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Large enhancement in mechanical properties of the 6061 Al alloys after a single pressing by ECAP

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Abstract

The equal-channel angular pressed (ECAPed) 6061 Al alloys processed with various pre- and post-ECAP heat treatments were compared in terms of the balance between strength and tensile ductility, and it was concluded that the post-ECAP low-temperature aging treatment was most effective in improving the strength whilst retaining a moderate level of tensile ductility.

Keywords: Equal-channel angular extrusion; Aging; Aluminum alloy

1. Introduction

Equal-channel angular pressing (ECAP) is an effective method of enhancing the strength of metallic alloys through (sub) grain refinement to, typically, the submicrometer level by introducing intensive plastic strain into materials through repetitive pressing [1–4]. Kim et al. [5] studied the aging effect on the strength of the ECAP processed 6061 Al alloy and discovered that the pre-ECAP solid solution treatment combined with the post-ECAP low-temperature aging process produced a significant room-temperature strengthening effect. The effect was impressive when the result was compared with the data for the ECAPed 6061 Al alloys studied by other investigators [6]. For example, the yield stress after six pressings was 425 MPa in the post-ECAP aged 6061 Al alloy, while it was 275 MPa in the ECAPed 6061 alloy without a special heat treatment before and after ECAP [6]. This post-ECAP aging process was also more effective than the pre-ECAP peak-aging treatment studied by Ferrasse et al. [7]. Recently, Cai et al. [8] studied the effect of dynamic aging on the 6061 Al alloys during the ECAP process at 433 K, which was claimed to be an integrated process combining thermo-mechanical processing and aging treatment.

The main objective of the present study is to examine the effect of post-ECAP aging treatment on the mechanical properties of 6061 Al alloy after a single pressing by ECAP. Using a minimum number of pressings during the ECAP process is attractive to industries from the viewpoint of productivity. The mechanical properties of the ECAPed and unECAPed 6061 Al alloys processed by various thermo-mechanical routes were compared in terms of the balance between strength and tensile elongation and the results discussed.

2. Experimental procedures

For the sample preparation, the ECAP samples of 14.5 mm diameter × 100 mm length were machined from

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the extruded materials with a diameter of 18 mm. They were solid-solutionized at 803 K for 4 h and then cooled to room temperature by one of two different routes: rapid quenching into room-temperature water (water quenched, WQ) and slow cooling in the furnace (furnace cooled, FC). ECAP was conducted using a solid die made of SKD 61 with an internal angle of 90° between the vertical and horizontal channels and a curvature angle of 30°. For this die design, the effective strain accrued on a single pass through the die is ∼0.9 [9]. Molybdenum disulfide (MoS_2) was used as a lubricant. The ECAP process was performed for a single pass at two different temperatures, 343 K and 398 K. The ECAPed WQ samples were aged at 373 K for 48 h, which had been found to be the optimum condition for the post-ECAP aging [5]. Unlike in the previous study where the miniature tensile samples were used [5], standard sized samples were used in the current study with an extensometer (gauge length of 8.8 mm). Cylindrical tensile specimens (10 mm gauge length, 5 mm diameter and 10 mm shoulder radius) with the gauge length parallel to the longitudinal axis were extracted from the center portion of the ECAP processed alloys. Each tensile sample was prepared from each ECAPed rod. Tensile tests were carried out at room temperature with an initial strain rate of $5 \times 10^{-4}\ s^{-1}$. A tensile testing machine (Instron 8511) controlled under constant crosshead speed condition was used for the tension tests.

3. Results and discussion

The engineering stress–strain curves of the FC- and WQ-6061 alloys before and after ECAP are presented in Fig. 1(a). The strength of the ECAPed alloys differs depending on the pre-ECAP heat treatment and ECAP temperature. For the FC-ECAPed materials, the yield strength (YS) increased from 83 MPa to 205 MPa and 197 MPa when ECAP was processed at 343 and 398 K, respectively. These YS values are close to that of the ECAPed 6061 alloy after 1 pass (220 MPa) processed without a special heat treatment [6]. The strengthening effect by ECAP was more pronounced when WQ-alloys were ECAPed. The YS increased from 145 MPa to 328 MPa and 319 MPa when ECAP was processed at 343 and 398 K, respectively. These values are higher by ∼100% than those of the WQ-unECAPed alloy and by ∼300% than those of the FC-unECAPed alloy. Note that the strength of the WQ-alloy is higher than that of the FC-alloy even in the unECAPed state. The difference in the strengthening effect between the FC- and WQ-ECAPed 6061 alloys is attributable to the difference in dynamic recovery rate. As it is known that a high content of solute in the matrix can decrease the dynamic recovery rate effectively [10,11], the dislocation accumulation rate is expected to be higher in the WQ-alloys and hence a higher strengthening effect is obtained.

Fig. 1(b) shows the engineering stress–strain curves of the WQ-ECAPed alloys after aging treatment at 373 K for 48 h. For the alloy ECAPed at 343 K, the increment in YS is almost negligible after the aging, but the increment in the ultimate tensile strength (UTS) is about 10%. For the alloy ECAPed at 398 K, on the other hand, the strengthening is evident in both YS and UTS and the increment is similarly about 15% in both. These results indicate that static aging after ECAP is effective in improving the strength of the WQ-ECAPed alloy but its effect depends on the ECAP temperature. Dynamic aging might have occurred during the course of ECAP but it seemed not to occur so much as in the case where the sample was ECAPed at a higher temperature of 443 K. This postulation is based on the observation that static aging was effective after ECAP in the present case while it was ineffective when ECAP was processed at 443 K [8]. This indicates that a high solute content still remained in solid solution after ECAP in

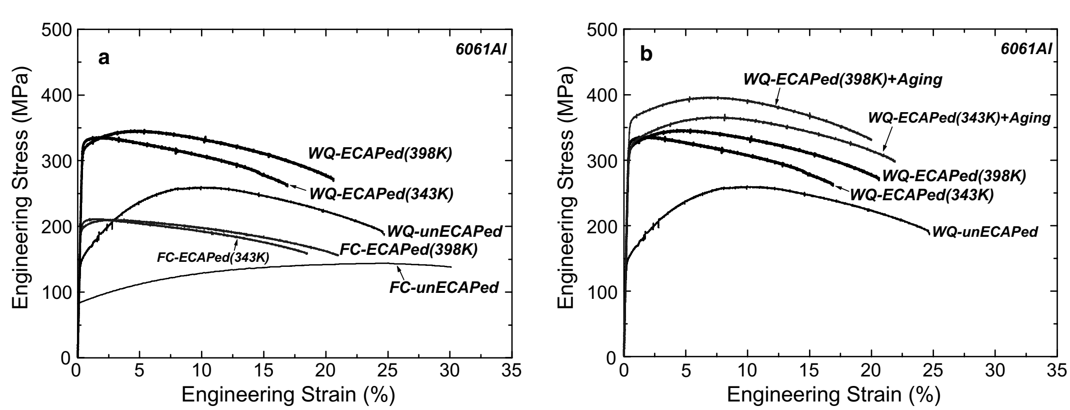

Fig. 1. The engineering stress–strain curves of (a) FC- and WQ-ECAPed alloys without aging treatment and (b) WQ-ECAPed alloys with aging treatment.