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Review

Effects of heat treatments on AA6061 aluminum alloy deformed by cross-channel extrusion

Cheng-Yu Chou[a], *Che-Wei Hsu*[a], *Sheng-Long Lee*[b,*], *Kuan-Wen Wang*[c], *Jing-Chie Lin*[b]

[a] *Department of Mechanical Engineering, National Central University, Jhongli, Taiwan*
[b] *Institute of Materials Science and Engineering/Department of Mechanical Engineering, National Central University, -Jhongli, Taiwan*
[c] *Institute of Materials Science and Engineering, National Central University, Jhongli, Taiwan*

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ABSTRACT

In this study, the relationship between microstructures and mechanical properties of the cross-channel extrusion (CCE) processed AA6061 alloy caused by different heat treatments were investigated. The ultimate tensile strength of the homogenized AA6061 can be strengthening to 194 MPa after extruded at 448 K for 8 passes. After T6 treatment, the strength was increased from 194 to 323 MPa caused by the formation of fine precipitates; however, the grains were coarsened. The Post-CCE aging treatment was applied on AA6061 alloy that the alloy was processed in supersaturated state at 448 K for 8 passes, and then artificial aged. A higher tensile strength of 364 MPa which is 13% higher when compared with the T6 treated sample was obtained since it consisted of fine-grained matrix with grain structure size of 0.2–0.5 μm and precipitation hardening effect. It demonstrates that the Post-CCE aging treatment is a suitable method for producing a heat treatable Al alloy with improved strength when applied to CCE process.

Contents

* *Corresponding author*. Tel.: +886 3 4267325; fax: +886 3 4254501.
E-mail address: shenglon@cc.ncu.edu.tw (S.-L. Lee).
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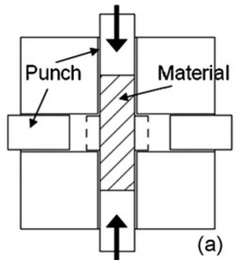

Fig. 1 – Schematic diagram of cross-channel extrusion process. The diagram is defined as 2 passes extrusion. The coordinate of sample is defined in (d).

1. Introduction

The development of producing bulk ultra-fine grained (UFG) materials by imposing severe plastic deformation (SPD) has received much attention over the last few years. Several methods were designed to produce UFG materials by accumulating strains without changing the initial dimension of the material, such as equal channel angular extrusion (ECAE) (Lee et al., 2007a; Sun et al., 2000), reciprocating extrusion (Chu et al., 2001; Lee et al., 2007b), rotary-die equal channel angular pressing (RD-ECAP) (Kim et al., 2003; Ma et al., 2005), etc. Cross-channel extrusion (CCE) (Chou et al., 2008; Chou et al., 2007) is a new method which is designed to improve the process of manufacturing a bulk fine-grained material.

A commercial AA6061 aluminum alloy is one of the Al—Mg—Si(—Cu) system alloys that can be significantly hardened by a proper heat treatment. Because of its medium strength, excellent corrosion resistance, and weldability, the AA6061 alloy has been widely used as structural material for construction, transportation and sports (Engler and Hirsch, 2002). In order to produce UFG material with fine precipitates in the matrix, the pre-ECAP heat treatment was purposed by Ferrasse et al. that the ECAP processed peak-aged material exhibited much higher strength than the ECAP processed over-aged material (Ferrasse et al., 1997). Kim et al. also reported a post-ECAP heat treatment method to lower extrusion load and extrusion temperature for ECAP (Kim et al., 2001). The purpose of this study is to investigate the effects of Post-CCE heat treatments on the microstructures and mechanical properties of AA6061 aluminum alloy produced by the CCE process. Another objective is to increase the possibility for industry application and also to obtain mass-producible material with improved mechanical properties.

2. Experimental procedure

The CCE die was made of SKD61 steel with two channels intersected to form a cross-shaped channel in the center of the die. The diameters of channels are fixed at 22 mm. The cross-section of CCE die is illustrated in Fig. 1 which also demonstrates the 2-pass deformation procedure (Chou et al., 2007). The sample can be deformed by two pairs of cylindrical punches which match with the four channels at each side of the die. As shown in Fig. 1a, the sample was inserted into the center of vertical channel, then, it can be deformed to the horizontal channel (Fig. 1b) by the inserted vertical punches. The sample was again deformed to the initial site by the horizontal punches, as shown in Fig. 1c. By fixing the horizontal punches, it can be rapidly removed out of the die by the upper punch (Fig. 1d). And then, a new sample can be reloaded and another new extrusion procedure starts.

For ECAE method, it has been known that the materials was shear stressed when it passed by the intersection plane of an L-shaped channel. The pressed billet has to be removed from the die and re-inserted into the die for the next pass, often after machining the billet to fit the channel size and re-heating it, which may resulted in the waste of time for production. To improve efficiency, Nishida et al. (Ma et al., 2005) have developed a new method using a rotary die, namely rotary-die equal-channel angular pressing (RD-ECAP). The billet does not need to be removed from the die and re-inserted for the next pass through rotating the die. The route of RD-ECAP is the same with Route A in ECAE. As regards the CCE process, the major differences of the procedure used in this study is that the material is pressed in the opposite direction in a cross-shaped channel (Chou et al., 2008). The ways of metal flow does not belonged to the routes of ECAE or RD-ECAP. Furthermore, the process overcomes the problem of exchanging the finished and new material, which would increase the con-

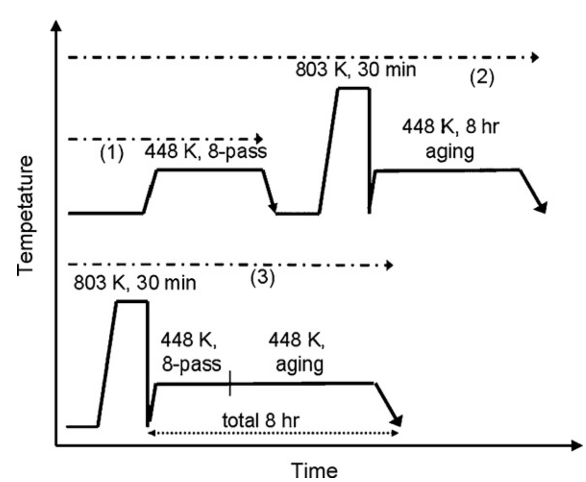

Fig. 2 – Heat treatments processes diagram (1) is the as-extruded sample; (2) is the T6-treated sample and (3) represents the Post-CCE aged sample.

tinuously working ability. Therefore, based on the opinions of metal flow and mechanism, the CCE is different from the ECAE or RD-ECAP methods.

The AA6061 aluminum alloy was produced from 99.9 wt.% pure aluminum which had been melted and then pure silicon, master alloy of Al–75 wt.%Cr, Al–50 wt.%Cu, and pure magnesium were added in order. The melted alloy was cast into a metal mold with the inner dimensions of 125 mm × 100 mm × 25 mm after degassing for 30 min. The chemical composition of the AA6061 is Al–1.1Mg–0.7Si–0.3Cu–0.2Cr in weight percentage. The AA6061 alloy cast was machined to pieces of a cylindrical shape with a diameter of 21.5 mm and a length of 120 mm, and then, homogenizing treated at 803 K for 8 h and slowly cooled down in an air furnace. The initial specimen (0-pass) means the homogenized AA6061 alloy with an average grain size of 700 μm measured by the linear intercept method.

In order to investigate effects of heat treatments on CCE-extruded samples, three kinds of specimens were prepared. The as-extruded sample means the homogenized AA6061 alloy deformed by CCE process at 448 K for 8 passes. The T6-treated sample represents the as-extruded sample followed by T6 treatment which consists of solid solution treatment at 803 K for 30 min and artificial aging at 448 K for 8 h. The Post-CCE aging treatment is that before CCE process, the homogenized AA6061 alloy was solid solution treated at 803 K for 30 min and then quenched into water. After CCE process at 448 K for 8 passes, the material was aged at 448 K for 7.5 h. The total period of time under the temperature of 448 K is 8 h. The processes diagram is shown in Fig. 2.

Work pieces were coated with MoS_2 to reduce the friction between the work pieces and the channel wall. The extrusion speed was fixed at 0.5 mms^{-1}.

Discs with a diameter of 3 mm were punched out form the center of testing samples and mechanically ground to 2000

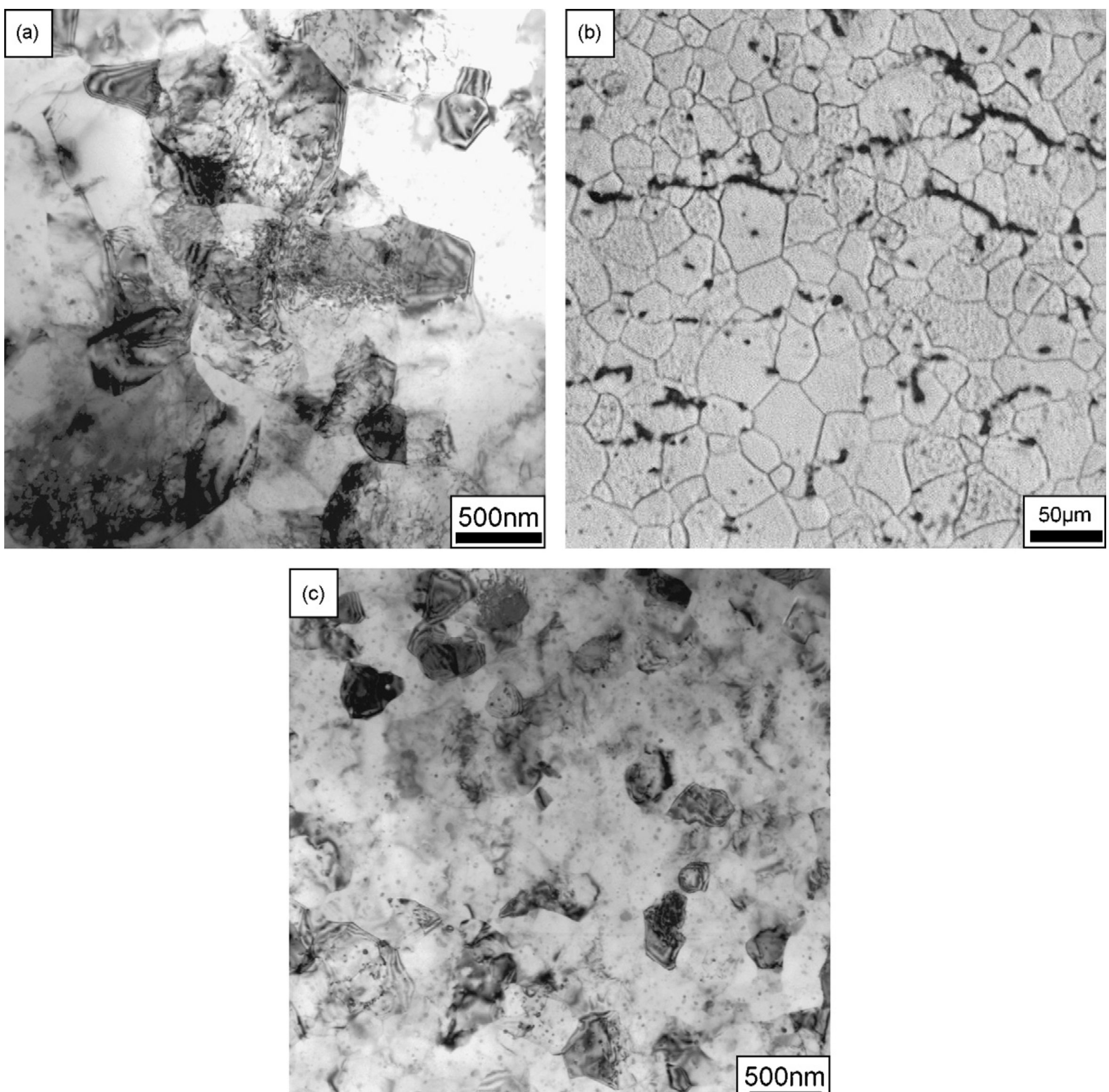

Fig. 3 – Micrographs of the testing samples: (a) 448 K and 8-pass, as-extruded sample; (b) T6 treated sample; (c) Post-CCE aging treatment sample.

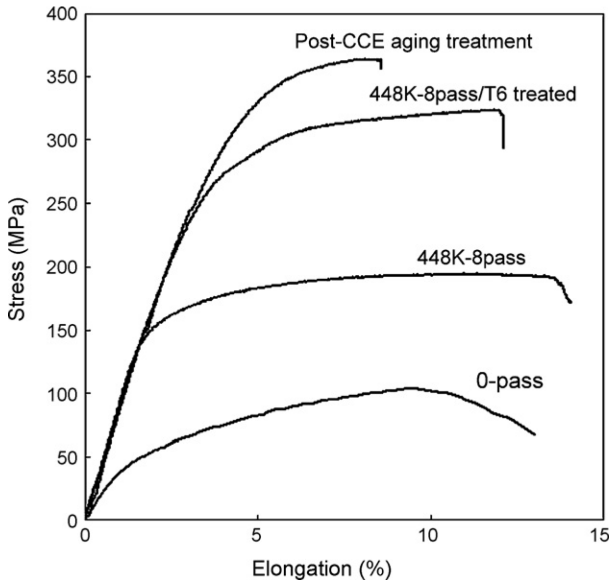

Fig. 4 – Tensile curves of the specimens with different heat treatments.

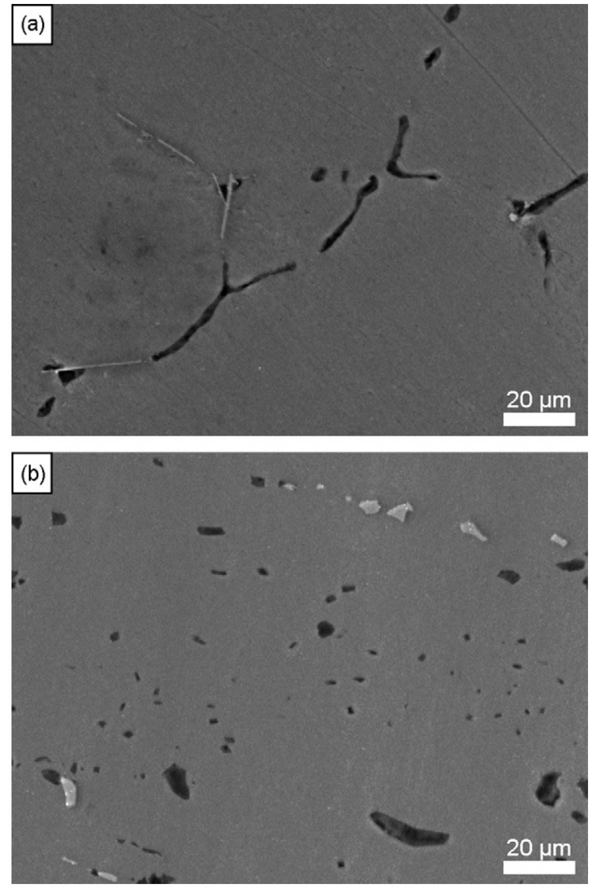

Fig. 5 – SEM images of the (a) 0-pass; (b) 448 K and 8-pass AA6061 alloy. The black and white phases are the Mg_2Si and Fe-bearing phase respectively.

grade SiC paper, and then thinned by Twin Jet Polisher. A transmission electron microscope (Jeol 200FX II) was used for sample observation.

Tensile tests were performed at room temperature using an Instron machine on tensile specimens with a length of 13 mm in gauge and dimensions of 6 mm × 2 mm in cross-section. Tensile specimens were cut from the longitude direction of the Y–Z plane. The tensile speed was fixed at cross head speed of 5×10^{-3} mms^{-1}. Hardness was measured by a Rockwell hardness tester at a load of 100 Kgf for 15 s (HRB scale). Hardness was also determined on Y–Z plane by averaging a total of eight different measurements.

3. Results and discussions

The as-homogenized sample has an average grain size of 700 μm. The initial large grains were subdivided by grain boundaries and dislocation boundaries that finer grain structure can be observed after deformed by CCE methods. Fig. 3a shows the TEM micrograph of the 448 K, 8-pass sample that the grain structure size of the as-extruded sample is about 0.2–0.5 μm. The extruded sample was then T6 treated to obtain precipitation hardening effect. However, recrystallization happened when the sample was solid solution treated at 803 K. The mean grain size was grown to about 35 μm, as shown in Fig. 3b. The Post-CCE aged sample shows the micrograph with grain structure size of 0.2–0.5 μm. The grain structure size is similar to Fig. 3a resulted from the same extrusion temperature and the number of extrusion passes.

Tensile tests were carried out at room temperature. The testing results were recorded and shown in Fig. 4. The 0-pass sample (as-homogenized) has the lowest tensile strength of 103 MPa. The tensile strength was increased to 194 MPa after extruded at 448 K for 8 passes due to the finer grain structure and working hardening effect. The elongation of the 0-pass sample was about 13%, and increased to 14% after extrusion due to the annihilation of defects of a casting alloy such as porosities or shrinkages. The elongation might also be enhanced by the cracked dispersions. As shown in Fig. 5, the white dispersion analyzed by EDS is AlFeSi or AlFeCrSi phase, and the black phase is Mg_2Si. The Fe-bearing phase and some of the Mg_2Si performed as large and acicular shape in the 0-pass sample (Fig. 5a). After extruded for 8 passes, the dispersion was obviously cracked and refined (Fig. 5b). After T6 treatment, the strength was drastically increased to 323 MPa due to the formation of fine precipitates, i.e. Mg_2Si. However, recrystallization happened during T6 treatment that led to the increase of grain size and the annihilation of working hardening effect. Therefore, the Post-CCE aging treatment was carried out to form a UFG material with precipitates formation. The Post-CCE aging treated sample expectably shows the highest strength of 364 MPa, however, the elongation is lowered.

Compared with the 0-pass and the as-extruded samples, the value of tensile strength was increased about 91 MPa due to working hardening and fine grain hardening effects. Moreover, an increase of 220 MPa was obtained from the T6-treated sample when compared with the 0-pass sample mainly caused by the fine precipitates. And obviously, the enhancement on tensile strength caused by precipitates is greater than the fine grain and working hardening effects when extruded at 448 K. The Post-CCE aged sample should consist of the three

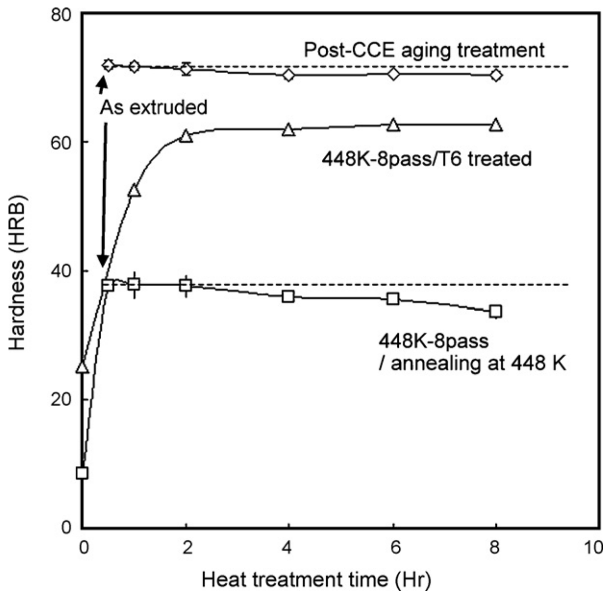

Fig. 6 – Hardness curves of various heat treated samples.

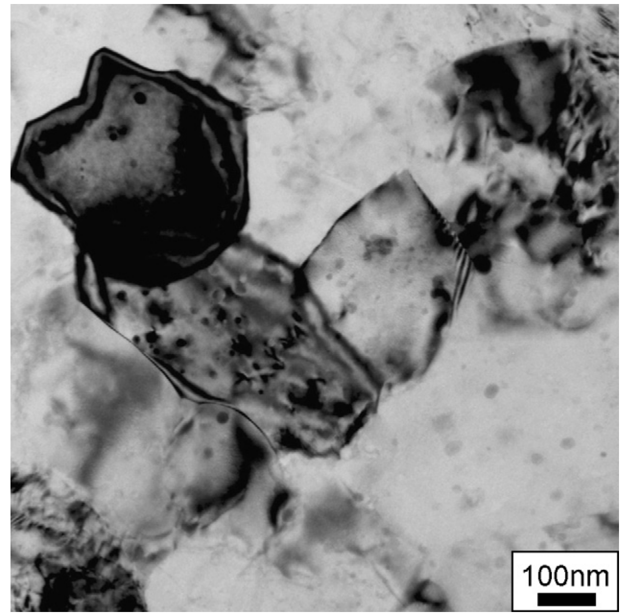

Fig. 7 – TEM micrograph of the Post-CCE aged sample.

strengthening mechanisms, but only 261 MPa was increased after processed instead of 311 MPa (91 and 220 MPa). The suppression in strength might be caused by the aging process that recovery maybe occurred at such temperature.

In order to investigate the influences of annealing or aging on working hardening effect, the as-extruded sample was annealed at 448 K for 7.5 h to be comparable with the Post-CCE aged sample. The values of hardness were recorded and presented in Fig. 6. The hardness of 0-pass sample is only 9, and increased to 38 after extruded for 448 k and 8 passes. After annealing for 7.5 h, the hardness was decreased from 38 to 33 caused by the recovery behavior. As regards the solid solution treated sample, the hardness value was raised to 61 in the first 2 h when aged, and then slowly increased to 63 until the aging treatment was finished. As regards to the Post-CCE aged sample, the highest hardness value of 72 was obtained when extrusion finished. However, the hardness value slowly decreased to 70 after aging treatment due to recovery. The curve of the Post-CCE aged sample is more flat than the 448 K, 8-pass sample may have resulted from the gradually formed precipitates counteracting the softening effect from recovery.

The precipitates, needle shaped β'' or rod-shaped β', with diameters smaller than 8 nm have been commonly observed in commercial Al—Mg—Si(—Cu) alloy after T6 treatment (Perovic et al., 1999; Miao and Laughlin, 1999; Murayama and Hono, 1999). Fig. 7 shows a detailed TEM micrograph of the Post-CCE aged sample. In this figure, several grains can be easily recognized with the size about 200 nm. The spherical precipitates with a size range from 10 to 20 nm were existed around or in the grains. The strengthening effect would be weakened by the larger precipitates. The formation of large precipitates had been reported by Kim et al. (2001) that the differences in precipitate morphology and size may be associated with increased diffusion and strong stress filed induced by the significant increase of dislocation density and other defects. It is also worth noting that the Post-CCE aged sample has the highest hardness obtained when extrusion finished meaning that most of the precipitates were formed during process. However, the T6-treated sample shows that most of the precipitates were formed within the first 2 h. The higher hardening rate of the Post-CCE aged sample also demonstrates that the higher dislocation density would accelerate aging kinetics.

Therefore, though the Post-CCE aged sample shows the highest tensile strength, however, its value is suppressed by the recovery during aging and the formation of large precipitates.

4. Conclusion

The CCE process is an efficient method for producing a bulk fine-grained material, since the material can be continuously deformed in the cross-shaped channel and removed out of the die by punches. Different heat treatments were carried out in this study to investigate the relationship between microstructures and mechanical properties. The bulk fine-grained AA6061 alloy was obtained after extruded for 8 passes at 448 K with a grain structure size between 0.2 and 0.5 μm. The Post-CCE aged sample shows the highest tensile strength of 364 MPa since it consists of fine-grained matrix and precipitation hardening effect. It demonstrates that the Post-CCE aging treatment is a suitable way to produce a heat treatable Al alloy with enhanced mechanical properties.

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