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Improvement in toughness of semi-solid light metal by the ECAP process

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Abstract

To improve the formability of high strength aluminum alloys (extra super duralumin 7075), the authors focused on two methods, semi-solid casting and Equal-Channel Angular Pressing (ECAP) processing. Solidified semi-solid cast samples of two different solid fractions were prepared. The samples were processed by ECAP, and the improvement in mechanical properties were investigated. Improvement in ductility increased with lower solid fraction. Four-pass ECAP-processed semi-solid cast AA7075 had higher strength and ductility than wrought AA7075-O.
Keywords: equal-channel angular pressing, semi-solid casting, 7075 aluminum alloy, grain refinement.

1 Introduction

There has been a requirement for an improvement in the fuel consumption of transportation equipment and this is achieved by weight saving. The application of aluminum alloys to a structural material has been expected because aluminum alloys have the low density and high specific strength. Although alloying and heat treatment widely change the mechanical properties of aluminum alloys, it is difficult to write high strength and ductility out of the equation. If they possess the properties of both high strength and ductility, aluminum alloys will be used for important components.

There has been some interest in the improvement in ductility of semi-solid cast alloys. Flemings [1] of MIT began research on casting in the semi-solid state for the reduction of solidification shrinkage, compositional segregation, and cavities

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in the early 1970s. It was observed in our papers [2, 3] that semi-solid casting, i.e., the homogenization of heating distribution by means of a stirring operation and high cooling rate, provides a reduction in micropores, spheroidizing of the primary phase, and grain refinement. Several investigations have been conducted on semi-solid casting using both aluminum cast and wrought alloys. It was found that solidified semi-solid casting alloys have mechanical properties close to the wrought target [4] and higher elongation and fatigue strength than those of the conventional cast alloys [5]. On the other hand, the effectiveness of severe plastic deformation (SPD) has been confirmed as a method for improving strength. Much research has been reported on the Equal-Channel Angular Pressing (ECAP) process, one of the SPDs, with various materials (e.g. Valiev and Langdon [6]) since Segal [7] first introduced the method in 1981. ECAP processing, which introduces severe shear strain to a billet, provides grain refinement and improvement in strength [8]. Grain refinement has an advantage in that it does not impair toughness. Our previous research [9, 10] revealed that modification of the eutectic microstructure by a combination of the two methods, semi-solid casting and ECAP processing, changes the morphology of brittle Si particles, from coarse acicular flake to fine spherical fiber, and improves the formability of AC4CH (Al-Si) cast alloy to a level comparable with that of annealed AA3003 wrought alloy. One of the reasons for obtaining the positive results may be the high castability of Al-Si cast alloy. There is a need to verify whether similar results are obtained in the case of wrought alloys.

The purpose of this study is to evaluate the mechanical properties of ECAP-processed semi-solid cast AA7075. The influence of the quenching temperature in semi-solid casting, i.e., solid fraction, on ECAP effectiveness is investigated.

2 Semi-solid casting

Semi-solid casting is defined as a method, in which semi-solid slurry coexisting in solid and liquid phase is cast into a mold. The high viscosity of the slurry metal leads to laminar flow during the casting and reduces the entrainment of gas and internal defects [11]. The solidified microstructure of the primary phase becomes refined and spheroidized because the molten metal is stirred in order to obtain semi-solid slurry with fine dispersed nuclei, while cooling to the prescribed quenching temperature. Therefore, it has been reported that elongation and the fatigue strength of semi-solid casting alloys are higher than those of the conventional alloy.

3 Processing of equal-channel angular pressing

ECAP processing is one of method of grain refinement by introducing high shear strain to a billet. The process of grain refinement in metal materials is generally known as a way to improve their strength without losing toughness and ductility. A typical die used for ECAP processing is shown in Fig. 1. The die has a channel with the same cross section of the inlet and outlet. Features of the channel are intersection angle, φ, and curvature of outer corner, ψ. The billet is subjected to shearing in the corner. The equivalent strain generated in the billet, ε_N, depends on the channel configuration and the number of ECAP passes, N, and is theoretically given by the following relation [12]:

$$\varepsilon_N = \frac{N}{\sqrt{3}}\left\{2\cot\left(\frac{\varphi}{2}+\frac{\psi}{2}\right)+\psi\csc\left(\frac{\varphi}{2}+\frac{\psi}{2}\right)\right\} \tag{1}$$

It is known that Route Bc, *i.e.*, a billet, is rotated 90° in the same sense about the extrusion direction between consecutive passes, provides finer microstructure owing to a three-dimensional deformation [13]. It was reported that grains become fine as a result of dynamic recrystallization without work hardening, which is accompanied by severe deformation [14, 15].

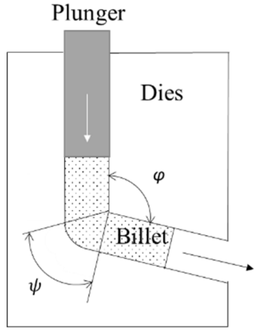


Figure 1: Schematic of a typical die for ECAP processing.

4 Experiments

4.1 Test materials and casting process

Semi-solid cast AA7075 aluminum ingots (Φ65 × 150 mm in height) were prepared. While molten AA7075 in a crucible was stirred by an electromagnetic stirrer, the temperature of the center portion of the slurry metal was monitored with a thermocouple. When the slurry was cooled to the prescribed quenching temperature, the thermocouple was pulled out and the crucible of the slurry was water quenched without pressure. The solid fraction depends on the quenching temperature, Tq. Semi-solid cast samples of two different solid fractions were prepared by quenching at Tq = 899 K or 893 K. The ingot was not heat treated after the casting. Wrought AA7075-O was used for comparison with the semi-solid cast AA7075.

4.2 Experimental conditions of ECAP processing

Billets having a rectangular shape (10 mm × 10 mm × 80 mm) for the ECAP processing were prepared from the test materials by avoiding visible cavities. The ECAP die shown in Fig. 2 had a channel with a square section (10 mm × 10 mm) and configurations, φ=90°, ψ=0°. It is theoretically expected that $\varepsilon_{N=1}$=1.15 is applied to a billet during one pass, according to Eq. (1). A billet was extruded by pressing a plunger at 0.5 mm/s on a universal testing machine (Shimadzu Corp., AG-500kNI). Cartridge heaters were used to control the die temperature at 473 K.

The inner die wall was lubricated using graphite paste. The extrusion load required for ECAP processing was monitored. ECAP processing was conducted repeatedly one-, two-, or four-times via Route Bc.

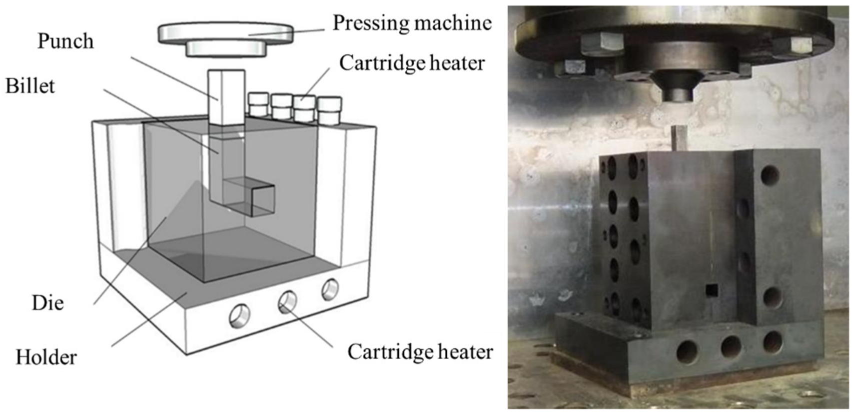


Figure 2: Schematic of ECAP facility.

4.3 Tensile test

The quasi-static deformation characteristic at a mean strain rate of 1.6×10^{-3} s^{-1} at room temperature was obtained by using a universal testing machine (Instron Corp., 5500R). Dumbbell-shaped specimens, with a gauge of 12 mm in initial length, 4 mm in width, and 3 mm in thickness, were cut by a wire-electric discharge machine along the extrusion direction.

4.4 Microstructure observation

Samples cut in the longitudinal section with respect to ECAP extrusion were mechanically polished and were observed using a laser microscope. Ten photographs of binarized microstructures measuring 1.4 mm × 1.0 mm were captured at random positions. Then average and standard deviations of the solid fraction, *Fs,* were calculated by the area fraction of the primary phase.

5 Results and discussion

5.1 Observation of microstructure

Figure 3 shows an as-cast ingot. The hole in the center of ingot was traces that was inserted a thermocouple. The microstructure of the test materials is shown in Fig. 4. The primary phases were spheroidized and contained micro voids. The solid fractions at 899 K and 893 K, measured by the solidified microstructure, were 58±3% and 68±4%, respectively. Semi-solid cast AA7075 alloys with two kinds of solid fraction were successfully fabricated. However, the target of the solid fraction was not achieved because the slurry temperature would drop with exposure to air at the free surface. Although AA7075 alloys have a deep solidification range [16], it is necessary to pay more attention to control of the slurry temperature.

Figure 3: Cross-section of a part of semi-solid AA7075 ingot.

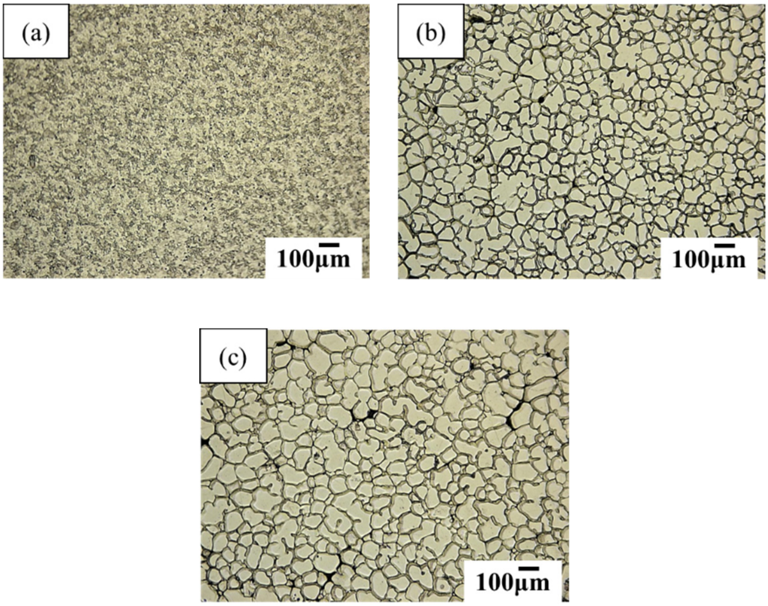


Figure 4: Microstructure of (a) wrought AA7075-O and semi-solid cast AA7075 (Fs = (b) 58±3%, (c) 68±4%).

The microstructure of ECAPed semi-solid AA7075 is shown in Fig. 5. The primary phase was refined with an increasing number of ECAP passes with the exception of four-pass ECAPed 58% solid fraction sample as shown in Fig. 5(c).

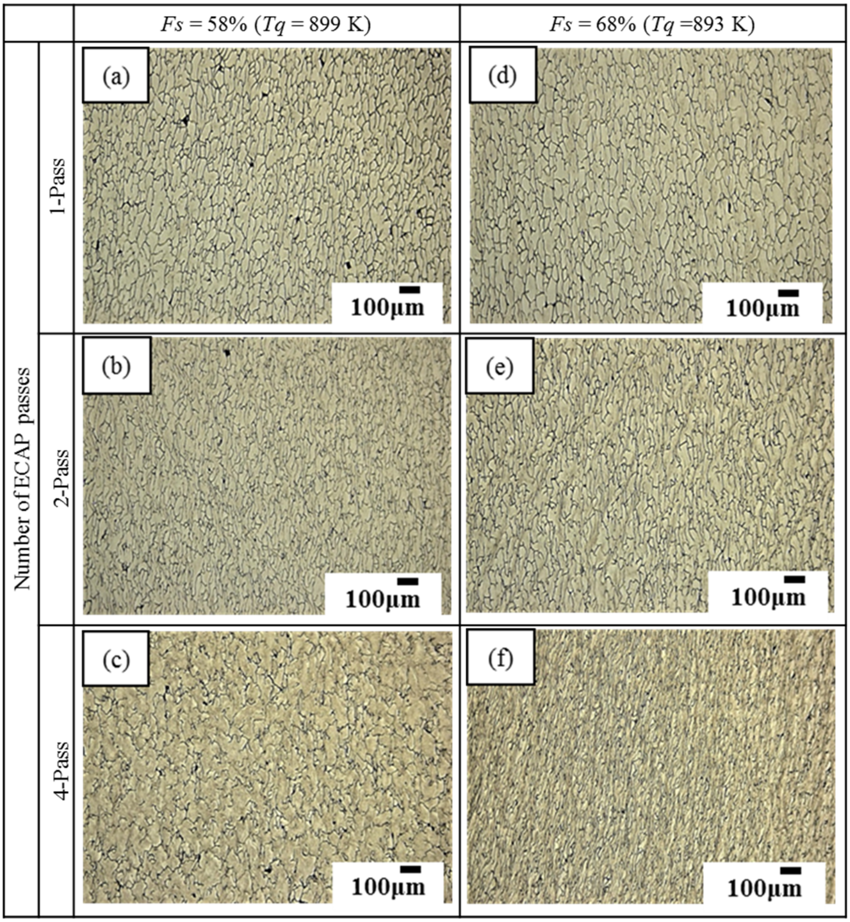


Figure 5: Microstructure of ECAP-processed semi-solid AA7075.

5.2 Extrusion load during ECAP processing

The relationship between the number of ECAP passes and the maximum extrusion load is shown in Fig. 6. The extrusion load required for a second pass (ε_N=2.30) showed a high value. This result is consistent with that reported in ref. [17]. It was found that the change in hardness of pure aluminum associated with the equivalent strain imposed by SPD reaches a maximum at about ε_N=2 [17]. The trend is concerned with the balance of the increase and decrease in dislocation density induced by stabilization of subgrain boundaries formed during SPD. The extrusion load of the 58% solid fraction sample was lower than that of the 68% solid fraction sample.

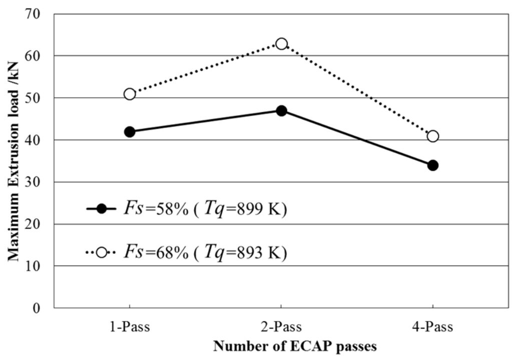
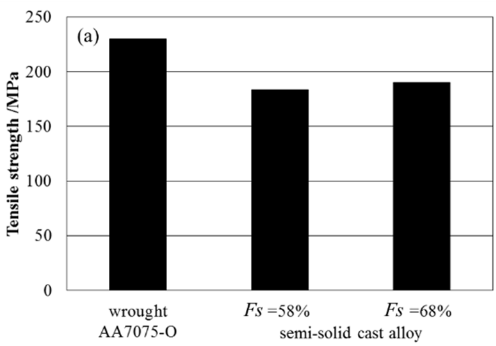


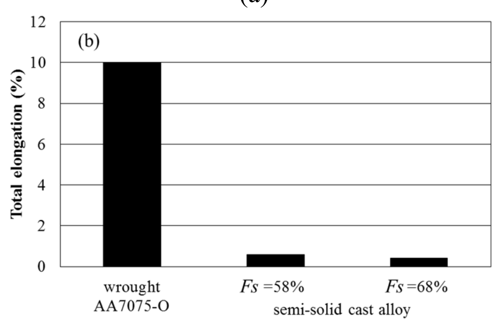
Figure 6: Change in the maximum extrusion load required for ECAP with number of processing passes.

5.3 Mechanical properties

Tensile test results of as-semi-solid cast AA7075 with two kinds of solid fraction are shown in Fig. 7. Both tensile strength and total elongation of as-semi-solid cast samples were lower than wrought AA7075-O, regardless of the solid fraction.



(a)

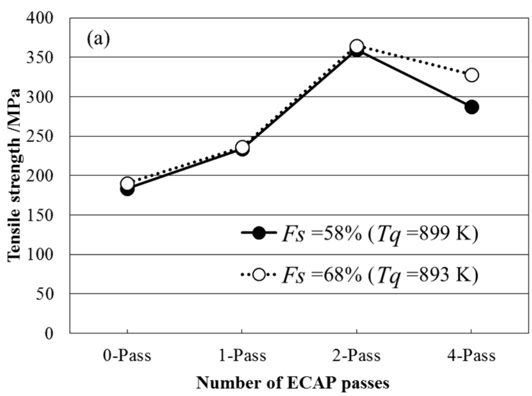


(b)

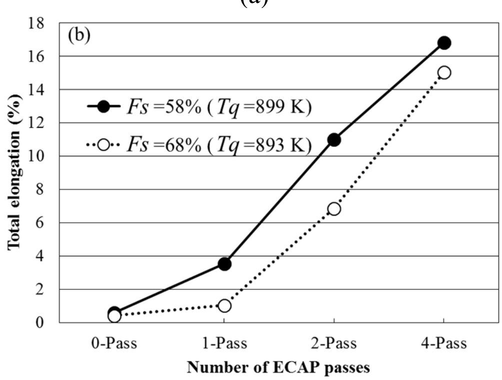
Figure 7: Influence of solid fraction on (a) tensile strength and (b) total elongation.

The change in mechanical properties brought about by ECAP is shown in Fig. 8. Both strength and ductility were improved by ECAP. The result showing that improvement in tensile strength reached a peak at second ECAP pass agrees with the extrusion load discussed in the preceding section. Total elongation improved with an increasing number of ECAP passes. As-cast samples showed brittle fractures, owing to the presence of micropores. Tensile strength and total elongation of four-pass ECAPed semi-solid samples were higher than those of wrought AA7075-O because the micropores were closed by the second ECAP pass.

The tensile strengths of semi-solid samples with two kinds of solid fraction were almost the same before the second ECAP pass. The tensile strength of the four-pass ECAPed 58% solid fraction sample was lower than that of the 68% sample, corresponding to growth of primary phase size. The elongation of the ECAPed 68% solid fraction sample was lower than that of the 58% solid fraction sample before the fourth ECAP pass.



(a)



(b)

Figure 8: Change in (a) tensile strength and (b) total elongation with number of ECAP passes.

6 Conclusion

ECAP-processed semi-solid cast AA7075 aluminum alloy was prepared. The authors discussed the relationship between the solid fraction of the solidified semi-solid microstructure and the improvement in mechanical properties brought about by ECAP. The obtained results are as follows:

1) Tensile strength and total elongation of four-pass ECAP-processed semi-solid samples were higher than those of wrought AA7075-O.
2) Tensile strengths of semi-solid samples with two kinds of solid fraction were almost the same before the second ECAP pass. The tensile strength of the four-pass ECAP-processed 58% solid fraction sample was lower than that of the 68% solid fraction sample.
3) Elongation of the ECAP-processed 68% solid fraction sample was lower than that of the 58% solid fraction sample before the fourth ECAP pass.

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