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Short Communication

Combination of sever plastic deformation and precipitation hardening processes affecting the mechanical properties in Al–Mg–Si alloy

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A B S T R A C T

Sever plastic deformation processing has been frequently used to refine grain size and to improve properties in metals and alloys. The impact of combination of equal channel angular pressing (ECAP) and precipitation hardening on mechanical properties of 6063 aluminum alloy was investigated in this paper. These two processes were also tested individually in order to know if the combination affects the microstructure and tensile properties. According the experimental results, the yield and ultimate strength increase twice and three times respectively after ECAP processing. Having the processed samples naturally aged, the microstructure and mechanical properties remain almost unchanged. However, artificial aging at 180 °C after ECAP, improves the ductility of the material and decreases the strength slightly due to dislocation annihilation occurring during heat treatment. It can be deduced that individual processes of ECAP and aging enhance some mechanical properties and worsen some others; but combination of these processes improves the material's properties. In order to compare quantitatively the overall mechanical properties a new factor, denoted by SNMP, is introduced which is the Sum of Normalized Mechanical Properties. According to the results, the value of SNMP for combination of processes is much higher than that for individual processes.

1. Introduction

Aluminum–magnesium–silicon alloys (Al–Mg–Si; also denoted as 6xxx series), are medium strength, heat treatable alloys with good formability and corrosion resistance [1] which makes them good candidates for automotive, aerospace and construction applications. In most of the applications, both work hardening and precipitation strengthening are important contributors of strength [2,3]. Additional strengthening mechanism i.e. grain refinement by severe plastic deformation (SPD) processing, is highly desirable for the applications.

Many severe plastic deformation processes have been proposed recently for local grain refinement [4] or for bulk grain refinement processing [5]. Equal-channel angular pressing (ECAP), first introduced by Segal [6] in the late 1970s, is one of the most promising SPD techniques for processing of bulk ultrafine-grained materials [5–19]. The process is limited to batch mode operation and can be performed in a single or multi pass approach. ECAP grain refinement retains the initial geometry and dimensions of the work piece and therefore is a zero shape change process. Unlike the conventional metal forming processes, for instance cold rolling or drawing, SPD processing techniques produce very large strains in their samples. Iwahashi et al. [8] developed a theoretical equation for maximum plastic strain achieved in workpiece by ECAP. The accumulated strains could lead to high-angle grain boundary and granular structure in the material with average grain sizes less than ~1 μm [5,6,13,14]. These submicrometer polycrystals with strain hardening is responsible for tremendous property changes in the processed material.

The mechanism of grain refinement of pure aluminum during ECAP process was experimentally investigated by Zhu and Lowe [9]. Murayama et al. [15] studied the microstructural evolution of precipitation hardened Al–1.7 at.% Cu alloy after equal-channel angular pressing. They used transmission electron microscopy (TEM) and energy filtered transmission electron microscopy (EF-TEM) to investigate the feasibility of further strengthening of deformed material by aging. Chaudhury and coworkers [10] used the AA6061 samples processed by ECAP as ingots for extrusion and forging. They found this as an efficient way to improve workability and to reduce the forming defects. Zheng et al. [16] studied the influence of annealing and aging on the structures and properties of 7050 Al alloy produced by equal channel angular pressing. They concluded that pre-ECAP quenching and post-ECAP aging was most effective in improving strength. Behavior of nano-structured AA6082 under upsetting tests was examined by Agena [17].

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He observed that the flow stress of the material depends on the number of passes and the direction of the processing axis. Vaseghi and Kim [18] studied the static and dynamic aging during warm ECAP of AA6082. They presented an optimum aging cycle to achieve maximum hardness in deformed material. The effects of the two pressing routes B_C and C in ECAP on the mechanical properties and microstructure of commercially pure 1050 aluminum were investigated by El-Danaf [13]. Zhu et al. [19] studied the microstructure and mechanical properties of the commercial pure Cu with large grains processed by equal channel angular pressing. They found that the final grain size and microhardness of material depends on the initial grain size.

ECAP studies have been mostly limited to mechanical analyses of the technique. Moreover, the influence of heat treatment on ECAPed samples has not been studied principally. It is well known that both sever plastic deformation and precipitation hardening strengthen the material through different mechanisms. Also, improvement in strength usually leads to decrease in ductility. While the combination of these processes is employed, some competitive phenomena occur in the microstructure. The aim of present work is to study not only the mechanical properties of 6063 aluminum alloy samples processed by multi pass ECAP, but also the impact of precipitation hardening on ECAPed specimens resulting in improvement of both strength and ductility.

2. Materials description and experimental procedures

Table 1 shows the chemical composition of 6063 aluminum alloy used in this study. The 6xxx series aluminum alloys, can be heat treated to produce precipitation in various degrees [2,20]. Mg and Si are the major solute elements in this series of aluminum alloys and responsible for increasing the strength of the alloy by precipitation hardening.

In the present work, the microstructural and mechanical properties changes during SPD individually and in combination with heat treatment have been studied.

2.1. Heat treatment

In order to obtain the optimum precipitation hardening conditions, some samples were subjected to solution treatment at 520 °C for one hour followed by water quenching. Natural aging (T4) was performed for 30 days and artificial aging (T6) carried out at 180 °C for 1, 2, 3, 4, 6, 8, 10 and 12 h using resistance furnace.

2.2. Multi passes ECAP processing

In this study, sever plastic deformation was carried out through equal-channel angular pressing. The ECAP samples were taken from AA6063-O rods which had a diameter of 20 mm and a length of 120 mm. In O temper, the material is annealed to obtain the lowest strength. Fig. 1 shows a simple ECAP die with the channel angle ($\Phi = 90°$) and the outer corner angle ($\Psi = 20°$). Both of circular channels are 20 mm in diameter. For the given configuration, a maximum effective strain of 0.976 can be achieved when a single pass is applied. The strain value is estimated using the models developed by Iwahashi and coworkers [8]. The ECAP die was manufactured from two assembled tool steel blocks. Four passes of ECAP were conducted through the B_C route in which the sample is rotated by 90° around the longitudinal axis between subsequent pressings. It has been reported that deformation in B_C route results in smaller grain size and higher hardness and yield strength values [5,13]. The workpieces were lubricated using MoS_2. Pressing was performed with a speed of 1 mm/s at room temperature without back pressure.

Table 1
Chemical composition of 6063 aluminum alloy (wt.%).

Mg	Si	Cu	Fe	Zn	Ti	Al
0.51	0.28	0.02	0.16	0.04	0.02	Bal.

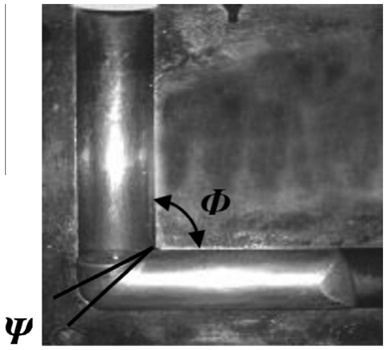

Fig. 1. Photograph of the die for equal-channel angular pressing.

In order to study the influences of combination of SPD and heat treatment on the mechanical behavior of material, different thermal–mechanical combinations have been considered. These conditions are listed in Table 2.

Tensile test specimens were machined from the thermally and (or) mechanically treated ECAP samples according to ASTM: B557M specifications. The long axis of the test specimens was parallel to the longitudinal axis of ECAP workpiece. The gauge length and gauge diameter were 45 mm and 9 mm, respectively. Tensile tests were performed at room temperature with a crosshead speed of 1 mm/min. Stress–strain curves were then analyzed to determine yield strength, ultimate tensile strength, fracture strength and elongation. Vickers hardness was measured with 1 kgf load to indent the samples. The reported hardness values represent the average of at least three measurements. The microstructure evolution of the samples was studied using scanning electron microscopy (SEM) with the attachment of an X-ray energy dispersive system (EDS).

3. Results and discussion

3.1. Individual processing of ECAP/aging

In order to compare the mechanical properties of ECAPed samples with heat treated samples, raw material (R.M.) subjected to ECAP at room temperature, solution treatment and T4, T6 treatment individually. The results are presented in Fig. 2. As illustrated in these figures, heat treatments do not change the strength and hardness of the material considerably; however the strength of material increases dramatically after sever plastic deformation. It is due to two strengthening mechanisms i.e. grain refinement and strain hardening occurring during equal-channel angular

Table 2
Different thermal–mechanical treatments used in this study.

Sample	Description
S	Solution treatment at 520 °C + water quenching
ECAP	At room temperature
T4	Natural aging for 30 days
T6	Artificial aging at 180 °C, 8 h
S + ECAP	Solution treatment + ECAP
S + ECAP + T4	Solution treatment + ECAP + natural aging for 30 days
S + ECAP + T6	Solution treatment + ECAP + artificial aging at 180 °C, 1 h