolled and the annealed specimens up to 250°C showed the deformation structure. However, the 300°C specimen showed the recrystallization structure in most regions, although the deformation structure still remained partially near surface regions. This means that the recrystallization occurred at lower temperature in 4L-CRB than in CR. The specimens annealed at 400~500°C showed the complete recrystallization structure over all regions. The grain diameter of the 500°C specimen was also slightly smaller than that of the 400°C specimen over almost all regions. The morphologies of the grains observed in surface and center regions of the 300~500°C specimens are shown in Fig. 3. The 300°C specimen showed AR of 2.0 in both surface and center regions. This is due to the occurrence of complete recrystallization over all regions at 300°C, different from the CR. The average grain diameter in surface regions was 12.5 μm, slightly smaller than 13.1 μm of center regions. The 400°C specimen showed the average AR of 1.8 and 1.9 in surface and center regions, respectively, as shown in Fig. 3(b). The average grain diameter was smaller in surface (13.2 μm) than in center (17.4 μm). As shown in Fig. 3(c), the 500°C specimen showed the average ARs of 1.7 and 1.9 in surface and center regions,

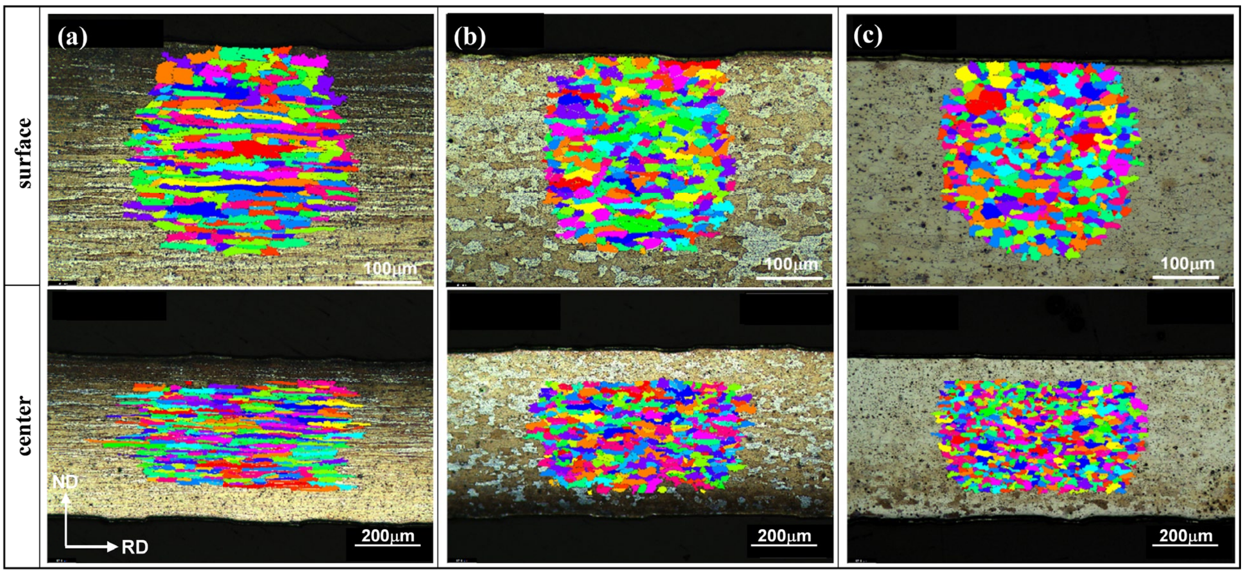

Fig. 1. Optical microstructures showing morphologies of grains observed at surface and center regions of specimens annealed at 300°C (a), 400°C (b), and 500°C (c) after the conventional rolling (CR)

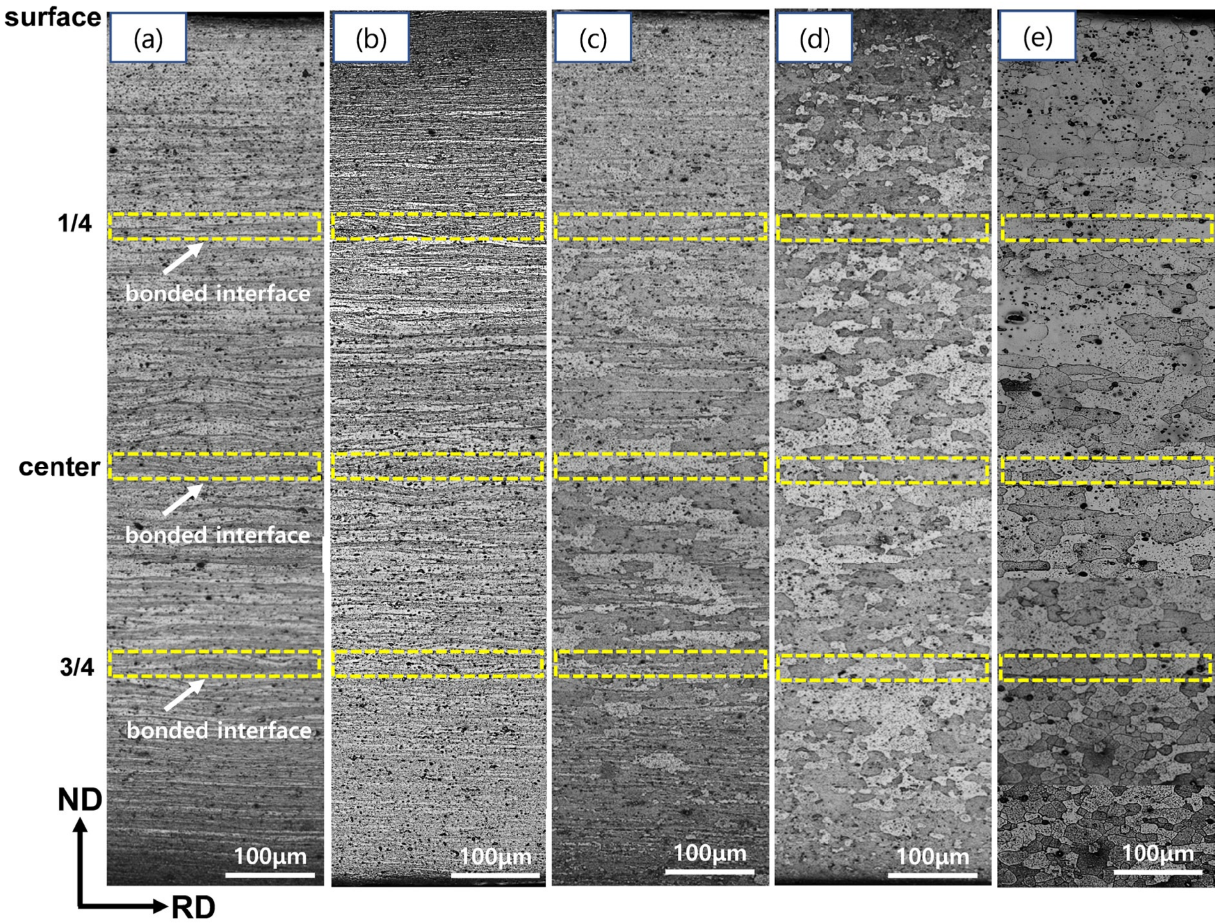

Fig. 2. Changes in optical microstructure with the increase of annealing temperature for the specimen processed by 4-layer cold roll-bonding (4L-CRB). (a) the as-rolled, (b) 200°C, (c) 300°C, (d) 400°C, and (e) 500°C

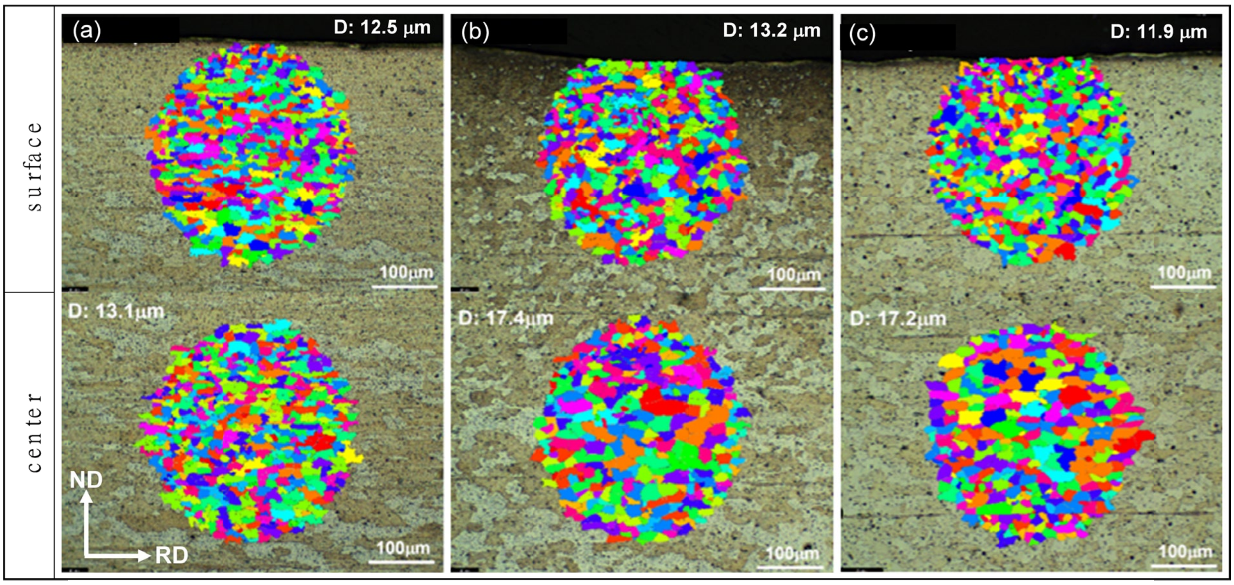

Fig. 3. Optical microstructures showing morphologies of grains observed at surface and center regions of specimens annealed at 300°C (a), 400°C (b), and 500°C (c) after 4-layer stack cold roll-bonding (4L-CRB)

respectively. These are almost the same as those of the 400°C specimen. However, the average grain diameter was rather smaller than that of 400°C specimen in both center and surface regions, even if higher temperature.

3.2. Mechanical Properties

Fig. 4 shows the change in average hardness with increasing the annealing temperature for the CR and 4L-CRB specimens.

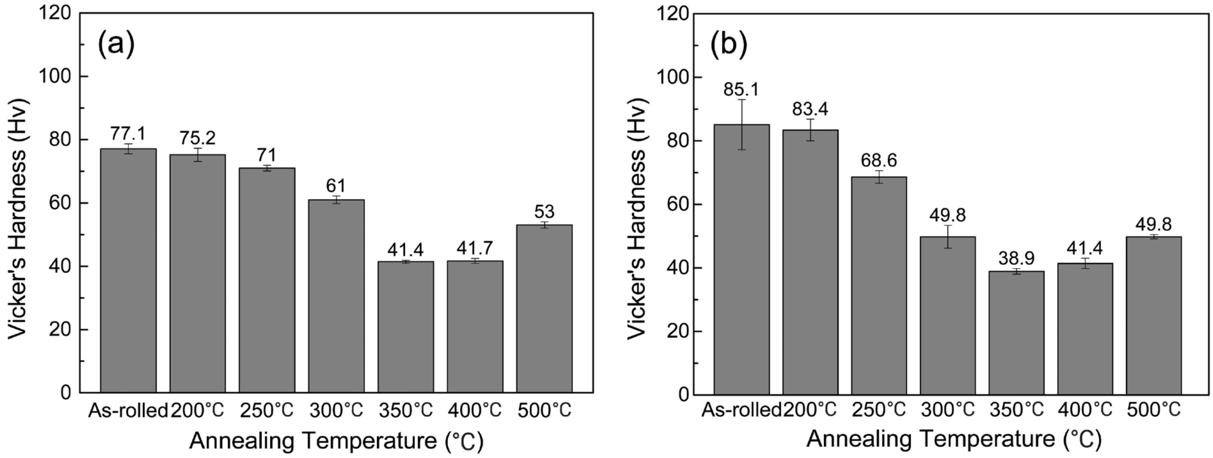

Fig. 4. The change in the average Vickers hardness with the increase of annealing temperature for CR (a) and 4L-CRB specimens (b)

The average hardness in both the CR and the 4L-CRB specimens tended to decrease gradually with increasing the annealing temperature up to 400°C, but above 500°C it rather increased. The reason that the hardness decreased with the increase of annealing temperature is due to active occurrence of recovery and recrystallization. In particular, the drastic decrease in hardness for the CR-350°C specimen and the 4L-CRB specimens above 300°C is probably due to occurrence of the complete recrystallization. In the way, the increase in the average hardness for the 500°C specimens is due to the occurrence of age-hardening in AA6061 alloy that the minimum temperature for solution treatment is about 500°C.

Fig. 5 shows the nominal stress-nominal strain (s-s) curves and strength-elongation diagram for the CR and 4-CRB specimens. As shown in the figure, both the as CR and the as 4-CRB specimens showed the s-s curves with high strength and very

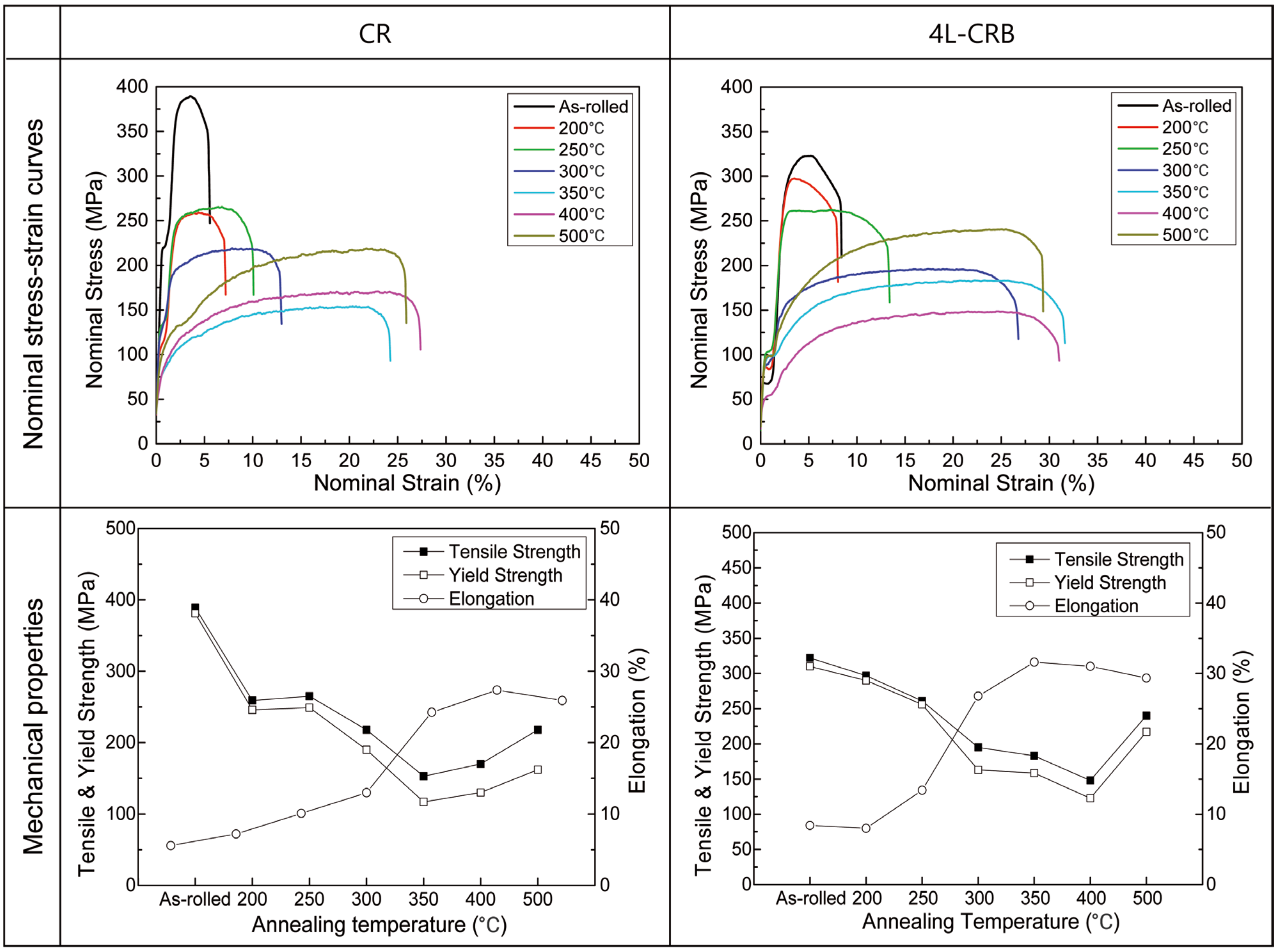

Fig. 5. The changes in nominal stress-nominal strain curves and mechanical properties with the increase of annealing temperature for CR and 4L-CRB specimens

low elongation because they are work-hardened due to cold rolling. However, they showed the typical softening curves that the strength decreased, while the elongation increased, with increasing the annealing temperature. In addition, the difference between the tensile and the yield strength was small up to 250°C, but it increased at temperatures more than 300°C, and the gap hardly changed even in more higher temperatures. This means that the contribution of yield strength to tensile strength was greater than that of the work hardening.

Fig. 6 shows tensile strength-elongation diagram of the specimens processed by CR and 4-CRB and subsequently annealed. As shown in the figure, at all conditions, the valence of mechanical properties of the 4L-CRB specimens was better than those of the CR specimens. Here, let's consider the reason why the mechanical properties of the 4L-CRB material are superior to that of the CR material. In general, the strength of metallic materials is determined by solid solution strengthening, grain refinement strengthening, precipitation strengthening, and work hardening. In this study, most conditions such as the material used, rolling reduction, and annealing temperature were the same for both CR and 4L-CRB, but there are two differences; one is difference in thickness of the specimen before and after, and the other is difference in the number of stacking layers. Therefore, solid solution strengthening and precipitation strengthening terms would have had little effect on the difference in strength, and work hardening and grain refinement strengthening would have had a significant effect on the strength. That is, the work hardening, including wire-brushing in the case of 4L-CRB, played the biggest role on the strengthening for low-temperature annealed materials, and the grain refinement for the specimens annealed at 350°C or higher temperatures. In addition, it is considered that the differences in the initial thickness (4 mm and 2 mm) and final thickness (1 mm and 0.5 mm) for the CR and 4L-CRB affected the differences in microstructure and mechanical properties. The shear strain introduced during the 4L-CRB was greater compared to that of the CR, resulting in lower recrystallization temperature in 4L-CRB than in CR [18].

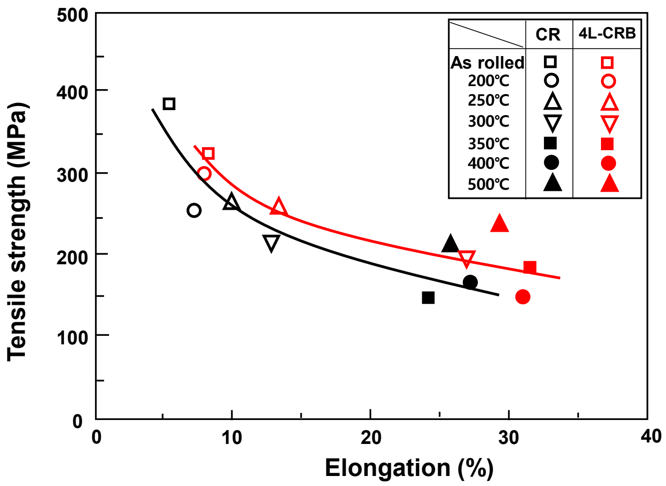

Fig. 6. The relation between tensile strength and elongation of the specimens processed by the CR and the 4L-CRB

Another difference between the CR and 4L-CRB specimens is the existence of roll-bonded interfaces. That is, in case of the 4L-CRB specimen, three bonding interfaces exist, however there is no interfaces in case of the CR specimen. The bonding interfaces are the places where the wire-brushing was performed to enhance the bonding strength between the Al sheets before rolling. In addition, the wire-brushing process is a kind of friction process to remove the hard Al_2O_3 film on the surface of the Al sheet. During the wire-brushing, temperature of the Al surface rises largely due to the frictional heat, resulting in recrystallization structure consisted of ultra-fine grains. It was reported that the wire-brushing forms ultra-fine grains of about 200 nm just below the Al surface [19]. The formation of such ultra-fine grains would contribute partially to the increase in yield and tensile strengths of the 4L-CRB specimens.

4. Conclusions

4L-CRB process was applied to improve the mechanical properties of AA6061 sheet and compared with the results of the CR, the conclusions were as follows.

1) There is the difference in recrystallization behaviors between the CR and 4L-CRB; the recrystallization temperature of the 4L-CRB specimen was 300°C, while it exhibited the complete recrystallization structure was 350°C for the CR specimen.
2) The morphologies and size of the recrystallized grains were different in surface and center regions in thickness direction between the CRB and the CR specimens; the differences in size and aspect ratio of grains in thickness direction was smaller in the 4L-CRB than in the CR specimens.
3) The hardness and strength in both CR and 4L-CRB specimens tended to decrease gradually decreased with increasing the annealing temperature up to 400°C, but above 500°C it increased due to age hardening.
4) The mechanical properties of the 4L-CRB specimens were relatively superior more than those of the CR specimens. This is mainly due to work hardening and grain refinement by wire-brushing and effective introduction of the shear strain during rolling.

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