THERMAL CONDUCTIVITY OF ALUMINUM FABRICATED BY EQUAL CHANNEL ANGULAR PRESSING

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Abstract: Equal channel angular pressing (ECAP) has the advantage of enabling an ultrafine grain size. Aluminum 1060 is used as a power plant material because of its favorable electrical properties. However, the weak strength of aluminum limits its application. In this study, the thermal conductivity and electrical conductivity of Al 1060 made by ECAP was investigated. ECAP was conducted through the die having a channel angle of 90° and a corner angle of 20° at a temperature of 473 K with a strain rate of 2 mm·s^{-1}. The specimen was then processed with 1 to 8 passes by the route Bc method with 90° rotation. In the case of eight passes, the grain size was reduced to as small as 300 nm. The thermal conductivity gradually decreased with ECAP passes, because of the decreased grain size by ECAP.

Keywords: Aluminum, ECAP, Thermal conductivity.

1. INTRODUCTION

Equal channel angular processing (ECAP) is a method of severe plastic deformation that enables a high level of strain without changes in surface area and is being used to refine grain size to a submicron or smaller level [1]. For metal materials, the strength increases with decreasing grain sizes. Use of ECAP has been studied for the grain refinement of metals, including steel, aluminum, and copper [2-3]. In particular, the grain refinement of aluminum alloys below submicron size has been difficult due to the low-temperature recovery with a high stacking fault energy, but ECAP application enables a significant improvement [1]. Characteristics of superplasticity due to high grain boundary formation are reported at low temperature as well [4]. Aluminum 1060 contains 99.6 % aluminum and slight amounts of silicon and iron as impurities. It is also a common conductor among 1xxx alloys used as materials for power transmission or distribution systems. Despite its superior electrical properties, aluminum 1060 has low strength and thus requires heat treatment and rolling.

This study used ECAP on aluminum 1060 to refine its structure, and then observed the strength with increasing passes; the mechanical properties of the refined structure; and the changes in thermophysical properties of ultrafine grained aluminum. ECAP was used to improve strength through refinement, and thus to enhance mechanical properties, while maintaining electrical properties. The thermal conductivity was calculated from the measured values of the specific heat capacity, thermal diffusivity, and density. Four-probe electrical resistivity measurements were taken, and the electrical conductivity was calculated with the thermal conductivity using the Wiedemann-Franz method.

2. EXPERIMANTAL

An aluminum 1060 alloy with 99.6 % purity was used for this study. The extrudate is processed into a round bar specimen with a diameter of 17.5 mm and a length of 125 mm, and was treated with annealing at 723 K for 2 h. The specimen was processed through the die having a channel angle (Φ) of 90° and a corner angle (Ψ) of 20° at a temperature of 473 K with a strain rate of 2 mm·s^{-1}, with one to eight passes via route Bc with a strain rate of 2 mm·s^{-1} [5]. MoS$_2$ lubricant was applied on the surface of the specimen in order to minimize friction between the die and specimen during ECAP.

Densities were measured using the Archimedes method at room temperature, but for the high-temperature region, they were calculated from the measurement of the coefficient of thermal expansion. A differential scanning calorimeter (DSC: Netzsch, DSC 404C) was used for the measurement of the specific heat capacity, with calibration using indium, tin, zinc, aluminum, and gold (99.9999 %). The DSC environment was conditioned by the flow of inert gas (argon, 99.999 %) at 50 mL·min^{-1}. Specific heat capacities were measured while the temperature was raised between room temperature to 600 °C at a rate of 10 K·min^{-1}, and the averaged specific heat capacity of each 50 °C temperature interval was taken. Each specimen was processed to have a diameter of 4 mm and thickness of about 2 mm, and the NIST SRM-720 (α-sapphire) standard material was used. The thermal expansion coefficient was measured using methods from a dilatometer (Netzsch, DIL 402C) raising the temperature at 5 K·min^{-1} in an environment of pure nitrogen (99.999 %) at 50 mL·min^{-1}. The thermal diffusivity was measured by the laser flash method (ULVAC, TC-7000) [6] with a correction by the Azumi method [7]. The TEM specimen was polished with 90 μm sand paper, and then jet polishing was conducted with 25 % nitric acid and 75 % methanol under 25 V voltage at -30 °C. JEOL Model 2010 was used as the TEM

(transmission electron microscope), conditioned with an acceleration voltage of 200 keV.

3. RESULTS AND DISCUSSION

Fig. 1 shows the microstructure of Al 1060 as received from the optical microscope. Grain size is about (200~300) μm on average. Parallel subgrain bands formed on the entire surface of the 1 pass case, as shown in Fig. 2(a). The grain size is about 600 nm ~ 700 nm. Multiple dislocations on the grain are observed to be irregularly placed. Subgrain band on the 2 passes case, in Fig. 2(b), was especially wide, whereas the grain size was approximately 500 nm. Grain sizes in 4 passes and 8 passes, shown in Fig. 2(c) and (d), decreased to be 400 nm and 300 nm, respectively, and the grain appears to be more homogenously formed compared to the one in 2 passes. We find out that the grains are more finely and homogenously formed with the increase of ECAP, except that 1 and 2 passes had inhomogeneous structures.

Figure 2 shows the result of specific heat capacity measurements between room temperature and 600 $^{\circ}$C using the enthalpy method. The specific heat capacity of the as-received material is 0.9349 $J \cdot g^{-1} \cdot K^{-1}$ at room temperature. This decreases to 0.9265 $J \cdot g^{-1} \cdot K^{-1}$ after one pass, 0.9232 $J \cdot g^{-1} \cdot K^{-1}$ after 2 passes, 0.9279 $J \cdot g^{-1} \cdot K^{-1}$ after 4 passes, and then to 0.9209 $J \cdot g^{-1} \cdot K^{-1}$ after 8 passes, which is a 1.5 % decrease from the as-received state at room temperature. The difference remained constant up to 600 $^{\circ}$C. Although it is within the range of ±2 %, the combined uncertainty, the difference remained constant in repeated experimental results. The decrease of the specific heat capacity is considered to be the effect of grain size and deformation by ECAP. But this difference by ECAP is less than 2 %, and within the uncertainty of the system.

Figure 3 shows the thermal diffusivity of aluminum 1060 at different stages - in the as-received state and by the number of ECAP passes - measured by the half-time method. At room temperature, the thermal diffusivity was 9.26x10^{-5} $m^2 \cdot s^{-1}$ but decreased to 8.87x10^{-5} $m^2 \cdot s^{-1}$ after 8 passes. This difference remains constant up to 600 $^{\circ}$C, but the difference in thermal diffusivity becomes minimal above 400 $^{\circ}$C. At 600 $^{\circ}$C, the thermal diffusivity of the specimen in the as-received state and after 8 passes are similar, being 7.48x10^{-5} $m^2 \cdot s^{-1}$ and 7.42x10^{-5} $m^2 \cdot s^{-1}$, respectively. The decrease of thermal diffusivity is regarded as being caused by the scattering of electrons from grain refinement. The thermal diffusivity is the lowest after 2 passes, presumably due to the formation of a grain band, and thermal conduction disturbance by dislocation, as seen from Fig. 2.

Figure 4 shows the coefficient of thermal expansion of the aluminum 1060 alloy at the as-received state and after 1, 2, 4, and 8 passes, using the dilatometer. It was confirmed that the coefficient of thermal expansion does not differ signficantly between the as-received state and after different ECP passes. Figure 8 shows the density of aluminum 1060 alloy at the as-received state and after 1, 2, 4, and 8 passes, calculated using the measured thermal expansion coefficient. The documented value of aluminum is 2698 $kg \cdot m^{-3}$ [8], which is close to the estimated value for the as-received state, 2703 $kg \cdot m^{-3}$.
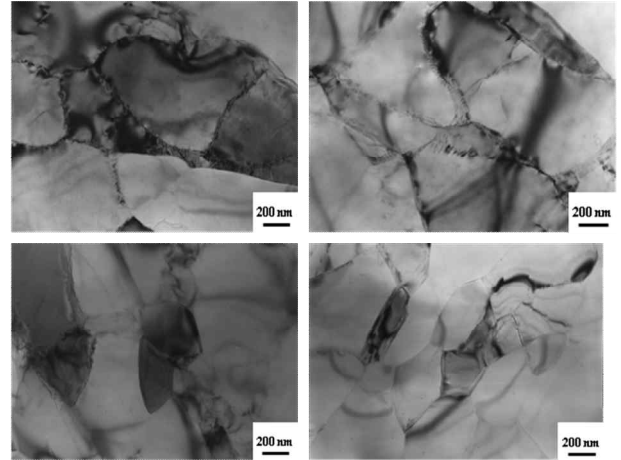

Fig. 1 TEM micrographs of aluminium by ECAP, (a) 1pass, (b) 2 passes, (c) 4 passes, and 8 passes.

The thermal conductivity (λ) was calculated with the experimentally measured specific heat capacity (c_p), thermal diffusivity(α), and density (ρ).

$$\lambda = \rho c_p \alpha \quad (1)$$

Figure 5 shows the thermal conductivity values of aluminum 1060 alloy in the as-received state and after 1, 2, 4, and 8 passes. The thermal conductivity of Al 1060 was 238 $W \cdot m^{-1} \cdot K^{-1}$ in the as-received state and 223 $W \cdot m^{-1} \cdot K^{-1}$ after 8 passes. Rather than uniformly decreasing with the increase in number of passes, the thermal conductivity is the highest after 1 pass, and then after 4 passes, 8 passes, and 2 passes, in descending order. This order of thermal conductivity was the same in Gendelman's experiment with ECAP-deformed pure copper at room temperature. This was explained using the equilibrium grain size distribution function [6], and Fig. 2 shows that our experiment suggests the same trend. In other words, the thermal conductivity is the lowest after 2 passes, due to the thermal conduction inhibition by the grain band formation and dislocation. The difference between the thermal conductivity values decreases with the increase in temperature, because of the development and re-formation of grains. The recovery and reformation of materials at higher temperatures decreases the densities of dislocation, enables easier electron movements, and thereby reduces the difference of thermal conductivity in specimens, between the as-received and ECAP states.

Figure 6 shows the Wiedemann-Franz electrical conductivity, calculated with the measured thermal conductivity. The electrical resistivity at room temperature is 3.069x10^{-8} $\Omega \cdot m$ for the as-received state and 3.179x10^{-8} $\Omega \cdot m$ after 8 passes, about a 3 % decrease, and is highest for 1 pass, 4 passes, 8 passes, and 2 passes in descending order. In line with the original purpose, the aluminum strength could be enhanced by ECAP without significant changes in the electrical conductivity, using aluminum refinement. The four-probe electrical resistivity of the as-received state is 2.88x10^{-8} $\Omega \cdot m$ and 2.95x10^{-8} $\Omega \cdot m$ after 8 passes, with about 2.4 % difference. This suggests that the grain refinement by ECAP significantly improves the strength, and the effects on

electrical conductivity are minimal. There is an approximately 6 % difference between the calculated electrical resistivity using the measured thermal conductivity and electrical resistivity, which is reasonable considering the errors of thermal property measurements and electrical measurements. The measurements generally correspond to the reference values.
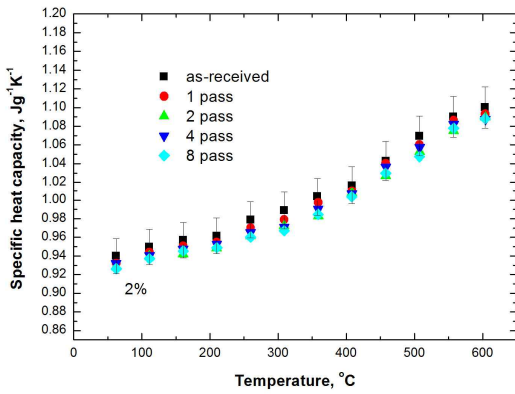

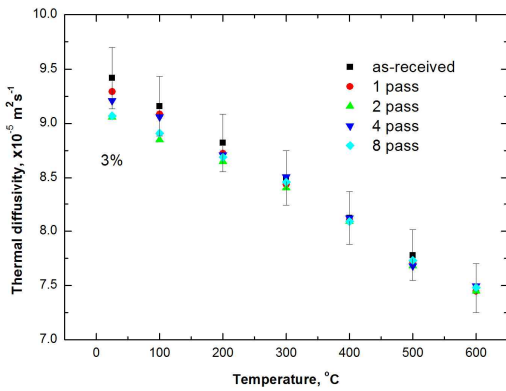Fig. 2 The specific heat capacity of Al 1060 by ECAP.

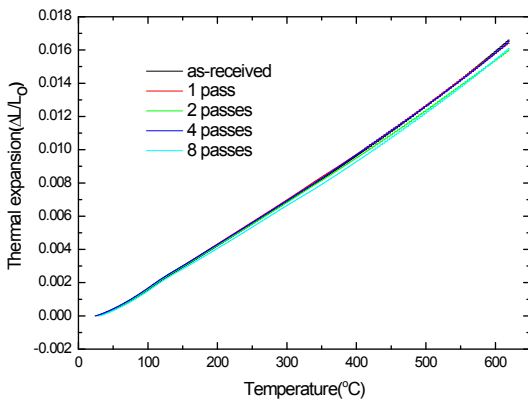Fig. 3 The thermal diffusivity of Al 1060 by ECAP.
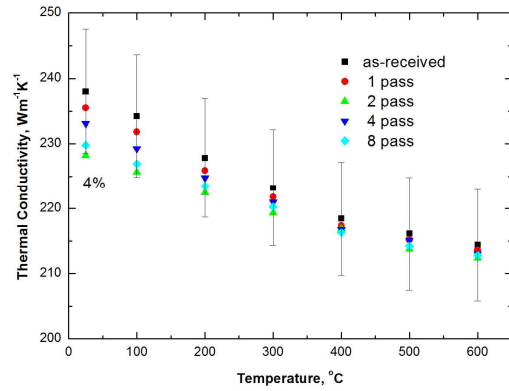

Fig. 4 The thermal expansion of Al 1060 by ECAP.

Fig. 5 Thermal conductivity of aluminium fabricated by ECAP, (a) 1pass, (b) 2 passes, (c) 4 passes, and 8 passes.
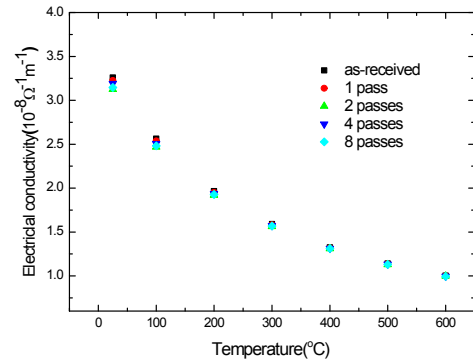

Fig. 6 Electrical conductivity of aluminium fabricated by ECAP.

4. SUMMARY

In order to study mechanical changes in the refined structure of aluminum 1060 by ECAP, the thermal conductivity was investigated based on the specific heat capacity, thermal diffusivity, and densities. The thermal conductivity decreased by approximately 8 % after 1 pass, compared to the as-received state. However, thermal conductivity values after 2, 4, and 8 passes were not significantly different from that after 1 pass. The thermal conductivity does not decrease in an inversely proportional manner with the number of passes. This is the result of thermal conductivity inhibition by grain band formation and dislocation density. The difference in thermal conductivities of the as-received state and an ECAP specimen becomes smaller above 200 °C, due to the recovery occurring between 150 °C and 200 °C.

5. REFERENCES

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