Fabrication of Al-Cu alloy with elongated pores by continuous casting technique

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Abstract. Al-4.5wt%Cu was unidirectionally solidified by continuous casting technique under hydrogen pressure of 0.1MPa at the transference velocities ranging from 1 to 50 mm·min\(^{-1}\). The fabricated slabs have microstructures of columnar \(\alpha\)-dendrite and eutectic, which are typical for hypo-eutectic Al-Cu alloys. Elongated pores are observed in the eutectic region surrounded by several columnar \(\alpha\)-dendrites. The shapes of the pores are affected by that of the surrounding \(\alpha\)-dendrites. The average pores diameter is several ten \(\mu\)m smaller than the average dendrite arm spacing, which decreases with increasing solidification rate. Therefore, the pore diameter varies from about 200 \(\mu\)m to 30 \(\mu\)m with increasing transference velocity from 1 to 50 mm·min\(^{-1}\). The porosity of the fabricated samples is in the range between 2 ~ 6 %. There is not significant dependence of the porosity on the transference velocity in the range of the present study. The porosity is similar to the reported value of Al-Si, where the area fraction of eutectic region is smaller than that of \(\alpha\)-dendrite.

1. Introduction
Lotus-type porous aluminum alloys (lotus aluminum alloys), which possess small aligned pores in one direction, are expected to be used as lightweight structural materials for transport machinery. In recent years the fabrication methods for lotus aluminum alloys have been developed. Park \textit{et al.} reported that fabrication of lotus Al-Si alloy became possible by continuous casting technique \cite{1}. The lotus aluminum alloys are produced by unidirectional solidifications in pressurized hydrogen atmosphere. The pores are evolved by insoluble hydrogen when the melt dissolving hydrogen is solidified \cite{2,3}. Now it is desired to apply this fabrication technique to various kinds of aluminum alloys. However, the porosity and the pore morphology are affected complicatedly by the solidification conditions and the alloying elements, as known in previous investigations of casting defects \cite{4}. Therefore it is still difficult to predict the pore formation in each aluminum alloy under each solidification condition. Systematic investigations of pore formation are necessary for fabrication of lotus aluminum alloys.

The present study was undertaken to investigate the pore formation mechanism in binary aluminum alloys during unidirectional solidification using continuous casting technique in a pressurized hydrogen gas. As the aluminum alloy, Al-Cu was selected because it is widely used as structural materials and its solidification behavior has been investigated by many researchers \cite{5,6}. This paper reports the relationship between the microstructure and the pore morphology in the Al-Cu slabs fabricated by the continuous casting technique in order to elucidate the pore formation mechanism.
2. Experimental

Figure 1 shows the schematic drawings of the continuous casting technique in this study. Pure aluminum ingots and Al-40wt.%Cu ingots were set in the crucible so as to be Al-4.5wt.%Cu of 500 g in weight. The ingots were melted by induction heating under hydrogen pressure of 0.1 MPa.

The crucible had a rectangular hole (10×30 mm$^2$) at the bottom, to which the mold was connected. A dummy bar of graphite was placed in the mold before the transference. The temperature of the molten Al-Cu in the crucible was measured by a thermocouple, and was maintained for longer than 600 sec after the temperature reached 1173K in order to dissolve hydrogen sufficiently into the melt.

Then the melt was pulled down by the dummy bar through the mold by the pinch rollers. The transference velocity of the dummy bar was controlled by the rotation of the pinch rollers. The transference velocity was set at 1, 2, 5, 20 and 50 mm·min$^{-1}$. Thus, a long Al-Cu slab with pores was fabricated by the continuous casting technique.

The fabricated Al-Cu slabs were cut using a spark-erosion wire cutting machine (Model LN1W, Sodick Co.) in directions parallel and perpendicular to the transference direction. The cross-sections were polished, etched and observed by an optical microscope. The weight and the volume of a prismatic sample piece cut out from the lotus carbon slab were measured and the density of the sample piece was calculated.

3. Results and discussion

Figure 2 shows the density of the Al-Cu slabs fabricated at the various transference velocities. There seems the density does not depend on the transference velocity in the range between 1 and 50 mm·min$^{-1}$. The average density with the standard deviation is 2.73(± 0.03) x10$^3$ kg·m$^{-3}$. The porosity $p$ of the fabricated slabs was estimated from the following equation.

$$p (%) = (1 - (\text{density with pores} / \text{density without pores})) \times 100 (%) \quad (1)$$

The estimated porosity varies between 2 and 6 % when the density of Al-Cu alloy without pore is assumed to be 2.8 x 10$^3$ kg·m$^{-3}$ [7]. The difference in density between the samples with and without pores is so small that the variation of the estimated porosity is sensitive to the deviation of the density. Therefore, significant dependence of the porosity on the transference velocity is not found in the present study.

The cross-sections of the Al-Cu slabs fabricated at various transference velocities are shown in figure 3 in the direction perpendicular and parallel to the transference direction. The cross-sections show pores elongated in the transference direction with a diameter smaller than several hundred μm.

![Figure 1](image1.png)  
**Figure 1.** Schematic drawings of continuous casting technique in a pressurized gas chamber for fabrication of lotus metals.

![Figure 2](image2.png)  
**Figure 2.** Density of fabricated Al-Cu slab.
The cross-sections show the tendency that pores become smaller with increasing transference velocity. Figures 4 and 5 show the microstructure and the pores on the cross-sections perpendicular and parallel to the transference direction, respectively. The white and dark phases are α-dendrite and eutectic phase, respectively. The microstructure is typical for hypo-eutectic Al-Cu alloys [4]. The pores are observed in the eutectic region among several dendrites (figure 4) and elongate along the surrounding columnar α-dendrites in the transference direction (figure 5). The shape of the pores is affected by the surrounding α-dendrites.

The primary dendrite arm spacing (DAS), which is the distance between dendrites as shown in figure 4, was measured for more than 50 pairs of dendrites at each transference velocity and the average values and the standard deviations are shown in figure 6. The dendrite arm spacing decreases with increase in the transference velocity due to the increase of the solidification rate.

The statistics of the size of the pores observed on the cross sections are shown in figure 6, as well. These results show that the average pores diameter is several ten μm smaller than the average dendrite arm spacing. These pores are considered to form and grow in the eutectic region surrounded by several primary α-dendrites. It has been reported that the pore forms in the eutectic region in the case of unidirectional solidification of Al-Si alloys in hydrogen atmosphere [1], and Al-Cu in air and in vacuum [8]. The rejected hydrogen atoms during the solidification of α-dendrites are considered to escapes to the mushy zone or the liquid phase so that large pores are not formed. On the other hand, the eutectic region solidifies later than the α-dendrites, the rejected hydrogen atoms during the solidification of the eutectic phase are considered to form at the interface between the liquid and the eutectic phase [1].

The pores become smaller and irregular because the pore growth is disturbed by the surrounding dendrites with decrease in area fraction of the eutectic region in the case of lotus Al-Si [1]. As the Al-4.5wt.% Cu in the present study has a smaller area fraction of eutectic region than that of α-dendrites. Therefore the shape and the size of the pores seem to be limited by the surrounding α-dendrites.
Figure 5. Pores and microstructures on the cross-section parallel to the transference direction (2 mm·min⁻¹).

Figure 6. Pore diameter and dendrite arm spacing of the fabricated Al-Cu slab against the transference velocity.

The investigation on the pore formation in hypo-eutectic Al-Si alloys indicated that the porosity increases with increase in Si content, because of the increase in the area fraction of the eutectic region where pores form [1]. The Al-Cu alloy in the present study has a smaller area fraction than that of the α-dendrite and has porosity, which is similar to that of Al-Si alloys with a small area fraction of the eutectic region, such as Al-4wt.% Si.

4. Summary
Al-4.5wt.%Cu slabs with pores were fabricated by unidirectional solidification with using the continuous casting technique in a pressurized hydrogen atmosphere.

(1) The porosity of the fabricated Al-Cu slabs is in the range between 2 and 6 % and has no significant dependence on the transference velocity. The porosity in the present study is similar to the reported value of Al-Si, where the area fraction of eutectic region is smaller than that of α-dendrite.

(2) Pores elongated in the transference direction are observed in the eutectic region among several α-dendrites. The shape of the pores is determined by that of the surrounding α-dendrites. The pore diameter is similar to the primary dendrite arm spacing, which decreases with increasing transference velocity.

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References
[1] 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>
[2] Nakajima H 2007 Prog. Mater. Sci. 52 1091
[3] Shapovalov V 1998 Porc. Mater. Res. Soc. Symp. 521 281
[4] Samuel A M and Samuel F H 1992 J. Mater. Sci. 27 653
[5] Sharp R M and Flemings M C 1973 Metall. Trans. 4 997
[6] Lee P D and Hunt J D 1997 Scripta Mater. 4 399
[7] Smithells C J 1992 Metals Reference Book (Oxford: Butterworth-Heinemann Ltd.) pp 14-14
[8] Nishi S and Kurobuchi T 1974 J. Jpn. Inst. Light Metals 24 245