Effects of Heat-Treatment Conditions on Microstructure and Mechanical Properties of Aluminum Alloy with Rare Earth Addition

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In this study, we investigate the microstructure and mechanical properties of as-extruded Al-1.0RE alloys. The molten Aluminum alloy was maintained at 800 °C and then poured into a mould at 200 °C. Aluminum alloys were hot-extruded into a rod measuring 12 mm thick with a reduction ratio of 38:1. The microstructure and electric conductivity properties of as-extruded Al-1.0RE alloy under different annealing processes were investigated and compared. After extrusion, the intermetallic compound having a needle shape in the cast state was finely decomposed based on the direction of extrusion. Significant changes in the microstructure were detected after annealing at 500 °C with fragmentation and sphering of eutectic particles. The annealing temperature of Al-1.0RE alloy increased proportionally to the electrical conductivity. The formation of Al-RE intermetallic compounds increases the electrical conductivity and improves the mechanical properties of the alloy through precipitation hardening.

Keywords: *Aluminum Alloy, Rare Earth, Heat-Treatment, Microstructure, Mechanical Properties*

Introduction

Al alloys materials are lightweight with good strength and workability. They alloys are widely used in aircraft, subsea structures, vehicle bodies and mechanical equipment, and plays an important role as an industrial material. Currently, it is being applied in the following areas; aerospace, aviation materials, defense materials and vehicle structures[1)]. In particular, the 1000-series aluminum alloy has excellent processing ability, corrosion resistance and surface treatment, is an excellent electrical and thermal which makes it suitable for use as a transmission, distribution and heat dissipation material. However, because of its low mechanical strength, it is difficult to use in certain fields. However, the addition of an element to aluminum reduces its electrical conductivity of electron scattering by solute atoms, grains boundaries, dislocations and precipitates. The most important effect on the reduction of electrical conductivity is due to solute atoms[2, 3)].

Therefore, an Al-based immiscible system such as Al-RE or Al–Fe appears to be a promising material for high-conductance materials because of its negligible effect on the electrical conductivity since the solubility of the Al alloy is zero[4, 5)]. In addition, when the metal phase is uniformly distributed throughout the alloy, it precipitates as small particles and possesses mechanical strength and thermal stability[6)]. However, the concentration of the immiscible element compound should be excessively controlled, which may lead to a loss of electrical conductivity as shown in the Al–Fe alloy[7, 8)].

The heat treatment exhibits excellent properties at low cost and process convenience while also homogenizing and refining eutectic microstructure and improving the alloy properties[9)].

In this study, we investigated the effects of rare earth elements and heat treatment in Aluminum based alloys on the microstructure and electric conductivity.

Experiment

Aluminum alloys with RE (Rare Earth) additions were applied for comparative research. First, Al was placed in a graphite mold and melted in a furnace. We cast the molten alloy into a steel mold (D 75 mm × H 250 mm), heated at 200 °C, at a pouring temperature of 800 °C. We then preheated the billets and die to 400 °C and 200 °C, respectively prior to the extrusion process. The diameter of the extruded bar was 12 mm. To stabilize the microstructure and properties of the extruded rods, they were annealed at different temperatures (100, 200, 300, 400, 500 and 570 °C) for an hour. In order to observe their microstructures, the specimens were polished using a diamond suspension of ㎛ and 1 ㎛. Silica was then used for the final polishing. We obtained the microstructures and phase information by combining of scanning electron microscope (SEM; JSM7000F), energy-dispersive X-ray spectrometer (EDS) and electron backscatter diffraction (EBSD). To evaluate the mechanical properties, we conducted tensile tests at room temperature using a universal material testing machine (SHIMAZU AG-IS). Mechanical tests were done at an initial strain rate of 1.0×10^{-3} s^{-1}.

Results

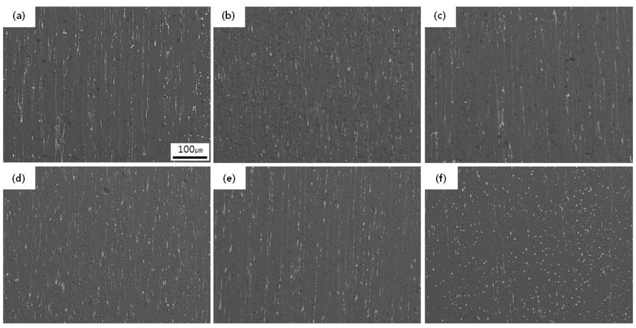

Figure 1. SEM image of the as-extruded (a) Al-1.0 wt.%RE after annealing at (b) 100, (c) 200, (d) 300, (e) 400 and (f) 500 ℃.

Annealing at 100, 200, 300 and 400 °C does not significantly affect the microstructure (Figs. 1(b–e)).

Significant changes in the microstructure are detected only after annealing at 500 °C with fragmentation and sphering of eutectic particles. As a result of annealing at 500 °C for 1 hour, the alloy structure is similar to the structure of a rapidly crystallized alloy formed after heating. Evenly distributed spherical particles with an average particle size of 1 ㎛ appear in the aluminum matrix (Fig. 1(f)). The instability characteristics of structures such as plates in annealing were considered in detail for various eutectic alloys.

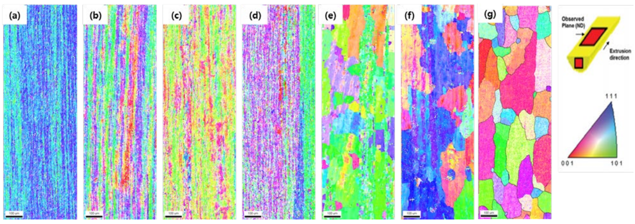

Figure 2. EBSD image of the as-extruded (a) Al-1.0 wt.%RE after annealing at (b) 100, (c) 200, (d) 300, (e) 400, (f) 500 ℃ and (g) 570 ℃.

EBSD analysis was performed to establish the grain size and texture of the extruded Al alloy. Figure 2 shows Inverse Pole Figures (IPF) of the as-extruded Al-1.0 wt.%RE alloy after annealing at different temperatures. The preferred orientation distribution of Al in the extruded Al-1.0 wt.%RE alloy was also established, and the EBSD analysis of the Al grain was performed on the longitudinal section. The average grain sizes of the as-extruded Al-1.0 wt.%RE alloy, after annealed at 100, 200, 300, 400, 500 and 570 °C were 12.77, 15.54, 11.19, 106.93, 222.66 and 222.00 ㎛, respectively.

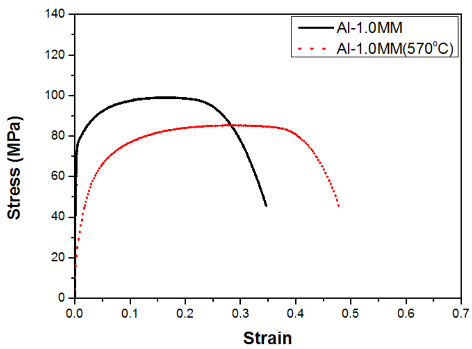

Figure 3. Tensile stress-strain curves of the Al-1.0 wt.%RE alloy extruded material and annealed extruded material at room temperature.

Figure 3 shows tensile properties of Al-1.0 wt.%RE alloy extruded material and materials extruded through annealing at room temperature. The ultimate tensile strengths of the Al-1.0 wt.%RE alloy extruded material and the heat-treated material at room temperature were 99.08 and 85.35 MPa, respectively. In addition, the increase in length of the extruded material after heat treatment increased from 34.69 to 47.77% compared to the as-extruded Al-1.0 wt.%RE alloy. From this study, we observed that the annealing temperature of 570 °C reduces the strength and increases ductility of material. Maintaining the temperature above 500 °C causes considerable decrease in strength due to coagulation of the intermetallic compounds of the main hardening phase of $Al_{11}RE_3$-Type.

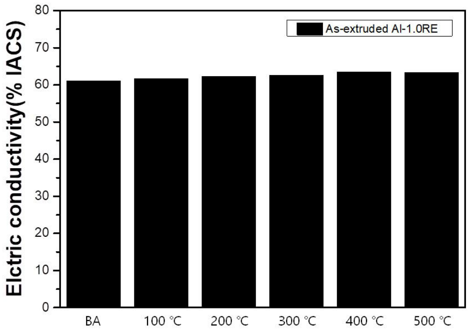

Figure 4. Electric conductivity of as-extruded Al-1.0 wt.%RE after annealing at 100, 200, 300, 400 and 500 ℃.

Figure 4 shows the electrical conductivity of the as-extruded Al-1.0 wt.%RE alloy after heat treatment at 100, 200, 300, 400, and 500 °C. As the heat treatment temperature of as-extruded Al-1.0 wt.%RE increased to 100, 200, 300 and 400 °C, the electric conductivity increased to 61.64, 62.22, 62.60 and 63.48% IACS respectively. The as-extruded Al-1.0 wt.%RE alloy had a conductivity of 61.08% IACS after annealing at 100 °C, which is approximately the conductivity of pure aluminum. Observing all conditions, the main trend of all alloys is the increase in conductivity with an increase in the annealing temperature. This effect is pronounced especially for high annealing temperatures and low concentration of rare earth elements. In addition, the formation of Al-RE intermetallic compounds increases the strength of the alloy through precipitation hardening while increasing the conductivity of the alloy[10]).

Conclusions

The microstructure and mechanical properties of as-extruded Al-1.0 wt.%RE alloy under annealing processes were comparatively investigated by conducting tensile tests, scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD). In this microstructure of as-extruded alloys, intermetallic compounds were broken down into fine particles and arranged laterally to the extrusion direction due to the severe deformation during hot extrusion. Substantial changes in the microstructure were detected after annealing at 500 °C with fragmentation and sphering of eutectic particles taking place. The elongation increased from 34.69% to 47.77% as the Al-1.0 wt.%RE alloy extruded material was heat-treated. The annealing temperature of Al-1.0 wt.%RE alloy increased proportionally to the electrical conductivity. The formation of Al-RE intermetallic compounds increases the electrical conductivity and improves the mechanical properties of the alloy by precipitation hardening.

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