Military Technical College
Cairo, Egypt

12th International Conference
on Applied Mechanics and
Mechanical Engineering (AMME)

# FINE GRAINED 6061 ALUMINUM ALLOY SHEETS PRODUCED BY ACCUMULATIVE ROLL-BONDING (ARB) PROCESS

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## ABSTRACT

In the present study the accumulative roll-bonding (ARB) process was applied to the 6061 alloy sheets and to clarify the evolution of the microstructures of produced sheets. The accumulative roll-bonding (ARB) process is intense plastic straining process. In the ARB process, a strip is neatly placed on top of another strip. The two layers of material are joined together by rolling (reduction degree of 50%) like a roll-bonding process. Then, the length of rolled material is cut into two halves. These two haves are again stacked and roll-bonded. The whole process is repeated again and again. By the ARB process, a very fine grain structure of 6061 Al alloy, less than three micron, was formed and the material was strengthened dramatically.

## KEY WORDS

Accumulative Roll Bonding (ARB) process - Roll Bonding - Solid State Welding - Grain Refining - 6061 Aluminum Alloy

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## 1. INTRODUCTION

Aluminum alloys are of great interest to the transportation industry and to automobile producers, in particular. The ever increasing use of aluminum alloy is driven by the goal of reducing vehicle mass. The use of aluminum alloy sheet materials for typical automobile body – in – white could provide a mass reduction of up to 50% compared to current steel construction. One of the difficulties that must be over come for increased use of aluminum alloys in such application is low formability. Formability of commercial steels currently used in sheet stamping , the primary process by which automotive body panels are produced, are significantly higher than aluminum alloys. There have been many efforts in recent years to develop aluminum alloys with improved formability by first understanding the microstructural aspects which control deformation behavior and then optimizing which enhance formability. As a result of which these alloys have become alternative candidate materials for replacing steel in the manufacture of at least some automotive components[1,2].

There is much current interest in producing metals with very small grain sizes. This interest arises because a reduction in grain size leads to an increase in both the strength and toughness of the material at ambient temperatures. If the small grain sizes are retained to elevated temperatures, where diffusion is reasonably rapid, there is also a potential for achieving good formability and superplastic ductilities[3-7]. Traditionally, small grain sizes are obtained through the development of appropriate thermomechanical processing routes. This procedure is specific for each selected alloy. The processing routes must be adjusted when there are significant changes in the alloy composition and the smallest grain sizes attained through these methods are often in the range 1–10 $\mu$m. As a consequence of these routes, there is a need to develop simple processing procedures for fabricating materials with ultra-fine grain sizes in the submicrometer or nanometer range[7]. Fine grain structure can be produced by various methods: rapid solidification, mechanical milling/alloying of powder metals, vapor deposition crystallization of amorphous and severe plastic deformation (SPD) . Among these methods , SPD is the most promising process for producing fine grained materials. There are three principle methods for subjecting a material to severe plastic deformation: these are known as equal-channel angular pressing (ECAP), high pressure torsion (HPT), and The accumulative roll-bonding (ARB) process.

The accumulative roll-bonding (ARB) process was developed recently by Saito et al[8], and many of researchers[9-13] to achieve ultra-fine grains in metallic materials without changing the specimen dimensions. The accumulative roll-bonding (ARB) process is intense plastic straining process. In the ARB process, a strip is neatly placed on top of another strip. The two layers of material are joined together by rolling (reduction degree of 50%) like a roll-bonding process. Then, the length of rolled material is cut into two halves. The two strips are again stacked and roll-bonded again. The whole process is repeated again and again , see Fig (1) .

This process can introduce ultra-high plastic strain without any geometrical change, if the reduction in thickness is maintained to 50% in every rolling pass, because the increase in width is negligible in sheet rolling. The achieved strain is unlimited since repetition times are endless in principle. Arbitrarily large deformation is possible by the ARB process. When the reduction is 50% per cycle;

The thickness of the initial layer T after n cycles is

$$T = \frac{T_o}{2^n}$$

where $T_0$ is the initial thickness of strips.

The total reduction $\boldsymbol{r_t}$ after n cycles is

$$r_t = 1 - \frac{T}{T_o} = 1 - \frac{1}{2^n}$$

The total equivalent strain $\xi_t$ after n cycles is

$$\varepsilon = \left\{ \frac{2}{\sqrt{3}} \ln\left(\frac{1}{2}\right) \right\} x\ n = 0.8\ n$$

In the present study, the accumulative roll-bonding ARB process was applied to 6061 aluminum alloy sheets, (a typical Al–Mg–Si alloy) At 500 $^{o}$C. Since the 6061 alloy is an age-hardenable alloy, it can be strengthened appreciably by heat treatment. The 6061 alloy has been also currently attracted interests of many researchers[3,4,7,9] because its matrix shows high strength and a good formability . The objective of the present study is to investigate the evolution of the microstructures and the mechanical properties with number of ARB cycles for this material.

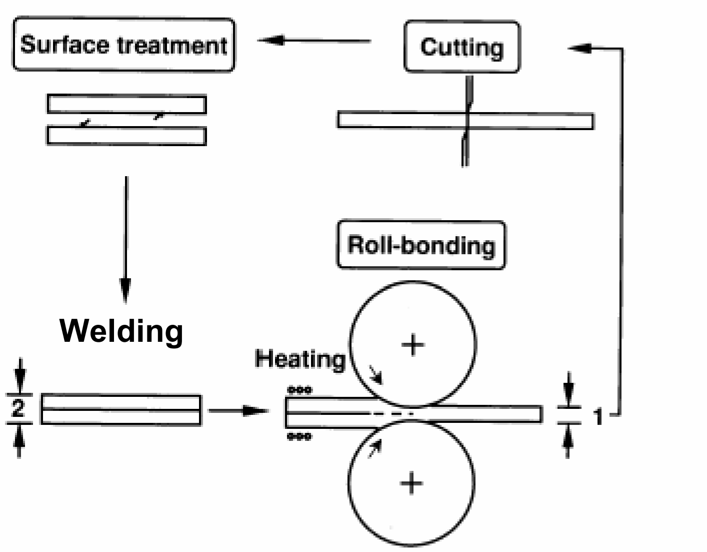



Fig.1 Schematic illustration showing the principle of the ARB process[9]

## 2. MATERAIL AND EXPERIMENTAL PROCEDURES

6061 Al-alloy with chemical composition as shown in Table(1) was used in the present study. The received material was extruded sheets of 6mm thickness at $T_0$ heat treatment condition, where $T_0$ is full annealed materials. These materials are subject to hot rolling at 500 $^oC$ until the thickness reached 1 mm in three passes. Then these sheets are undergone to the full annealing process again before they were subjected to accumulative roll bonding process at 500 $^oC$.

Table.1 Chemical Composition of 6061 Aluminum Sheets

| Element | Si % | Fe % | Cu % | Mn % | Mg % | Cr % | Zn % | Ti % | Others % | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| 6061 Al | 0.65 | 0.7 | 0.27 | 0.15 | 1.05 | 0.25 | 0.25 | 0.15 | 0.15 | balance |

### The Microstructure Examinations

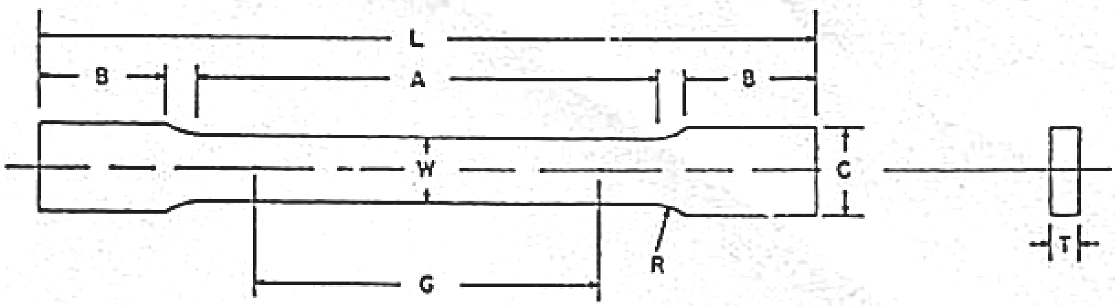
The microstructure was investigated by optical (OM) and scan electron (SEM) microscopes. The ARB sheets will be recrystallized by static annealing at 500 $^oC$ for 0.5 h, followed by water quenching. These test materials was cut in rolling direction, mechanically polished, and then etched with Graf Sergent etchant (15.5 ml HNO3, 0.5 ml HF, 3 g $CrO_3$, and 84 m water). Aging for 12 h at 150 $^oC$ prior to etching proved to be helpful to successfully reveal the grain structure by decorating grain boundaries by precipitates[14].

The grain size of the ARB process was too small to be determined by OM. Moreover, the contrast obtained by etching was insufficient for the observation in the SEM and, therefore, another method of visualization of grain boundaries had to be sought. The grain boundaries sliding (GBS) occurring during superplastic deformation leads to mutual shifts of grains and freshly exposed grain boundary facets may be observed at the prepolished surface. Supposing that all interfaces are concerned with the grain boundary sliding (GBS) process all grain boundaries should be visualized and the grain size might be determined[15].

### Tensile Test

Standard sheet tensile specimens, with cross sectional area of 6x1 mm and gauge length 25 mm were used. The tensile specimens were machined from the produced sheets after the accumulative roll boning process by Charmi wire cutting machine according to ASME (E8), as shown in Fig. 2.

Tensile tests were carried out to fracture at room temperature using an Instron tensile machine. The machine has loading range from 0 to 10 ton. The cross-head speed (C.H.S) used in this investigation was 2.0 mm / min.




| | | | |
|---|---|---|---|
| **G-Gage length** | **25.0 ± 0.1 mm** | **L-Overall length** | **100.0 ± 0.1 mm** |
| **W-Width** | **6.0 ± 0.1 mm** | **A-Length of reduced section** | **32.0 ± 0.1 mm** |
| **T-Thickness** | **1.0 ± 0.1 mm** | **B- Length of grip section** | **30.0 ± 0.1 mm** |
| **R-Radius of fillet** | **6.0 ± 0.1 mm** | **C-Width of grip section** | **10.0 ± 0.1 mm** |

**Figure 2 Tensile test specimen.**

## 3. RESULTS AND DISCUSSIONS

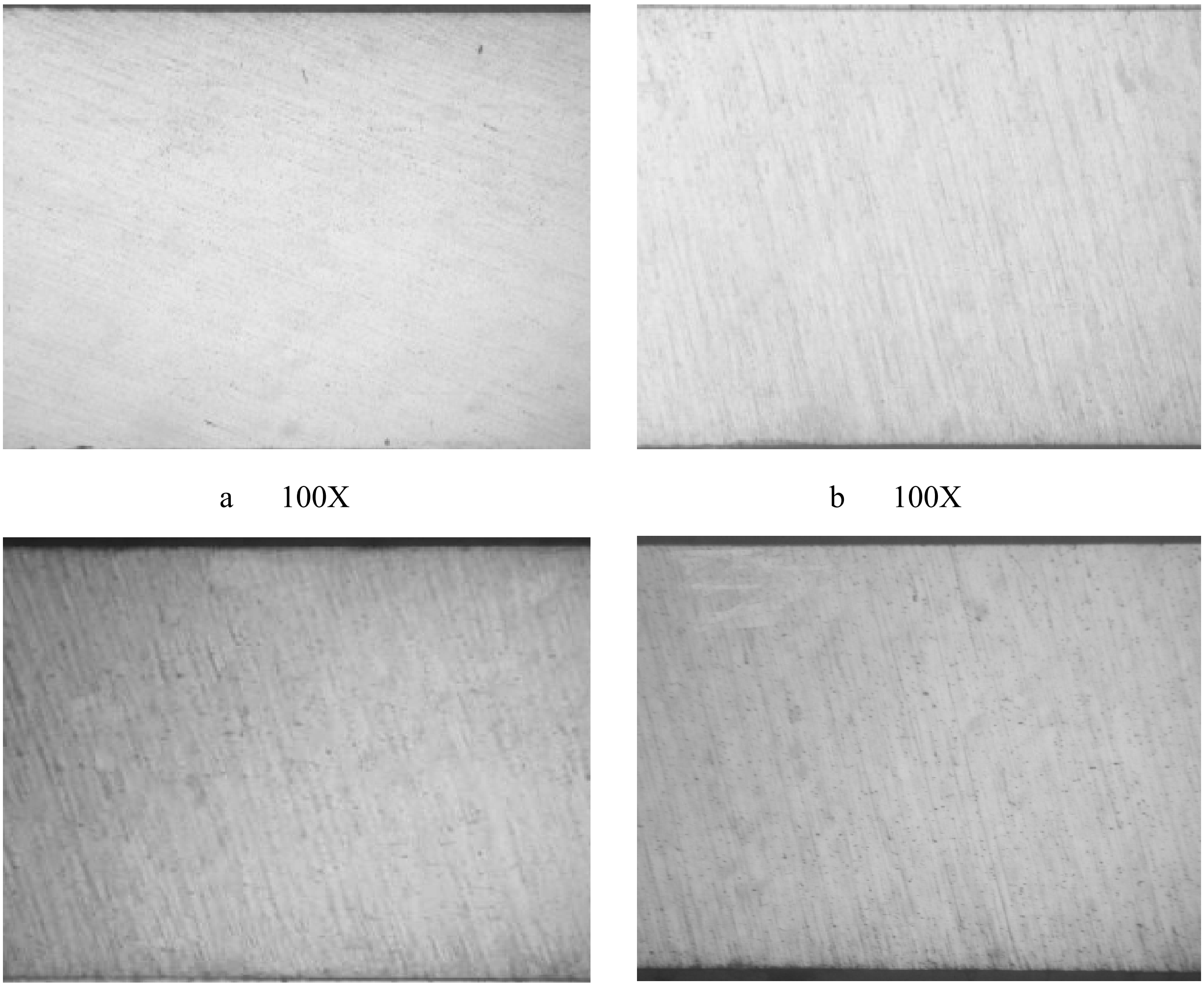
### Microstructure

The ARB process up to eight cycles has been successfully performed without shape defects of the specimen. Fig. 3 shows the optical polished specimens produced by one, three, six, and eight cycles of ARB process in rolling direction. The good bonding between the sheets was attained at every cycle of the ARB; if the rolling reduction was insufficient for bonding, the bonded interfaces between the sheets would be seen clearly. In particular, in case of the specimen of eight cycles, 127 interfaces must be observed in the half thickness. However, there are no unbonded parts of interfaces. This means that the roll-bonding was almost attained by the ARB.

After the first cycle a narrow line showing the bonding interface accompanied by aluminum and magnesium oxides particles was embedded at the center of the cross section of the roll-bonded sheet. After the third cycle, eight layers of 6061 al alloys and seven line of bond interface are created. It was difficult to identify these lines in the cross section. Though the specimen after six cycles of ARB should contains 64 aluminum layers and aluminum and magnesium oxides particles in the bond interface, we could not identify the bonding interfaces and layers. This result indicates that the aluminum and magnesium oxides particles were uniformly dispersed in the aluminum matrix, see fig. 4. In addition, these SEM micrographs suggested that the aluminum and magnesium oxides particles gradually fractured and decreased in size during the ARB process.

The microstructure of the 6061 Al alloy sheet before the ARB process is illustrated in Fig. 5. The grain size of these sheets was in range of 45 to 55 micron. The microstructural change of the produced sheets during the ARB process was observed by optical (OM) and scanning electron (SEM) microscope, see Fig 6. The microstructure of the specimen ARB-processed by one cycle has relatively large grains, elongated in the rolling direction with clear grain boundaries. As the number of ARB cycles increases, the microstructure became finer. At the early stages of the ARB, original grains were subdivided by deformation-induced boundaries such as dense dislocation walls and cell boundaries. With increasing ARB cycles, the lamellar boundaries parallel to rolling direction were introduced in the course of grain subdivision . For further cycles, the decrease in the spacing of the lamellar boundaries occurred with increasing ARB cycles and the lamellar boundaries were divided by interconnecting boundaries. Finally, in the high strain regime, the very fine grains with high angle grain boundaries, which have a pancake shape elongated along RD, were generated in the whole sample. The fraction of the very fine grained regions increased with increasing the number of cycles, i.e., strain. After 6 cycles of ARB (98.4% reduction), the whole volume of the material was filled with the very fine grains homogeneously[16,17,18]. In the examination of the microstructure by optical microscopic and scan electron microscopic, the contrast obtained by etching was insufficient for the observation of the grain boundaries after the cycle number three of ARB process. This was due to the grain size of the specimens became very small (i.e. less than 6 $\mu$m ). Therefore, another method of visualization of grain boundaries had to be sought[15,19,20]. When the specimen subjected to the tensile test at elevated temperature, the grain boundaries sliding (GBS) occurring during superplastic deformation leads to mutual shifts of grains and freshly exposed grain boundary facets may be observed at the prepolished surface. Supposing that all interfaces are concerned with the GBS process all grain boundaries should be visualized and the grain size might be determined by using SEM. Fig. 7 shows that the grain of produced sheet of 6061 Al alloy by ARB process was equiaxed grains and the size of these grains are less than three micron after eight passes of ARB process, Fig. 7 (c).

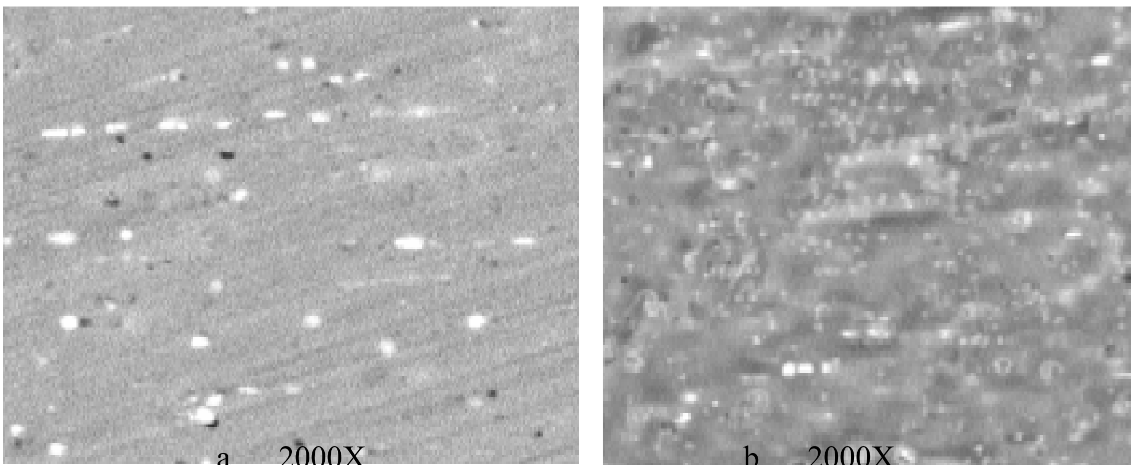
When the material is deformed in plane strain compression the structure is elongated and the grain boundaries are pushed towards each other as shown schematically in Fig 8. At elevated temperatures where the grain boundaries are mobile, and at large strain, adjacent grain boundaries may pinch off, leaving an equiaxed microstructure[21]. This continuous recrystallisation process, which is often termed geometric recrystallisation (GDR), has been observed in 6061 aluminum alloy produced by ARB process. Due to the relatively large amount of manganese in the 6061 Al alloy, this alloy contains a significant distribution of second phases and oxide particles formed during ARB cycles which facilitates the production and the stability of the fine grains. The largest second phase present through the material act as sites for nucleation of recrystallisation while the smallest pin the migrating grain boundaries and consequently hinder grain growth.



a 100X b 100X

c 100X d 100X

Fig.3 Optical micrographs of the plane perpendicular to the transverse direction of the specimens ARBed by: (a) one; (b) three; (c) six; and (d) eight cycles.



a 2000X b 2000X

Fig.4 SEM micrographs showed the disoperation of oxides particles during ARB process: a) three, b) eight cycles.

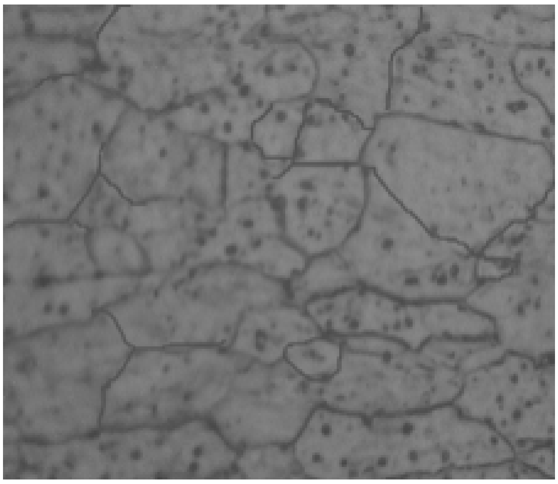
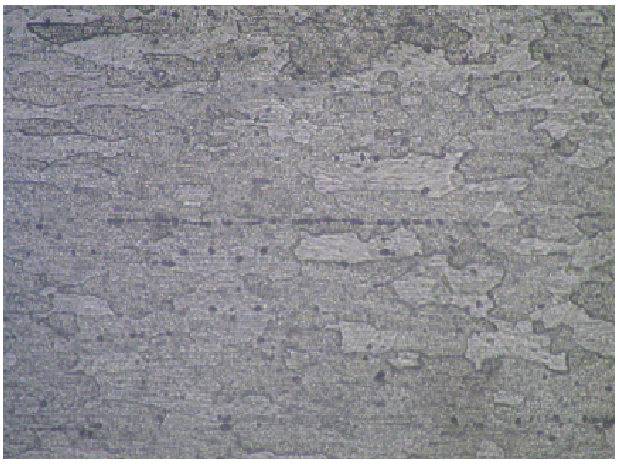
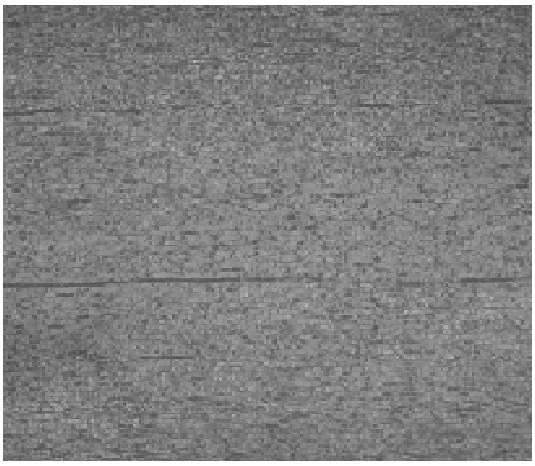


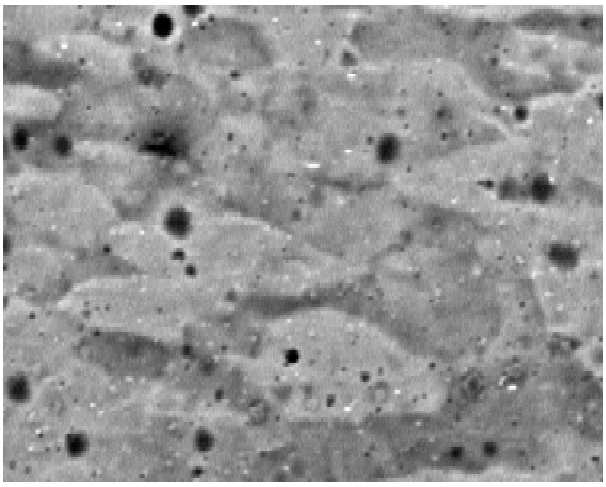
Fig.5 The microstructure of 6061 Al alloys before subjected to ARB (OM, 200 X)



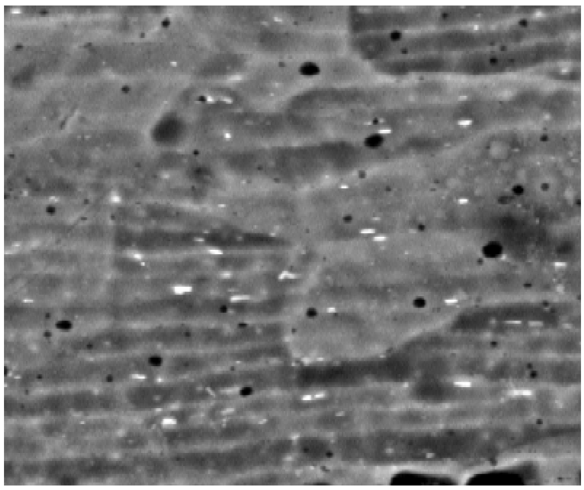
a) OM 500 X



b) OM 500 X

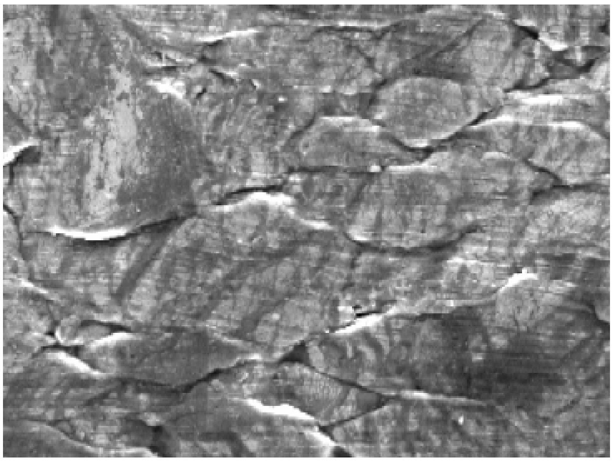


c) SEM 1200 X

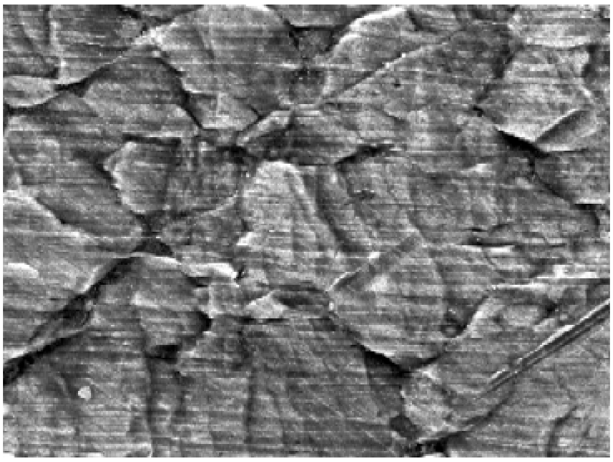


d) SEM 1200 X

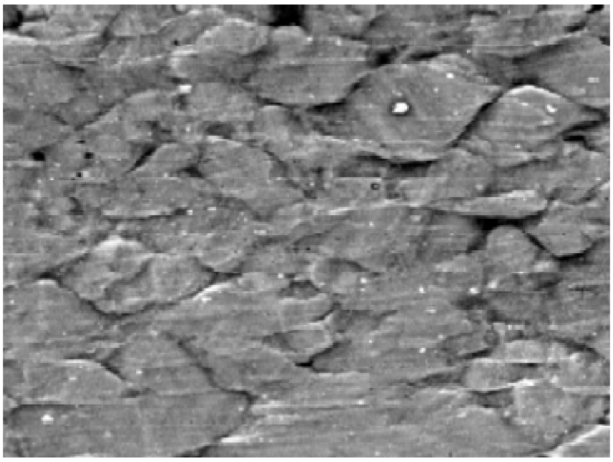
Fig.6 The microstructure of the ARB specimens after; a)one , b) three, c) three, d) eight cycle in the rolling direction.



a) SEM 2000 X



b) SEM 2000 X



c) SEM 2000 X

Fig.7 SEM micrographs of the ARB specimens after; a)four , b) six, c) eight cycle in the rolling direction

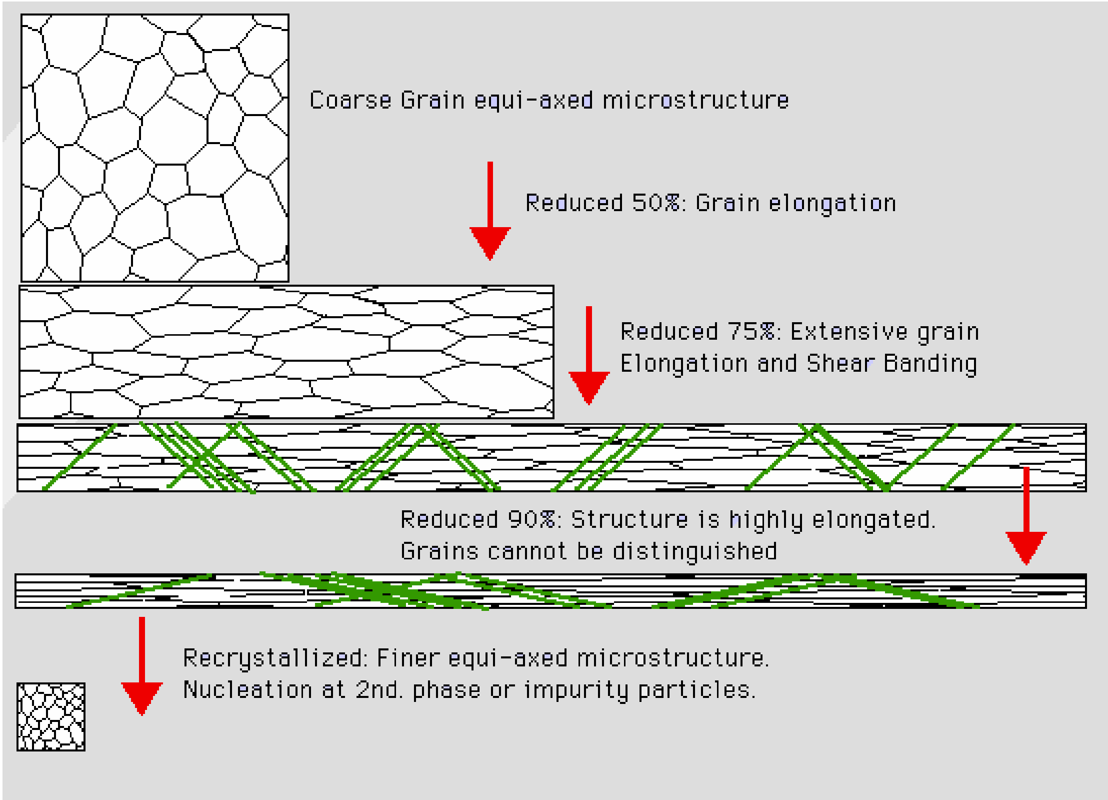



Fig.8 Grain Refinement Mechanism by hot working in one phase alloy [21]

The ARB process has been carried out without lubrication to gain a sound bonding. This means that a redundant shear strain is introduced being largest at the surface and giving rise to a location dependent shear strain through the sample thickness. Upon further stacking and rolling surface regions will be transferred into the sample interior. As a result, the shear strain at a given location will be accumulated. This shear strain is distributed in a complex pattern, however, with variation on a finer and finer scale as the number of rolling cycles is increased. Large shear strains are introduced through the sample thickness in the ARB process. Therefore, for the ARB samples the deformation is a combination of a rolling strain and a shear strain which may increase the local strain above the nominal strain corresponding to the thickness reduction. It should be pointed out that the details of the industrial rolling used for comparison to the ARB are not known. However, the texture measurement for the conventionally rolled thin sheets showed a typical rolling texture at high strains, indicating that a homogeneous rolling has been performed. The introduction of a shear strain may also alter the slip pattern from that which characterizes conventional rolling. This is supported by the observation that the texture evolution differs significantly between the samples deformed by ARB and by rolling. However, there is at present no established correlation between slip pattern and microstructural characteristics which can rationalize in more detail the observed differences between ARB samples and rolled samples[22].

**Tensile properties of the ARB processed sheets**

Nominal stress–strain curves of the ARB processed AA6061 sheets after hot rolling process at different ARB cycles are shown in Fig. 9. The ultimate tensile strength (UTS) level monotonously increased with increasing ARB cycles. The total elongation decreased with increasing the ARB cycles until 4 cycles, thereafter the total elongation began to increase slightly with increasing the ARB cycles. For example the UTS increased due to the ARB process for one cycle ($\xi_t$= 0.8) from 120 MPa (sheets in full annealed condition) to 170 MPa and fracture within 12 per cent of strain. However, after 3 cycles ($\xi_t$= 2.4), the flow stress increased slowly when the number of the cycles increased. The stress–strain curves showed nearly steady state, which indicated that they performed a large amount of substantially uniform deformation. The range of the steady-state increased with increasing number of the ARB cycles, so that the total elongation significantly increased up to 10 % after 8 cycles ($\xi_t$ = 6.4). These trends of strength correspond well with the reduction of the grain size, which suggests that the strength of the ARB processed AA 6061 alloy sheets is determined primarily by the very fine grained structures. At the same time, however, dislocation strengthening, solution strengthening and precipitation hardening must also affect the strength of the AA6061 alloy sheets.

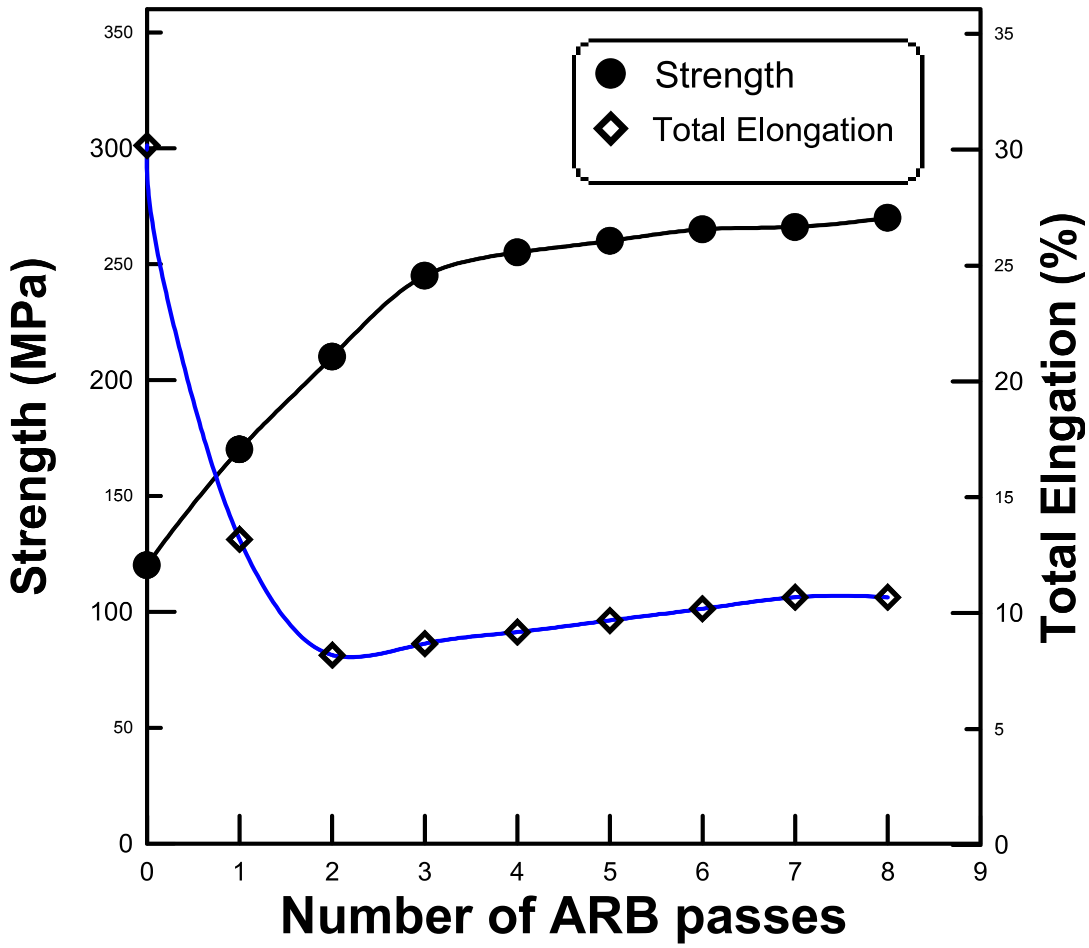



Fig.9 Tensile properties of the ARB processed at 500 $^{o}$C

## 4. CONCLUSIONS

The present results clearly showed that fine grained 6061 aluminum alloys with surprising strength can be easily obtained by ARB process. It is practically very important because rolling is the most appropriate process to produce the bulk materials. If this process were applied to practical use, we could obtain high-strength materials without using alloying elements by a simple process without complicated thermomechanical treatment. This satisfies the recent social demands of recycling and energy saving.

In addition to the grain refinement, the precipitation hardening by the precipitates formed during holding and rolling at 500 °C and the dispersion hardening by oxides which form on the surfaces and are taken inside during the repetition of stacking and roll-bonding would contribute to the strengthening to some extent in the present case.

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