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Producing high strength aluminum alloy by combination of equal channel angular pressing and bake hardening

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ABSTRACT

A combination of severe plastic deformation by equal channel angular pressing (ECAP) and bake hardening (BH) was used to produce high strength ultrafine-grained AA6061 aluminum alloy. 2, 4 and 8 passes of ECAP were performed, and the bake hardenability of samples was tested by 6% pre-straining followed by baking at 200 °C for 20 min. The microstructures obtained for various passes of ECAP were characterized by XRD, EBSD, and TEM techniques. The microstructures were refined from an average grain size of 20 μm to 212 nm after 8 passes of ECAP. Maximum bake hardenability of 110 MPa, and final yield stress of 330 MPa were obtained in the specimens processed by 8 passes of ECAP.

1. Introduction

The usage of bake hardened (BH) material is an effective way to reduce the weight of vehicles and obtain higher safety in transportation industry [1–4]. The use of controlled aging during paint baking of deformed materials is known as the bake hardening (BH) technique. During the industrial BH process, a low strength material is required before press forming, and a high strength material is obtained after the paint baking process [5,6]. Among aluminum alloys, Al–Mg–Si alloys are widely used to manufacture body structures of cars, because these alloys attain higher strength after paint baking [7–9].

In general, BH takes advantage of strain aging when the solute atoms segregate to the dislocations and lock them. The procedure to determine the bake hardenability of materials is as follows: (a) the specimen is pre-strained between 2 to 8% at the room temperature, (b) aging is carried out at 170–200 °C for about 20 to 30 min, and (c) the aged specimens are tensile tested at the room temperature. These three steps simulate the forming, panting and baking the paint in the real industrial process of car bodies.

Another effective way to improve the mechanical properties of metallic alloys is by producing ultrafine-grained (UFG) or nanograined (NG) microstructures [10]. Severe plastic deformation (SPD) is a practical approach to attain UFG or NG microstructures. SPD techniques, such as equal channel angular pressing (ECAP), are widely used to produce NG aluminum alloys [11,12].

A combination of a grain refinement process and BH may result in significant increase in the strength of metallic alloys [4,13]. There are only a few works about the BH behavior of aluminum alloys [13], and there is no work concerning the effect of UFG or NG microstructures produced by SPD on the BH behavior of AA6061 aluminum alloy. The main goal of this study was to investigate the effect of UFG structures on the BH behavior and mechanical properties of baked AA6061 aluminum alloy. For this propose, UFG samples of AA6061 were produced by different passes of ECAP process, and then, these samples were subjected to BH. The BH behavior and mechanical properties of UFG samples were compared with those of the coarse-grained (CG) samples.

2. Experimental procedure

In this work, AA6061 aluminum alloy was used for experiments. Before the SPD processing, the initial bars were heated to 550 °C for 5 h, followed by water quenching. Afterwards, the samples were cut to become 10 mm in diameter and 80 mm in length, which are required dimensions for ECAP process to attain UFG samples. The ECAP was conducted using a die made of SKD61 steel grade with an angle of 90° between the channels and a curvature angle of 0°. Samples were coated with molybdenum disulfide (MoS_2) lubricant during the ECAP process [12].

After different passes of ECAP, the grain size was characterized by XRD and EBSD techniques. Williamson–Hall equation was used to calculate the size of the produced grains [14]. The grain size of the alloy was also checked by the EBSD technique; EBSD was used to study the microstructure in areas of approximately 600 μm^2 [15].

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To study the BH behavior of AA6061 aluminum alloy, tensile specimens were cut from the ECAP-processed and un-deformed samples according to ASTM E8. To simulate the BH process, the samples were pre-strained for 6%, followed by baking at 200 °C for 20 min. Finally, the baked samples were tensile tested at the room temperature at a strain rate of $10^{-3}\,s^{-1}$. The BH amount was determined from the difference between the flow stress after pre-straining and the yield stress after baking.

3. Results and discussion

3.1. Microstructures of ECAP-processed samples before BH

The microstructures of samples before the ECAP process had an average grain size of about 20 μm. The microstructures and histograms of the samples processed by ECAP, characterized by EBSD, are shown in Fig. 1(a–c). The results show that the initial CG samples were significantly refined to produce UFG microstructures after the ECAP process. After only two passes of ECAP, there is a significant decrease in the average grain size (~755 nm) of the sample. With an increase in the number of ECAP passes, the grains were considerably finer, for example by applying 8 passed of ECAP, the initial average grain size of 20 μm was reduced to about 212 nm.

The grain size was also measured by XRD method. According to the XRD patterns, the peak of (2 0 0) was dominant compared with other peaks [16]. Also, the intensity of as-received samples is lower than that of ECAP-processed samples. As shown in Fig. 1(d), by increasing the number of ECAP passes, the intensity increases, there for more grain-refinement is achieved.

The average grain size of as-received and ECAP-processed samples determined by XRD and EBSD are summarized in Table 1(a).

3.2. BH behavior of samples

Effect of BH treatment and ECAP on mechanical properties: The BH curves obtained for samples processed by different passes of ECAP are shown in Fig. 2. These samples were pre-strained by 6%, and then baked at 200 °C for 20 min. Fig. 2 shows that the amount of BH of ECAP-processed samples is higher than that of as-received one. This indicates by applying 2 and 4 passes of ECAP followed by BH, there is about 50 and 85 MPa increase in yield stress, respectively. The maximum bake hardenability (110 MPa) and final yield stress (330 MPa) were obtained for the specimens subjected to 8 passes of ECAP and baked at 200 °C. As for the as-received sample, the measured BH and yield stress were respectively about 20 MPa and 100 MPa. These results show that baking after ECAP is an effective approach to improve the strength of aluminum alloys; nevertheless, its effect depends on the number of ECAP passes. The increase in the strength is also due to the formation of fine and UFG microstructures in the samples. It is well known that with grain refinement, the amount of grain boundaries increases. As the baking treatment is a diffusion control process, the diffusion of soluble atoms increases by increasing the volume fraction of grain boundaries [4]. In addition, the precipitation kinetics is increased due to the higher diffusivity in the UFG structures. Therefore, in the case of baked AA6061 with UFG microstructure, the effect of dislocation locking is enhanced and the BH is increased significantly. These subjects are discussed in details by Alihosseini et al. [4] and Dehghani [13].Obviously, a decrease in the grain size from 20 μm (CG state) to 200 nm (UFG state) led to a considerable increase in the bake hardenability and the final strength of the materials; this is clearly evident from the stress–strain curves presented in Fig. 2.

In Fig. 2, the return of yield point after baking indicates that aging is occurred. This is attributed to the diffusion of solute atoms to the dislocations generated during pre-straining and in turn to the formation of solute atmosphere around dislocations, resembling the Cottrell atmosphere. As dislocations are locked in this way, the higher stress (i.e. yield stress) is required to un-pin them.

Effect of bake hardening process on microstructures: TEM micrographs of the samples processed by 4 and 8 passes of ECAP and baked at 200 °C for 20 min are shown in Fig. 3. A low density of very fine precipitates (~25 nm) exists in the micrograph of samples processed by 4 passes of ECAP, Fig. 3(a). The precipitates

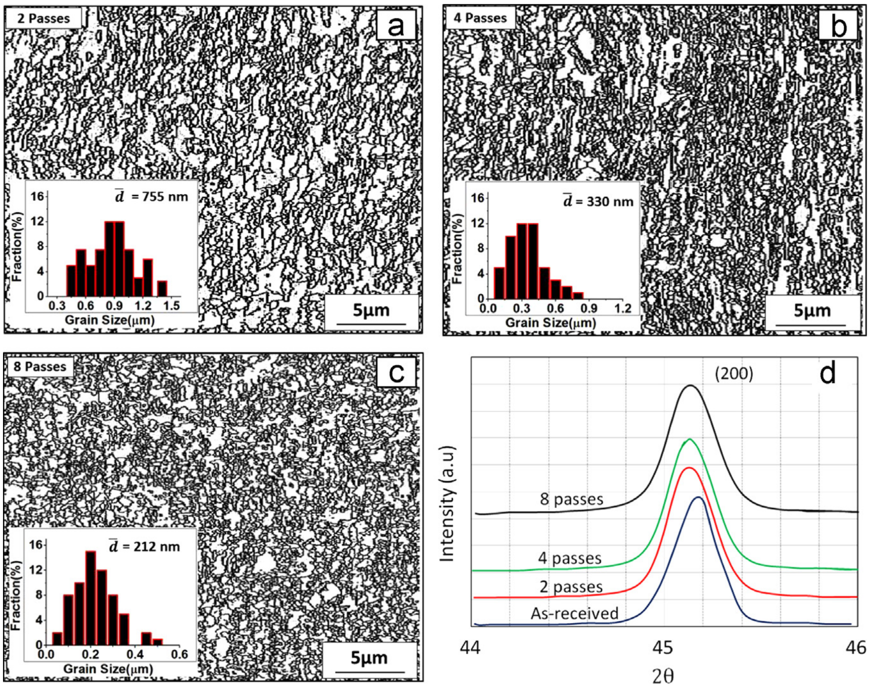

Fig. 1. Microstructures of the samples taken by EBSD after: (a) 2 passes, (b) 4 passes, and (c) 8 passes of ECAP; (d) XRD pattern of the ECAP-processed 6061 samples for the (2 0 0) peak.