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Producing Ultrafine Grain Al6061 Alloy by Accumulative Back Extrusion Process

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Accumulative back extrusion (ABE) is a kind of severe plastic deformation process to refine the microstructure, resulting in significant improvement in mechanical properties. In the present study, AA6061-T6 alloy was subjected to a newly designed ABE process at room temperature. One cycle of ABE was employed to the workpiece. The microstructural evolution was then characterized using optical microscopy and transmission electron microscopy (TEM) techniques. The results show that after one cycle of ABE, significant grain refinement was achieved. This led to the formation of ultrafine grains of smaller than 1 µm. Besides, there was about a two-fold increase in the hardness, increasing from approximately 88 Hv to 155-160 Hv after only one cycle of ABE.

Keywords 6061 aluminum alloy, accumulative back extrusion (ABE), ultrafine grain

1. Introduction

Ultrafine grain (UFG) materials with the grain size less than 1 µm exhibit superior mechanical properties compared to their coarse grain counterparts. The demand for the materials with high toughness and high strength has recently resulted in developing of new techniques in this regard. One practical and effective approach to produce the UFG materials is severe plastic deformation (SPD) (Ref 1-5). To overcome the shortcomings of conventional methods, they are modified, and the new SPD techniques have been developed (Ref 6-12). Among the conventional SPD techniques, equal channel angular pressing (ECAP) has been widely used because it is an effective and practical approach in producing UFG structures. Besides, it is almost the only process that can produce bulk UFG structure materials with the dimensions required for industrial applications (Ref 13-16). However, it should be considered that SPD is not the only technique used to produce bulk nanostructured or UFGed materials. For example, Dehghani and co-workers reported the production of bulk nanostructured aluminum alloys Al6061 and Al413 using melt-spinning method (Ref 17, 18).

1.1 Background of Accumulative Back Extrusion (ABE)

As ABE is a new extrusion technique, introduced for the first time in 2009 (Ref 19), there are not many studies in the literature in this regard. ABE is a kind of SPD in which the back extrusion (BE) and compression are carried out cyclically. As the BE and compression are performed many times on a workpiece, the term accumulate is adopted to differentiate it from the conventional extrusion process. The applied cyclic extrusion and compression leads to extensive grain refining. That is because of severe plastic deformation or accumulated strain introduced into the workpiece as the material undergoes several extrusion-compression cycles. One significant advantage of ABE over BE is the absence of cracks and porosity. Besides, it has been reported that ABE can be a very effective technique in producing the materials with ultrafine grains (UFGs) (Ref 19). As for the past studies on ABE, there are only a few of them, e.g., from the Fatemi-Varzaneh and Zarei-Hanzaki (Ref 19) on AZ31 magnesium alloy and Faraji et al. (Ref 20, 21) on AZ91 alloy. Fatemi-Varzaneh and Zarei-Hanzaki (Ref 19) applied the ABE to obtain ultrafine grains (about 1 µm) in AZ31. The grain refinement was attributed to the occurrence of dynamic recrystallization as well as to the changes in the strain path from the first half cycle to the second one (i.e., from shearing in BE to constrained compression). In another study (Ref 22), they studied the effect of shear stresses on the grain refining during the ABE of AZ31. According to their results, the distribution of shear stress during the BE was nonuniform. However, in the compression step, the distribution of shear stress was relatively uniform. As observed, all the past studies on ABE are pertaining to the AZ31 or AZ91. Thus, there is no study concerning the application of ABE to produce other UFG aluminum alloys including AA6061, which is the aim of present study. Besides, in the present study, a new ABE design is introduced to have a more homogenous structure after ABE.

2. Experimental Procedure

2.1 Materials

The AA6061-T6 with its composition and properties given in Table 1 was used in this study. The initial grain size was about 100 µm (Fig. 1). The cylindrical specimens of 20-mm diameter and 8-mm height were subjected to ABE. To reduce

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the friction between the workpiece and tool, a layer of graphite was used. The ABE was then carried out at room temperature.

2.2 Accumulative Back Extrusion Process

Back extrusion (BE) is a kind of indirect extrusion process, during which a hollow ram is used. As the ram is pushed into the workpiece, the material is extruded out through the die in the opposite direction. This process has the advantage that there is no relative movement between the container wall and the workpiece so that the friction and the required force are minimized. However, the use of a hollow ram limits the loads that can be applied. An advanced method to overcome such shortcomings of BE process is ABE (Fig. 2) used to produce the materials with enhanced mechanical properties.

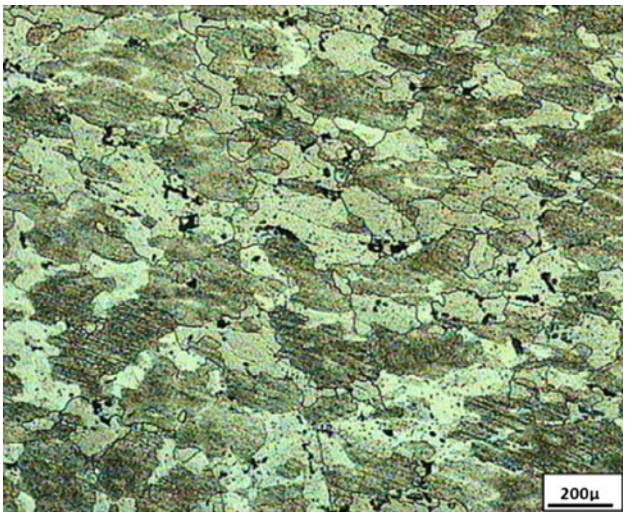

Fig. 1 Optical micrograph presenting the initial structure of AA6061 before ABE

The developed ABE used in the present study is illustrated in Fig. 2. In order to carry out the ABE, the workpiece is first placed into the die cavity, followed by the BE of workpiece into the gap between the punch and the die. This is the end of step 1 or a half cycle of process. Then, the workpiece is extruded back, but this time by the outer punch, as shown in the step 2 of Fig. 2. This results in moving the inner punch upward. The required force to push the inner punch upward is provided by the workpiece being deformed by the outer punch. The step 2 ends when the workpiece gets flattened, i.e., turning back to its initial shape again. At this stage, the first cycle is over (Fig. 2). It is of interest to note that there is no change in the shape of workpiece at the end of first cycle. In other words, the shape of workpiece at the end of step 2 is the same as that at the beginning of step 1, while the workpiece has undergone severe plastic deformation. This process (i.e., steps 1 and 2) can be repeated many times so that ABE results in a UFG structure. The dies, punches, and the workpiece (after step 1) processed by ABE are shown in Fig. 3.

2.3 Microstructural Evaluation

The microstructural evaluations after the ABE were characterized using transmission electron microscopy (TEM) and

Table 1 The composition and properties of studied AA6061

Material	Chemical composition, wt.%	Temper	Tensile strength, MPa	Yield strength, MPa	Elongation, %	Hardness, Hv
AA6061 aluminum	0.16Fe,0.19Cu,0.71Si,0.04Zn,0.02Mn, 0.94Mg,0.08Cr,0.03Ti,0.01Other	T6	260	240	11	88

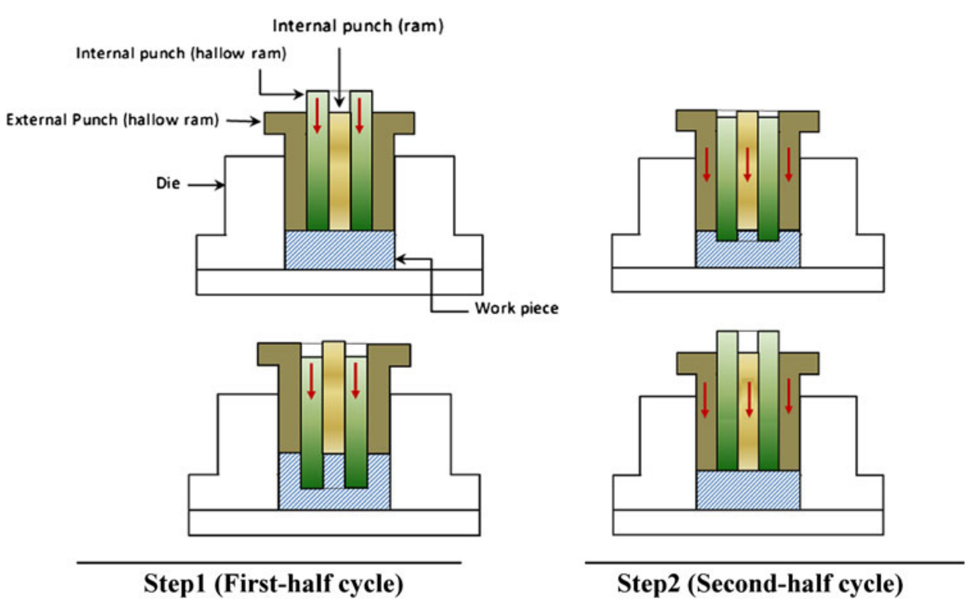

Fig. 2 The principles of ABE process used in the present study

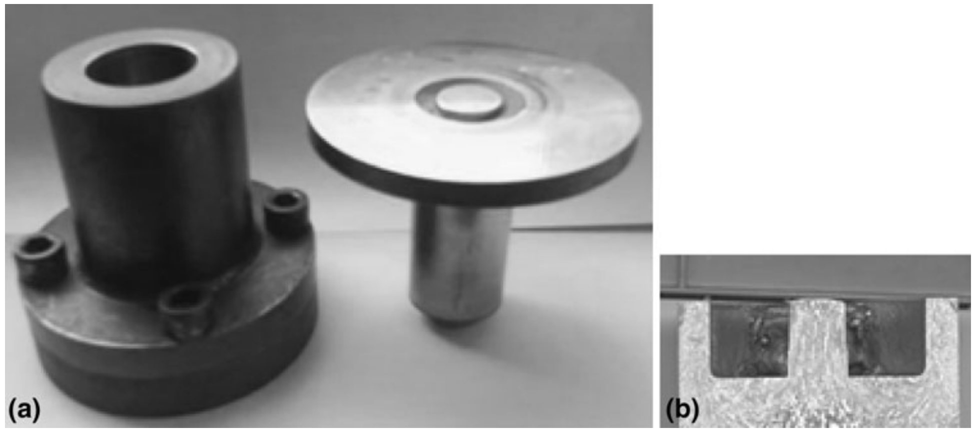

Fig. 3 (a) Die setup and (b) Cross section of the processed sample during ABE (first-half cycle)

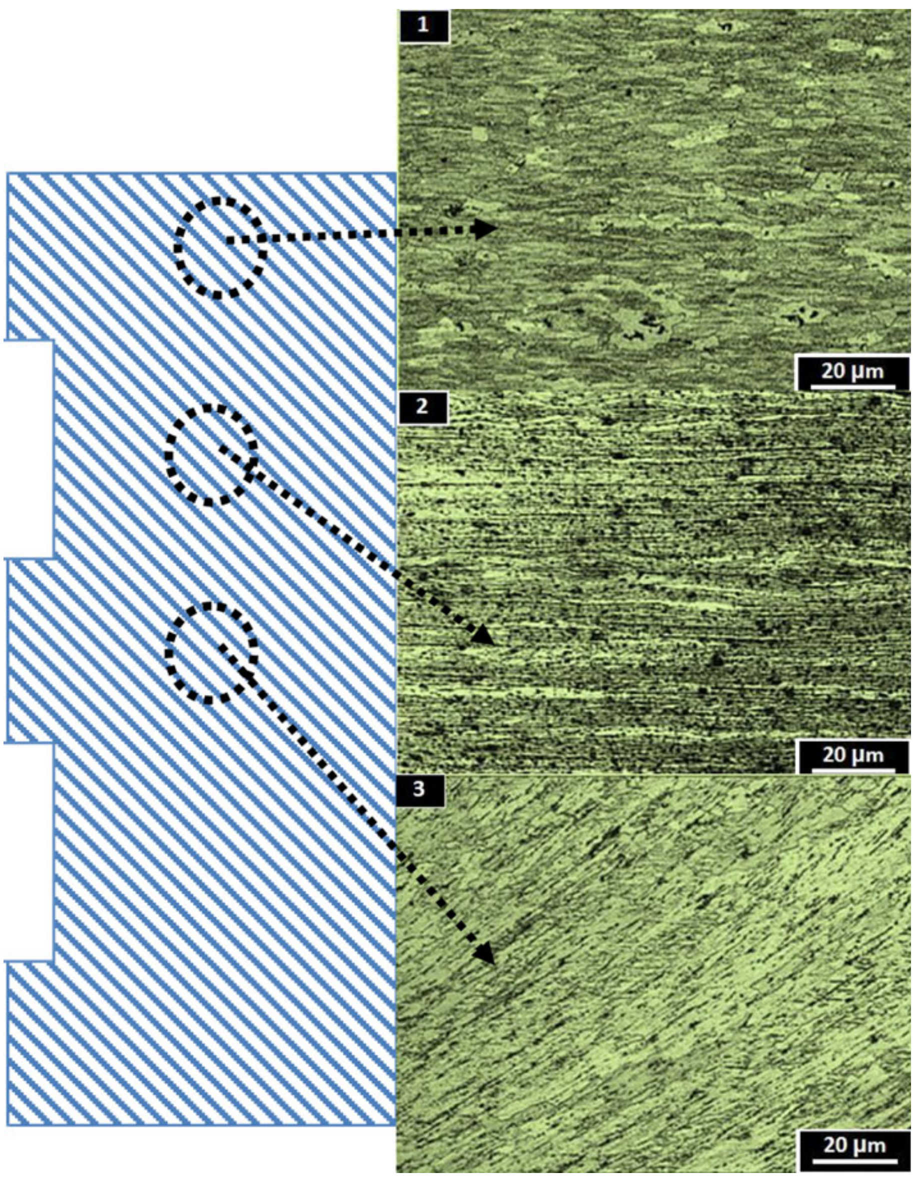

Fig. 4 The changes in the microstructure of workpiece during ABE

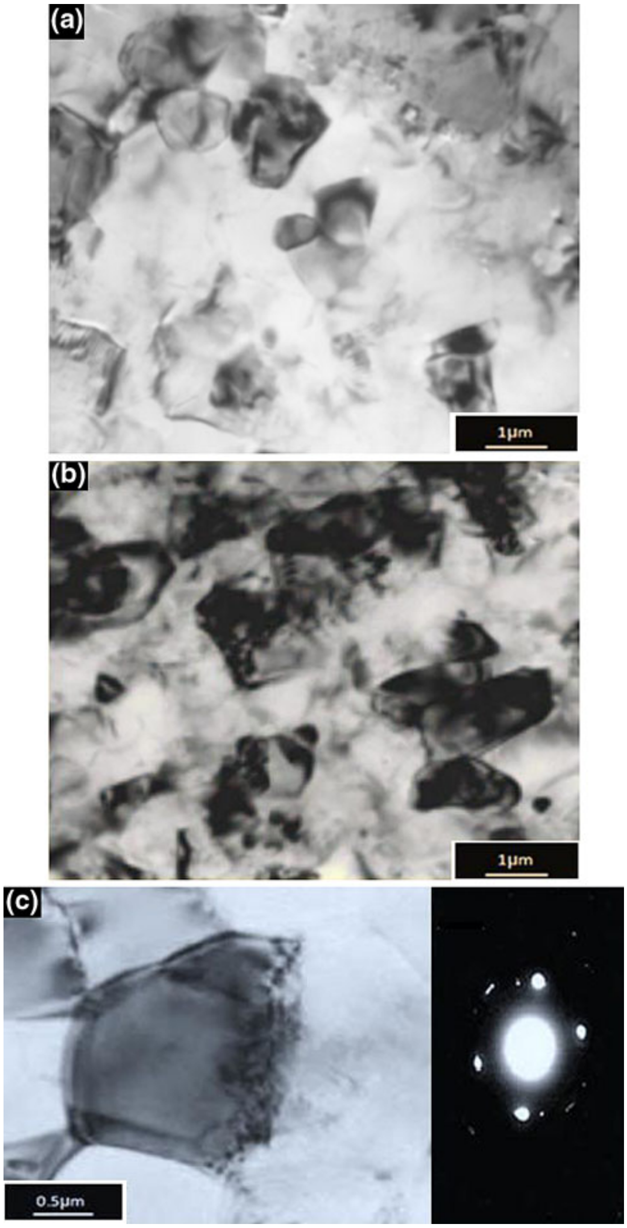

Fig. 5 TEM micrographs of AA6061 alloy after ABE; the UFG structure formed in the center of sample (a) and edge of sample (b), and (c) The SAD pattern indicating the misorientation existing between individual grains

optical microscopy (OM). The TEM specimens were prepared by electropolishing. Philips-FEG TEM microscope was used to study the changes in microstructures. Etching of the OM samples was carried out electrically using a solution of 110 mL perchloric acid (60%), 550 mL ethyl alcohol and 140 mL distilled water.

2.4 Microhardness Measurement

Vickers microhardness (Hv) test was carried out using a load of 0.3 kg for 10 s. The hardness measurements were performed on the radial direction of the ABE-processed samples. The average of 20 measurements was reported as the hardness.

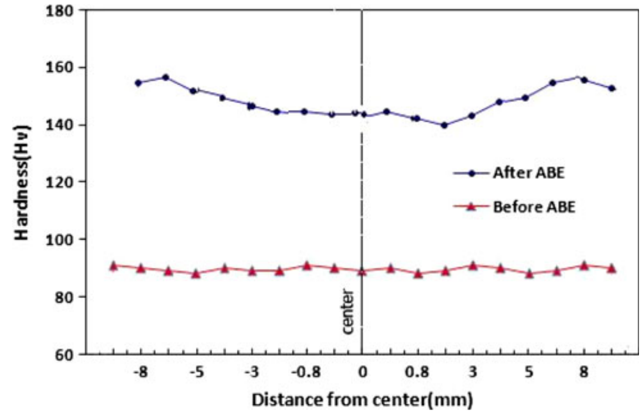

Fig. 6 The hardness profiles of the workpiece before and after ABE

3. Results and Discussions

3.1 Microstructure of ABE-Processed Aluminum

The changes in microstructure during ABE are shown in Fig. 4. Obviously, the ABE led to significant grain refinement. That is because the initial grain size of about 100 µm are broken down to the grains about 1 µm. Besides, the microstructure exhibits a homogeneous distribution of grain. It should be considered that such a microstructural refinement and a homogeneity are achieved by only one pass of ABE. The shear forces play the main role in grain refinement during severe plastic deformation via ABE. The dominant mechanism for grain refining is the shearing and/or the subdivision of the elongated grains (Ref 20).

The TEM images taken from the sample subjected to one ABE cycle are shown in Fig. 5. The TEM studies also confirm the production of UFG structure consisting of high angle grain boundaries formed by ABE. Figure 5(a) and (b) illustrates the UFG structures, with the average grain size of about 1 µm, formed in the center and edge of samples, respectively. The formed microstructure exhibits a homogenous distribution of equiaxed grains having distinct and sharp boundaries. The TEM results also clearly indicate that the ABE can successfully refine the grains and produce UFG structures in the present AA6061 alloy. As pointed out, this structure is obtained just after one cycle of ABE process. Figure 5(c) shows a higher magnification of Fig. 5(b), representing the ultrafine grains surrounded by strongly deformed boundaries along with its SAD pattern. According to Fig. 5(c), the grain boundaries are consisted mainly of subgrains and/or dislocation cell structures, though the dislocation density is much lower inside the grains. In other words, the microstructure after one cycle consists of recrystallized grains having dislocation tangles at their grain boundaries (Fig. 5c). The present results are similar to those regarding the formation of ultrafine grains in AA1100 and AA5083 processed by SPD (Ref 22).

During ABE, the main deformation mechanism is extensive slip in various grain accompanied by the rearrangement of dislocations into the random and geometrically necessary boundaries. As the strain increases, the random boundaries form a substructure having high-angle cells, whereas the geometrically necessary boundaries transform into deformation bands. Consequently, the misorientation angle increases and shear-band rotation occurs in the direction of the principal strain. This phenomenon leads to the formation of high-angle boundaries and the microstructures characterized by pancake/elongated grains (Ref 22). Also, it is worth noting that grain boundary sliding under shear stress can be another dominant deformation mechanism during ABE.

The mechanism of the UFGs formation during the SPD is still an issue under discussion. However, recent investigations suggested that the formation of UFGs is because of continuous dynamic recrystallization (CDRX) as well as grain subdivision. In such a case, the occurrence of extended dynamic recovery may result in the formation of distinct sub-boundaries and short-range grain boundary migration. For example, it has been reported (Ref 23) that the occurrence of CDRX led to the formation of both nanograins and ultrafine grains during the friction stir processing (FSP) of AA5083. CDRX is normally the dominant restoration mechanism in the case of materials with high stacking fault energy (SFE) such as aluminum alloys (Ref 23).

The continuous changes in the grains misorientation can result in high-angle boundaries via the rearrangement of the geometrically necessary dislocations and short-range diffusion. In case of aluminum alloys, short-range diffusion is possible even at ambient temperature because of the deformation heat generated by severe plastic deformation. Besides, the redundant shear strain due to friction between the die walls and the specimen plays an important role in the grain refinement by ABE. The role of redundant shear strain in grain refining has been considered in terms of equivalent strain, strain gradient, and strain path (Ref 24).

3.2 Changes in Hardness During the ABE of AA6061

Figure 6 shows the changes in the microhardness of AA6061 before and after ABE. The hardness of specimen before ABE is a constant value. However, there is almost a two-fold increase in the hardness after one cycle of ABE, i.e., reaching to 155-160 Hv from the initial amount of about 88 Hv.

The increase in microhardness at relatively low strains can be attributed to strain hardening (i.e., increase in density of dislocations and their interactions), subgrain boundaries and/or cell wall formation rather than grain refinement (Ref 25, 26). Generally speaking, aluminum alloys can be strengthened by four different mechanisms: (i) solid-solution strengthening, (ii) precipitation hardening, (iii) grain refining, and (iv) strain hardening. However, the contribution of each mechanism depends on the alloy composition and characteristics (e.g., heat treatable or non-heat treatable), dominant restoration mechanisms, and the severity of deformation (Ref 27). Among the aforementioned mechanisms, it is likely that the formation of ultrafine grains and strain hardening (due to severe plastic deformation) exhibit the major contributions in the hardening of the AA6061 processed by ABE.

As for the effect of ABE parameters on the homogeneity of produced microstructure, the penetration of inner punch plays an important role in this regard. The effect of penetration depth in backward extrusion was investigated by Moshksar and Ebrahimi (Ref 28, 29). According to their results, by controlling the amount of penetration, a homogeneous structure can be obtained after the extrusion. One of the advantages of ABE is that such a bulk homogenous structure cannot be achieved easily via the other SPD processes.

4. Conclusions

The microstructure and mechanical properties of AA6061 subjected to ABE (as a new SPD technique) were investigated. The main results are summarized as follows:

1. ABE can be considered as a novel method for severe plastic deformation in producing bulk materials with UFG.
2. The results showed that only one cycle of ABE process at room temperature led to significant grain refinement of AA6061.
3. Microstructural evolutions indicated a homogeneous distribution of grain size after one cycle of ABE.
4. The initial grains of 100 μm were reduced to the ultrafine grains of about 1 μm after ABE.
5. There was almost a two-fold increase in the hardness of workpiece, increasing from about 88 Hv to 155-160 Hv after ABE.

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