

Fabrication of Lotus-type Porous Aluminum by Continuous Casting Technique

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Lotus-type porous aluminum possessing directional pores aligned in one direction was fabricated through the continuous casting technique in the atmosphere of mixture of 0.25 MPa hydrogen and 0.25 MPa argon and only 0.5 MPa hydrogen at various transfer velocity. Porosity (volume fraction of pore) and pore diameter of lotus-type porous aluminum depends not only on partial pressure of hydrogen but also on transfer velocity. The porosity increases with increasing hydrogen pressure, which is explained by the Sievert's law. The porosity and pore size decrease with increasing transfer velocity, which is interpreted by increase in the supersaturated hydrogen and insufficient pore evolution through hydrogen diffusion. For fast transfer velocity, the hydrogen atoms in aluminum cannot migrate so long distance and contribute to the pore growth. For slow transfer velocity, the hydrogen atoms in aluminum can migrate longer distance and more supersaturated hydrogen atoms can contribute to the pore growth so that larger porosity is obtained.

Keywords: porous metal, lotus-type porous metal, aluminum, unidirectional solidification

1. Introduction

Aluminum and its alloys are used as light-weight materials in various industrial applications. On the other hand, porous aluminum possesses different features from bulk aluminum such as low density, permeability of fluid, energy and sound absorption [1] and is applicable to functional materials. Most of the porous metals possess isotropic and spherical pores. However, porous metals with cylindrical pore aligned in one direction (Lotus-type [2] and Gasar [3] porous metal) have also been developed. Since the cylindrical pore aligned in one direction provides no stress concentration around pores, the mechanical strength of lotus metals is higher than that of conventional porous metals [4,5]. Therefore, lotus-type porous aluminum is especially expected not only as functional materials but also as lightweight structural materials.

Although a few investigations for fabrication of lotus aluminum were carried out, the porosity (volume fraction of pore) was limited to be less than 20%. This is because hydrogen solubility in aluminum is quite low compared with other metals such as copper, magnesium and iron. Even for a metal with low solubility, higher porosity can be obtained by controlling gas pressure and solidification rate [6,7].

In the present study, lotus aluminum possessing directional pores aligned in one direction was fabricated through the continuous casting technique under various partial pressure of hydrogen and transfer velocity to obtain higher porosity.

2. Experimental Procedure

Continuous casting technique[8] was utilized for unidirectional solidification under controlling solidification condition. Figure 1 shows the schematic illustration of continuous casting apparatus. A pure aluminum (purity 99.99%) was melted by induction heating. Then the molten aluminum was pulled down through cooling mold at constant transfer velocity and continuously solidified in one direction. The solidification velocity was controlled by the transfer velocity.

In order to investigated the effect of hydrogen partial pressure, pure aluminum was melted in hydrogen 0.5 MPa, argon 0.5 MPa or mixture of hydrogen (0.25 MPa) + argon (0.25 MPa). The

transfer velocities were set at 0.9 mm/min. In order to investigate the effect of solidification rate, pure aluminum was melted in mixture of hydrogen (0.25 MPa) and argon (0.25 MPa) atmosphere, with changing the transfer velocity from 0.7 to 0.9 mm/min.

The cross-sections parallel and perpendicular to the solidification direction were cut out from the prepared aluminum ingots with a spark-erosion wire cutting machine (AQ325L, Sodik Co. Ltd., Kanagawa, Japan) and observed by an optical microscope. The porosity and pore diameter were obtained by image analysis (Macslope, Mitani Corp., Fukui, Japan).

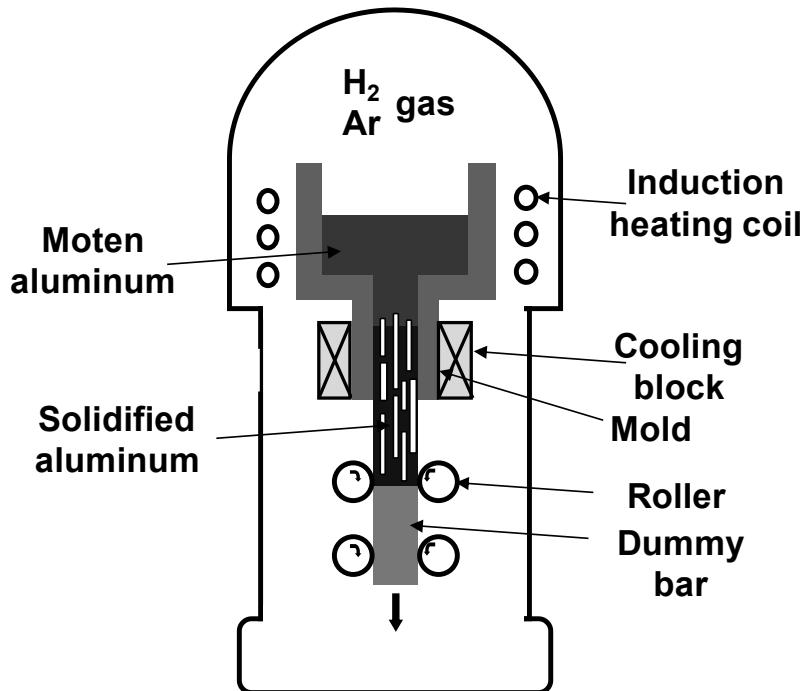


Fig. 1 Schematic illustration of continuous casting apparatus.

3. Experimental Results

3.1 Effect of Hydrogen Partial Pressure on Pore Formation in Aluminum

Figure 2 shows the pore morphology perpendicular ((a), (b) and (c)) and parallel ((d), (e) and (f)) to the solidification direction of the aluminum unidirectionally solidified at transfer velocity of 0.9 mm/min. No pores are observed in the ingot unidirectionally solidified in only Ar atmosphere (Fig 2 (a)). On the other hand, pores are formed in the ingots prepared hydrogen atmosphere (Fig 2 (b) and (c)). The porosities of the specimens in Figs. 2(b) and (c) are 10 and 17 %, and the average pore diameters are 582 and 1091 μm , respectively. The porosity and the pore diameter increases with increasing hydrogen partial pressure.

3.2 Effect of Solidification Rate on Pore Formation in Aluminum

Figure 3 shows the pore morphology perpendicular (upper row (a), (b) and (c)) and parallel (lower raw (d), (e) and (f)) to the solidification direction of the aluminum fabricated under the mixture of hydrogen/argon gas of 0.25/0.25 MPa. The transfer velocity are 0.7 ((a) and (d)), 0.8 ((b) and (e)) and

0.9 ((c) and (f)) mm/min, respectively. The porosities of the specimens in Figs. 2(a), (b) and (c) are 19, 14 and 12 %, and the average pore diameters are 975, 752 and 582 μm , respectively. Figure 4 shows transfer velocity dependence of (a) porosity and (b) average pore diameter. The porosity and average pore diameter decrease with increasing transfer velocity.

4. Discussion

Lotus aluminum is fabricated through unidirectional solidification in hydrogen atmosphere. The porosity increases with increasing hydrogen partial pressure and with decreasing transfer velocity. The hydrogen partial pressure dependence of porosity is the same tendency from that reported in other lotus metals [9, 10]. However the transfer velocity dependence of pore formation is different tendency from that reported in other lotus metals [8, 9]. Here, we first discuss the pore formation in aluminum, and next we clarify the transfer velocity dependence of pore formation in aluminum.

In metal-hydrogen system with exothermic reaction, the hydrogen solubility in the liquid phase is larger than that in the solid phase. When the melt is solidified in a hydrogen atmosphere, insoluble hydrogen in the solid is released at the solid-liquid interface during solidification and the hydrogen evolves the pores. Therefore, the porosity of lotus-type porous metals mainly depends on the magnitude of solubility gap of hydrogen between liquid and solid phases. We assume that the porosity p of lotus metals depends only on the hydrogen solubility gap between liquid and solid, C_{L-S} ,

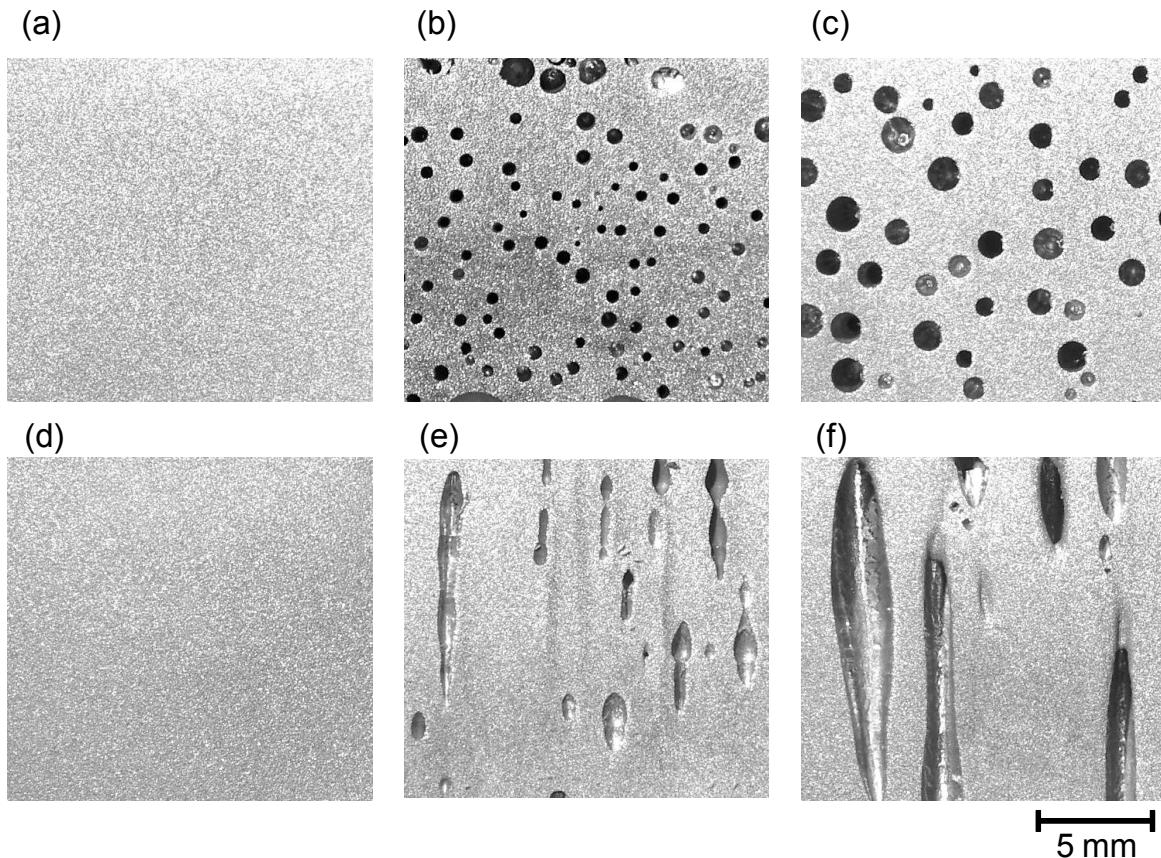


Fig. 2 Pore morphology perpendicular ((a), (b) and (c)) and parallel ((d), (e) and (f)) to the solidification direction of the aluminum unidirectionally solidified at transfer velocity of 0.9 mm/min.

The atmosphere is argon 0.5 MPa ((a) and (d)), mixture of hydrogen 0.25 MPa and argon 0.25 MPa ((b) and (e)) and hydrogen 0.5 MPa ((c) and (f)).

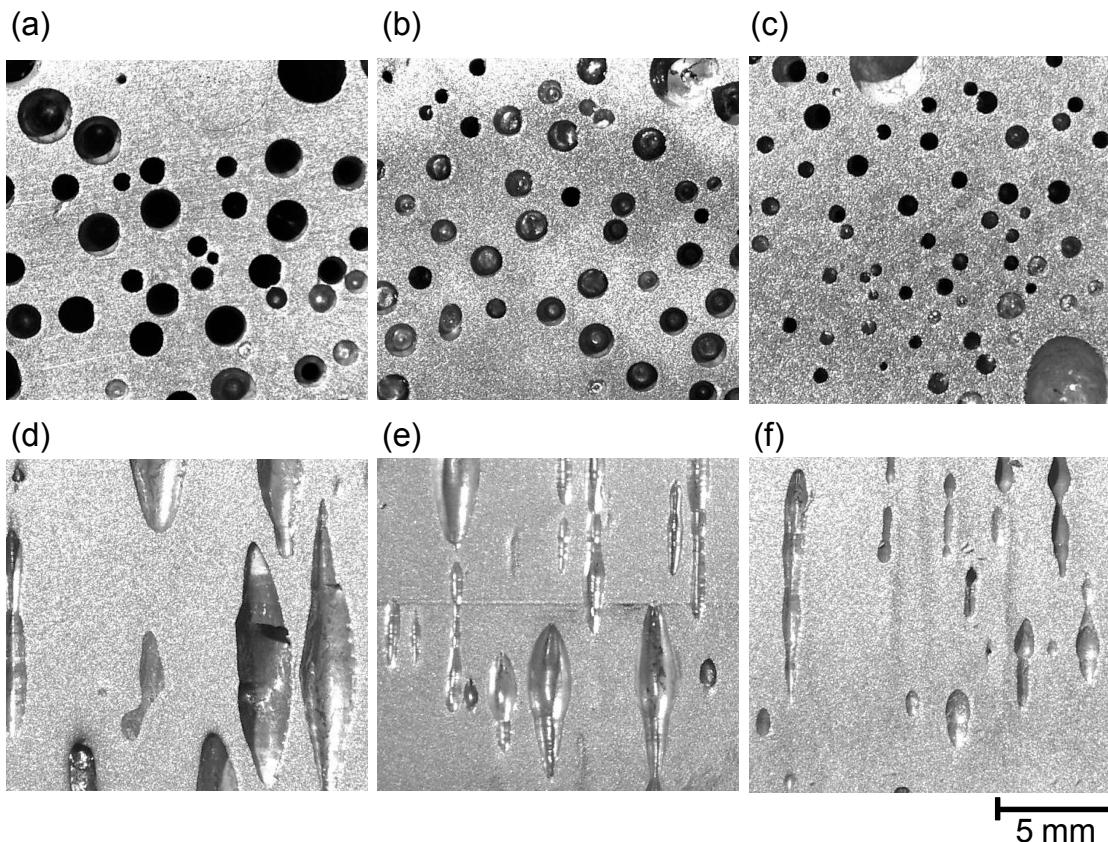


Fig. 3 Pore morphology perpendicular ((a), (b) and (c)) and parallel ((d), (e) and (f)) to the solidification direction of lotus-type porous aluminum fabricated under the mixture of hydrogen/argon gas of 0.25/0.25 MPa. The transfer velocity are 0.7 ((a) and (d)), 0.8 ((b) and (e)) and 0.9 ((c) and (f)) mm/min, respectively.

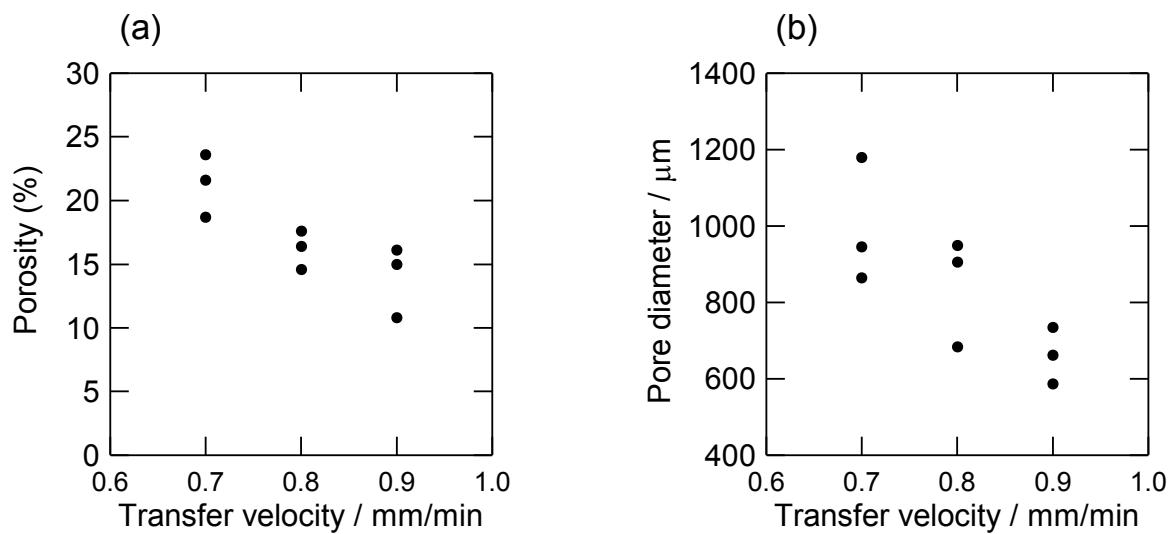


Fig. 4 Transfer velocity dependence of (a) porosity and (b) average pore diameter of lotus-type

porous aluminum.

at gas evolution-crystallization temperature T_n in hydrogen atmosphere of P_{H_2} [10-12]. It is well known that the porosity p can be written, by using C_{L-S} , as

$$p = \frac{C_{L-S}RT_n}{C_{L-S}RT_n + 2(1-C_{L-S})Vs(P_{H_2} + P_{Ar})} \approx \frac{C_{L-S}RT_n}{C_{L-S}RT_n + 2Vs(P_{H_2} + P_{Ar})} \quad (1)$$

where $C_{L-S} = C_L - C_S = (k_L - k_S)\sqrt{P_{H_2}/P_0}$, and C_L and C_S are respectively the solubilities of hydrogen in liquid and solid phases at T_n , and C_L and C_S follow the Sievert's law; the value of P_0 is 0.1 MPa. (In Eq. (1), the capillary pressure inside pores is ignored owing to negligibly small pressure compared with pressure of atmosphere.) V_s is the molar volume of solid metal, and V_{H_2} is the molar volume of hydrogen gas. R is the gas constant. When $C_L \ll 1$, $1 - C_L$ is approximated as 1, as shown in Eq. (1). By using eq. (1), we calculated $C_{L-S} = C_L - C_S = (k_L - k_S)\sqrt{P_{H_2}/P_0}$ from the porosity of lotus aluminum when T_n is 933 K. For two conditions ($p=10\%$ at $P_{H_2}/P_{Ar}=0.25/0.25$ MPa and $p=18\%$ at $P_{H_2}=0.5$ MPa), the same value of $C_{L-S}(9.1 \times 10^{-5}$ and $1.2 \times 10^{-4} \times \sqrt{P_{H_2}/P_0}$) are obtained. Therefore, porosity is approximately proportional to the partial pressure of hydrogen as shown Eq. (1). It is the same tendency from that reported in other lotus metals [8, 9] and suggests that pores are formed owing to hydrogen solubility gap between liquid and solid phase. Here, the difference between calculation and data from phase diagram was also reported in other lotus metals [10, 11].

However, the different transfer velocity dependence of pore formation from that of other lotus metals is found. For other lotus metals (such as copper [8] and stainless steel [9]), pore diameter decreases with increasing transfer velocity. It was suggested that when the solidification velocity increases, nucleation of pores easily occurs owing to increasing the degree of undercooling so that the average pore diameter decreases [8]. For lotus aluminum, the pore diameter also decreases with increasing transfer velocity. This is because of the low hydrogen solubility gap between liquid and solid aluminum. Therefore, in aluminum the supersaturated hydrogen atoms have to migrate relatively long distance toward the pores to contribute to the pore growth.

Here, the magnitude of difference of hydrogen solubility gap in aluminum (4.93×10^{-4} mol% [13]) is 40 times smaller than that in copper (2.09×10^{-2} mol% [14]) at H_2 0.1 MPa, while the magnitude of difference of diffusion coefficient of hydrogen (3.8×10^{-9} m²/s at 681 K [15]) is several times smaller than that in copper (2.2×10^{-8} m²/s at 1198 K [16]). Therefore, the diffusion distance of hydrogen in order to form pores is mainly affected by the low hydrogen solubility gap between liquid and solid aluminum. For fast transfer velocity, the hydrogen atoms in aluminum cannot migrate so long distance and contribute to the pore growth. For slow transfer velocity, the hydrogen atoms in aluminum can migrate longer distance and more supersaturated hydrogen atoms can contribute to the pore growth so that larger porosity is obtained.

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