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Grain Refining and Mechanical Properties of Equal-Channel Angular Pressed Al-Ni eutectic Alloy

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It is well known that an ultra-fine grain Al alloy as a light metal can attain high mechanical properties, which have potential usage as a ecomaterial. Equal-channel angular pressing (ECAP) is a severe plastic deformation method, which led to a huge plastic strain in bulk materials. In this study, Al-Ni eutectic alloy was ECA pressed with route A and route Bc methods at a temperature of 298 K. Results show that in the two as-deformed microstructures the α-Al crystals demonstrate very different distribution trends along deformation direction, and Al_3Ni particles are refined to sub-micrometer scale. The results show that Vickers hardness (Hv) of as-deformed samples approximately increased to double value of that before ECAP processing. The paper concludes that the ECA pressed Al-5.7mass%Ni eutectic alloy is suitable as an ecomaterial with high mechanical properties and low density.

Key words: Al-Ni eutectic alloy, ECAP, deformation, ultrafine grain structure, Vickers hardness

1. INTRODUCTION

Metallic materials with ultrafine-grained (UFG) structure are known to have superior mechanical properties [1]. Among several methods used to produce UFG materials, the equal-channel angular pressing (ECAP) has been successfully applied to produce various bulk UFG materials [2-4]. ECAP is a processing procedure by which a material is subjected to very intense plastic strain by pressing through a special die, without any concomitant change in the cross-sectional dimensions of the sample [5,6].

The principle of ECAP is illustrated schematically in Fig. 1 in the form of a cross-section of the die. The die contains two channels, equal in cross-section, which intersect at an internal angle of ϕ. ψ is defined as the angle of outer arc of curvature where the two channels intersect. It has been reported by Iwahashi *et al.* [7] that the shear strain, ε_N, introduced in ECAP is given by

$$\varepsilon_N = \frac{2N}{\sqrt{3}}\left(\cot\left(\frac{\phi}{2}+\frac{\psi}{2}\right)+\psi\operatorname{cosec}\left(\frac{\phi}{2}+\frac{\psi}{2}\right)\right) \quad (1)$$

where N is the number of ECAP passes through the die. In the present study, ϕ=90° and ψ=45° are applied to the die. Nakashima *et al.* [8] calculated that regardless of the value of ψ, a single passage through a die with ϕ=90° will result in a strain close to 1.0.

The ECAP method is defined as having four distinct processing routes [9]: route A, in which the sample is not rotated between repetitive pressings, route B, in which the sample is rotated by 90° between each pressing and route C, in which the sample is rotated by 180° between each pressing. A further possibility may be introduced when it is noted that route B may be undertaken either by rotating the sample by 90° in alternate directions between each individual pressing, termed route B_A, or by rotating the sample by 90° in the same direction between each individual pressing, termed route B_C.

Meanwhile, since the density of Al is only about one third of steel, Al and Al alloys are widely used in aero-, automobile and constructional engineering. The addition of alloying elements is made principally to improve mechanical properties, such as tensile strength, hardness and rigidity. As in the past studies, pure metal such as Al, Ti, Cu and its alloys have been subjected to ECAP process and grain refining in microstructure and advancement in mechanical properties have been researched [10-12]. However, few investigations about severe plastic deformation to eutectic alloy by ECAP method have been conducted, although eutectic alloy shows many significant mechanical properties, such as high plasticity and toughness. When some eutectic alloy samples are severely deformed by ECAP technique, it is expected to result in higher mechanical and other special properties. This study set out to understand the influence of ECAP process parameters on microstructure and mechanical properties, when an Al-5.7mass%Ni eutectic alloy is subjected to severe plastic deformation by ECAP of route A and route Bc methods. For this purpose, the microstructure evolution and mechanical properties of as-deformed samples were investigated.

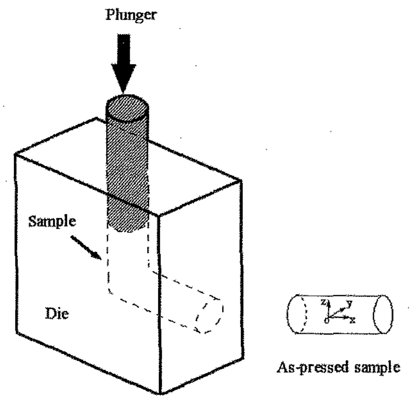


Fig. 1 Schematic illustration of ECAP facility including definitions of coordinate planes in as-deformed sample.

2. EXPERIMENTAL PROCEDUCE

In this experiment, rod-shaped Al-5.7mass%Ni eutectic alloy samples were prepared by casting at 850°C using a high-purity (99.99pct) Al ingot and an Al-20mass%Ni ingot. For ECAP process, cylindrical samples were machined with a diameter of 10 mm and a length of 60 mm.

The ECAP process was conducted with a pressing speed of 0.33 mms^{-1} at room temperature (298K) using MoS_2 as a lubricant. In this investigation, ECAP processes were performed with route A and route Bc methods, as described in the previous section. Repetitive pressings of the same sample were carried out up to eight passes through the die, since clearly visible cracks appeared on the surface of sample after the ninth pass.

After the ECAP process, the specimens were cut into small pieces by electrical discharge machining along two vertical sections called *x-o-y* and *x-o-z* planes, which were parallel to the deformation direction, and a cross section called *y-o-z* plane which was perpendicular to the deformation direction, as demonstrated in Fig. 1. These small pieces were mechanically polished and the surfaces were etched for 20 seconds in a 0.2% HF solution. The scanning electron microscope (SEM) observation was carried out on a Hitachi-8000 electron microscope.

In this study, as-deformed samples revealed the variation of crystal structure and phases during ECAP process, X-ray diffraction (XRD) analysis carried out on a monochrometer-attached diffractometer with radiation from a Cu-Kα (λ=0.15418nm) source. In addition, for each sample deformed by ECAP, the Vickers microhardness (Hv) values were measured with an Akaishi MVK-C microhardness tester. The values for Hv were the average of ten separate measurements taken at randomly at selected points by imposing a load of 350 g for 15 seconds.

3. RESULTS AND DISCUSSION

Figure 2 shows the SEM microstructure of Al-5.7mass%Ni eutectic alloy, which was cast at 850°C. It revealed that the eutectic lamella structure is made of white Al_3Ni particles alternating with gray α-Al matrix. In the initial state, it is estimated that the average lamellae spacing is about 1.5-2.0 μm.

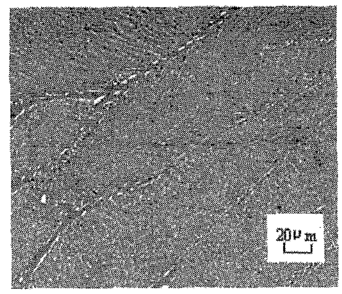
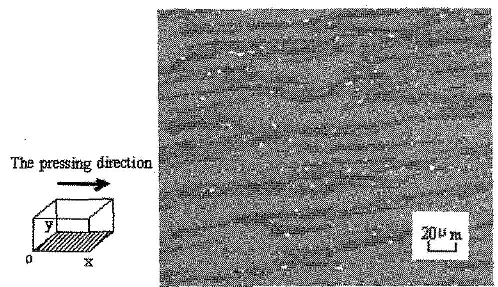
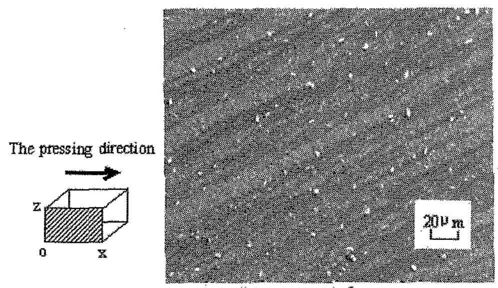


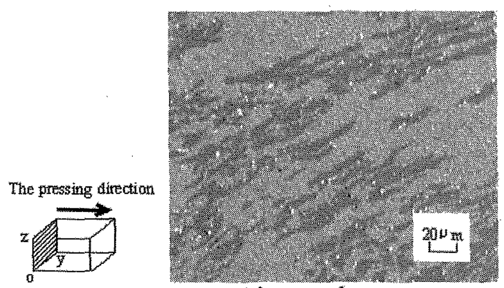
Fig.2 SEM micrograph of Al-Ni eutectic alloy before ECAP.



(a) *x-o-y* plane



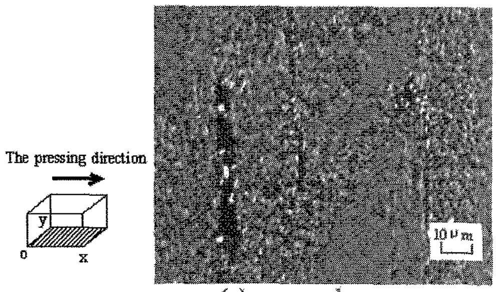
(b) *x-o-z* plane



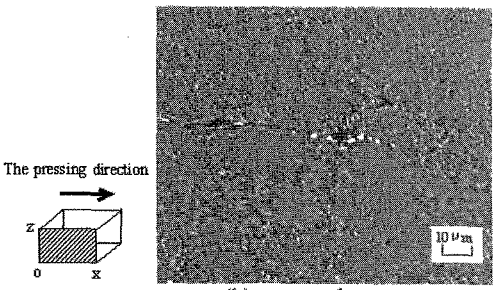
(c) *y-o-z* plane

Fig.3 SEM micrographs of Al-Ni eutectic alloy after 8 passes ECAP by route A method.

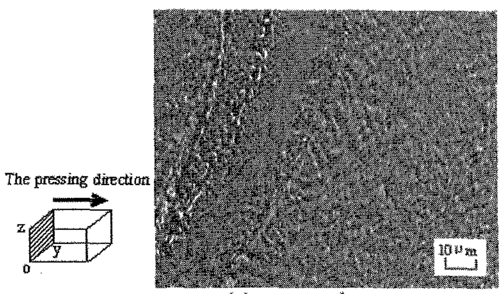
The SEM microstructures of Al-Ni eutectic alloy after 8 passes ECAP by route A method are shown in Fig. 3. As can be seen that the lamellae structure is re-arranged, in which the α-Al crystals distribute in parallel fine plates along an angle of about 15° to the deformation direction. Moreover, the α-Al crystals are elongated to below 5 μm in thickness, below 50 μm in width and limitless in length, while the white Al_3Ni particles are refined to a sub-micrometer scale. Simultaneously, in the case of *x-o-y* plane (Fig. 3a), the fibrous α-Al crystals are elongated parallel to the deformation direction. In the *x-o-z* plane (Fig. 3b), the gray α-Al crystals are elongated at an angle of about 15° to the deformation direction. In *y-o-z* plane (Fig.3c), the α-Al crystals are distributed in the parallel plates below 50 μm in width and below 5 μm in thickness.



(a) *x-o-y* plane



(b) *x-o-z* plane



(c) *y-o-z* plane

Fig. 4 SEM micrographs of Al-Ni eutectic alloy after 4 passes ECAP by route Bc method.

The SEM microstructures of Al-Ni eutectic alloy samples after 4 passes of ECAP by route Bc method are shown in Fig. 4. It is found that the as-deformed eutectic lamella structure is still made of white Al_3Ni particles alternating with gray α-Al matrix, while the evolution of the eutectic microstructure depend on the orientation of the Al_3Ni particles in respect to the shear plane with the microstructure distributed more evenly. At the same time the lamellae spacing in the areas oriented parallel to the shear plane reduce (Fig. 4a and Fig. 4b). From Fig. 4c, it is also found that the lamella structure become bent and wavy in the plane perpendicular to the deformation. It is estimated that the lamellae spacing is about 1.0 μm and Al_3Ni particles also are refined to about 0.5-1.0 μm in mean size.

Figure 5 shows the XRD patterns of Al-Ni eutectic alloy samples deformed by ECAP in route A method. In spite of ECAP process, all peaks are made of Al_3Ni particles and α-Al matrix. With the increase of ECAP passes, one of the α-Al phase peaks has a faint enhancement. This is possible because the α-Al crystals are re-arranged in elongated fibres as described in the preceding section.

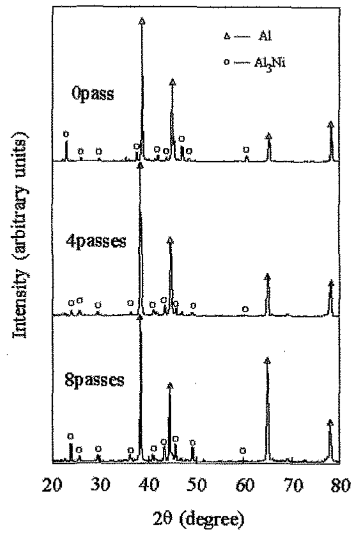


Fig. 5 XRD patterns of Al-Ni eutectic alloy sample deformed by ECAP in route A method.

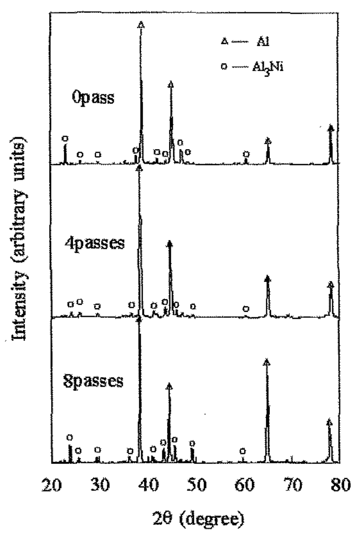


Fig. 6 XRD patterns of Al-Ni eutectic alloy deformed by ECAP with route Bc method.

Figure 6 shows the XRD patterns of Al-Ni eutectic alloy deformed by ECAP in route Bc method. In Fig. 6, all observable peaks are from Al_3Ni phase and α-Al matrix. From it, with the increase of ECAP passes, no obvious variation of peak intensities of Al_3Ni and α-Al matrix phases was found. This is due to the fact that in as-deformed samples, even though the lamellae eutectic microstructure became refiner to some degree, there was no essential impact on the results of the X-ray diffraction analysis.

Figure 7 shows the variation of the Vickers microhardness, Hv, together with the number of passes through the die for Al-Ni eutectic alloy by route A and route Bc methods, respectively. It was found that with an increase of ECAP passes, the Hv values of the Al-Ni eutectic alloy samples have an obvious enhancement from about 73 kg/mm^2 before ECAP processing to about 120 kg/mm^2 after 8 passes ECAP. At that time, though the alloy sample was subjected to only two ECAP passes, the Hv values attained a larger increase from those of the samples before ECAP. After four passes the Hv values showed only a faint increase. It was also found that the Hv values of as-deformed samples by ECAP of route Bc method are a little larger than that of samples by route A method.

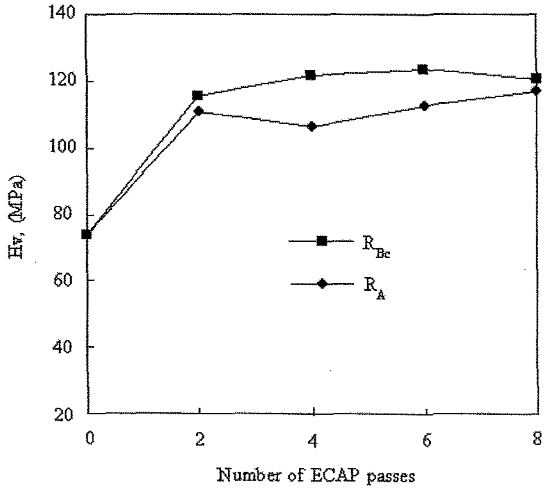


Fig.7 Variation of the Vickers microhardness, Hv, with number of passes through the die for Al-Ni eutectic alloy by route A and route Bc methods.

According to equation (1), a single ECAP passage through a die with ϕ=90° will always give a strain close to about 1.0 [9]. In reference [9] authors depicted the shearing strain characteristics within the crystalline sample when the sample was subjected to ECAP. Accordingly, when the ECAP process was in excess of two passes through the die, for route A method, shearing characteristics of similar and increasing distortions of original phases were generated. It was found that the α-Al crystals distributed at an angle of about 15° to the deformation direction for as-deformed samples by ECAP of route A, and uniform and fine sub-micrometer eutectic microstructures were attained. Whereas in the case of route Bc method, shearing strain directions will have a periodic restoration after totals of 4*n* passes, where *n* is an integer. In this study, because a large amount of shear strain was introduced into the samples during ECAP process, Al_3Ni particles were refined sub-micrometer scale and they were distributed more uniformly than before. As a result of this large strain introduced into the samples, work hardening occurred. Moreover, as the number of ECAP passes increased, many cracks were generated along the grain boundaries or in the inside of a crystal grain. So the Hv values of as-deformed Al-Ni eutectic alloy samples after ECAP processing significantly increased than that of before.

Al is known to be a light ecomaterial with low density of 2.7 Mg/m^3. Al-5.7mass%Ni eutectic alloy still retain a low density of 3.1 Mg/m^3. When the Al-5.7mass%Ni eutectic alloy was subjected to severe plastic deformation by ECAP technique, its hardness increased approximately to double the initial value. Therefore, the Al-5.7mass%Ni eutectic alloy with ECAP process is also suitable as an ecomaterial with high mechanical properties and low density.

4. SUMMARY

In this study, Al-5.7mass%Ni eutectic alloy was severely deformed by ECAP with route A and route Bc methods. The study demonstrated that in the as-deformed samples by ECAP of route A method, the α-Al crystals were evolved into elongated fibers at an angle of about 15° to the deformation direction and the Al_3Ni particles were cracked into fine sub-micrometer scale. For the as-deformed samples by route Bc method, the microstructures were mainly eutectic lamellae made of α-Al crystals alternating with fine Al_3Ni particles. It is estimated that the lamellae spacing is about 1.0 μm and Al_3Ni particles also are refined to about 0.5-1.0 μm in mean size. After ECAP processing, the Hv values of the Al-Ni eutectic alloy samples increased to about double values of that of before ECAP processing. Moreover, the Hv values after ECAP of route Bc method are a little larger than those of samples by route A method.

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