Fabrication of a lotus-type porous Al-Si alloy by continuous casting with a thermal decomposition method

T B Kim, S Suzuki, H Nakajima
The Institute of Scientific and Industrial Research, Osaka University,
8-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

E-mail: kim23@sanken.osaka-u.ac.jp

Abstract. Lotus-type porous Al-14 wt.%Si alloy was fabricated by continuous casting at a transference velocity of 10 mm·min⁻¹ in vacuum and by adding Ca(OH)₂ pellets to the crucible. The porosity and the pore diameter increased by varying the amount of Ca(OH)₂ from 0.2 g to 0.6 g. In the case of 0.6 g Ca(OH)₂, the average porosity was about 30 % and the average pore diameter was about 3.8 mm. XRD patterns of the pellets after continuous casting showed the Ca(OH)₂ pellet did not decompose completely during continuous casting. The TG-DTA analysis showed that the Ca(OH)₂ pellet decomposes more slowly than Ca(OH)₂ powder. These results suggest that the Ca(OH)₂ pellets gradually decomposed in the crucible during the continuous casting, which is suitable for the supply of hydrogen over extended periods.

1. Introduction

Porous metals are expected to be used as light-weight materials, catalysts, electrodes, vibration and acoustic energy damping materials, impact energy absorption materials etc. [1]. Porous aluminium alloys have especially attracted attention for use in various applications such as light-weight structural materials. While many kinds of metal foams have spherical pores [1] the lotus-type porous metals have pores aligned in one direction [2-5]. Lotus metals have superior mechanical properties that originate from unidirectional pores which are different from conventional porous metals that consist of almost isotropic and spherical pores [2, 3]. Therefore, fabrication of lotus-type porous aluminium alloys is desired in many industrial fields.

Park et al. reported a lotus-type porous Al-Si alloy that was fabricated using the continuous casting technique in a pressure hydrogen atmosphere [4]. However, the use of pressurized hydrogen gas is expensive because of the high-pressure chamber and special handling is required for the explosive H₂ gas. To address these problems a thermal decomposition method was developed to fabricate lotus metals without using pressurized hydrogen gas [6]. In this thermal decomposition method compounds containing potential gaseous elements are thermally decomposed in liquid metal and the decomposed gas atoms form pores at the solid – liquid interface during solidification because of the gas solubility gap between the solid and the liquid. Until now investigations on the thermal decomposition method have been done using the mould casting technique. However, the mould casting technique is limited by the length of samples and the control of pore distribution.

In this study the thermal decomposition method was applied to the continuous casting technique to control pore morphologies of lotus aluminium alloys. A long and continuous supply of gas to the melt was, however, required for this continuous casting method. Therefore a new additional technique was required for the continuous casting. Since solidification during mould casting is a short process the compound used should decompose quickly into a supply gas. Ca(OH)₂ was chosen for this study as the
compound for the thermal decomposition reaction because gaseous elements are supplied to the melt. Ca(OH)$_2$ decomposes at a temperature below the melting temperature of aluminium alloys. For continuous casting the compound powder was compacted into pellet form to reduce the surface area. This process was expected to reduce the reaction rate of the compound and thus lengthen the reaction time. This paper reports the fabrication of a lotus Al-Si alloy by the continuous casting technique and by the addition of Ca(OH)$_2$ pellets.

2. Experimental procedure
Ca(OH)$_2$ pellets of 15 mm diameter and 1.25 mm thickness were prepared by compression moulding of a mixture of aluminium powder and Ca(OH)$_2$ powder of equal weight. The compression load was 20 kN and the compression time was 60 s.

Ingots of Al-14 wt% Si (330 g) and pellets that included Ca(OH)$_2$ of 0.2, 0.4, 0.6 g were heated in the graphite crucible by an induction coil in vacuum. After the temperature reached 1023 K the melt was maintained for 300 s to dissolve and diffuse gas into the melt uniformly. The melt was pulled down by the dummy bar of non-porous pure aluminium through a cooled mould (10 mm in thickness and 30 mm in width) at a transference velocity of 10 mm·min$^{-1}$.

Fabricated slabs were cut by a spark-erosion wire cutting machine. Cross-sections were observed with an optical microscope. The porosity and pore diameter were measured on the cross-section perpendicular to the transference direction by the image analyzer (Win ROOF, Mitani Co.).

The decomposition temperature of the Ca(OH)$_2$ pellets was measured under an Ar flow of 150 ml/min and a heating rate of 10 K/min using a TG-DTA (TG-DTA2000SA, Bruker Co.). Ca(OH)$_2$ pellets before and after the continuous casting, aluminium powder and Ca(OH)$_2$ powder were analyzed using XRD (X-ray diffraction). Diffraction patterns were recorded between scattering angles of 10° and 70° at 10°/min (Cu Ka, RINT2000).

3. Results and discussion
Figure 2 (a) shows cross-sections in the perpendicular to the transference direction of the samples cut from the starting point of the transference to 100 mm at an interval of 10 mm. Figure 2(b) shows the cross-section parallel to the transference direction. Figure 2(a) and (b) show that the fabricated samples have cylindrical pores elongated in the transference direction. The sample fabricated with 0.6 g Ca(OH)$_2$ has an average porosity of approximately 30 % and an average pore diameter of about 3.8 mm.

Figures 3(a) and (b) show the effect of added Ca(OH)$_2$ pellets on the average pore porosity and the pore diameter, respectively. Both the porosity and the pore diameter increased as the amount of added
Ca(OH)$_2$ increased. At 0.2 g Ca(OH)$_2$ pores were not generated in the sample. The concentration of dissolved hydrogen does not obtain the equilibrium solubility of hydrogen in the liquid aluminium. Therefore, the amount of hydrogen excluded from the liquid to the solid – liquid interface is too small to generate pores. With an increasing amount of pellets the amount of excluded hydrogen increases and both the porosity and the pore diameter increases. Figures 3(a) and (b) indicate that there is no saturation until 0.6 g Ca(OH)$_2$ was used. Even for 0.6 g Ca(OH)$_2$ the concentration of hydrogen in the melt does not obtain the maximum solubility.

![Figure 2](image-url)

**Figure 2.** (a) Cross-sectional views parallel and (b) perpendicular to the transference direction of lotus-type porous Al-Si alloy fabricated with 0.6 g Ca(OH)$_2$.

![Figure 3](image-url)

**Figure 3.** Dependence of the average porosity (a) and the average pore diameter (b) on the amount of added Ca(OH)$_2$.

After the continuous casting, pellets with their original shape were found in the crucible. Figure 4 shows XRD patterns of aluminium powder, Ca(OH)$_2$ powder and Ca(OH)$_2$ pellets before and after the continuous casting. XRD peaks of the pellets before the continuous casting indicate that aluminium and Ca(OH)$_2$ did not change during compression moulding. The XRD pattern of the pellet after the continuous casting shows CaO peaks. CaO probably forms by the following chemical reaction:

$$\text{Ca(OH)}_2 \rightarrow \text{CaO} + \text{H}_2\text{O}(g), \quad \text{H}_2\text{O}(g) \rightarrow 2\text{H} + \text{O}_2$$

Furthermore, the pellet’s XRD shows that Ca(OH)$_2$ was still present after the continuous casting. The Ca(OH)$_2$ pellets, therefore, do not decompose completely during the heating up process and the continuous casting for about 100 min.

![Figure 4](image-url)

Figure 5 shows results of TG-DTA measurements for Ca(OH)$_2$ powder and a Ca(OH)$_2$ pellet before continuous casting. From DTA results the first reaction peak at 723 K is assigned to the decomposition reaction of Ca(OH)$_2$ [7] and the second reaction peak is the melting point of aluminium. From TG results, the amount of decomposed Ca(OH)$_2$ pellet is less than that of Ca(OH)$_2$ powder. The smaller reaction surface area of the compacted pellet reduces the decomposition rate and thus gas may be supplied for a longer time than would be the case for the powder.
4. Conclusion
Lotus-type porous Al-Si alloys were fabricated by continuous casting using the thermal decomposition method. The following properties were observed:
1. The average porosity was approximately 30 % and the average pore diameter was about 3.8 mm for the sample that was fabricated by addition of 0.6 g Ca(OH)$_2$.
2. By varying the amount of Ca(OH)$_2$ from 0.2 g to 0.6 g, the porosity and pore diameter increased.
3. As Ca(OH)$_2$ pellets have a lower decomposition reaction rate than Ca(OH)$_2$ powder the pellets may be used as a suitable gas supply source for the continuous casting.

Acknowledgements
This work was supported by the Grants-in-Aid for Young Scientists and the Global COE program (Centre of Excellent for Advanced Structural and Functional Materials Design) from the Ministry of Education, Culture, Sports, Science and Technology. The pure aluminium ingots were supplied by the Light Metal Educational Foundation, Inc.

Reference
[1] Banhart J 2001 Prog. in Mater. Sci. 46 559
[2] Hyun S K, Murakami K and Nakajima H 2001 Mater. Sci. Eng. A 299 241
[3] Nakajima H 2007 Prog. Mater. Sci. 52 1091
[4] Park J S, Hyun S K, Suzuki S and Nakajima H 2008 Metal. Mater. Trans. A accepted. Available from: <http://dx.doi.org/10.1007/s11661-008-9710-3>
[5] Shapovalov V I 1996 Mater. Sci. Forum 485 215
[6] Nakajima H, T Ide 2008 Metall. Mater. Trans. A 39A 390
[7] Sawada Y, Ito Y 1994 Thermochimica Acta 232 47