Fabrication of Porous Aluminum Alloy with Aligned Unidirectional Pores by Dipping Pipes in Base Metal Melt

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A pure aluminum pipe was dipped into Al–13 mass%Si melt at 873 K. After holding time, the specimen was cooled and solidified. With holding time shorter than 360 s, the pipe was connected with the base metal without melting of the inner wall. Aligned 37 pipes with internal diameter of 3 mm were dipped into the base metal, also. Even the distance between the pipes was as small as 0.5 mm, the melt of the base metal penetrated among the pipes. The result of the EPMA analysis showed metallic bonding between the pipe and the base metal by Si diffused into the pure aluminum pipe side. It became possible by this method to fabricate porous aluminum alloys with aligned unidirectional pores by controlling the porosity, pore diameter and pore distribution. [[doi:10.2320/matertrans.MAW201211](https://doi.org/10.2320/matertrans.MAW201211)]

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1. Introduction

Recently, weight reduction of transportation is strongly desired for resource and energy saving. Therefore, porous metals are actively investigated as light-weight materials to solve this problem.¹⁾ However, the specific strength of conventional porous metals decreases with increasing porosity, because of stress concentration near the cell walls. On the other hand, the specific strength of porous metals with aligned unidirectional pores does not decrease even with increasing porosity, because of lack of stress concentration.^{2,3)}

These kinds of porous metals with aligned unidirectional pores are usually fabricated with solubility gap of hydrogen between the liquid and the solid using unidirectional solidification processes.^{4,5)} They are known as lotus-type porous metals or Gasar metals. However, this method has some obstacles to solve for practical use, such as difficulty of pore shape control, complicated manufacturing equipment, and slow fabrication speed. From these reasons, much simpler fabrication method is strongly desired.

Therefore, we invented a new fabrication method of porous metals with aligned unidirectional pores by dipping pipes into metal melt. The principle of the fabrication method is as follows. First, pipes are aligned and set in arbitrary positions. Second, the pipes are dipped into base metal melt and held for given holding time. Then the pipes and the melt are cooled and solidified. At last the sample becomes a porous metal when the pipes remain and bond with the base metal metallurgically (Fig. 1(a)). This simple method is very advantageous because the pore shapes, size and porosity can be decided by the dimension of the pipes and the initial position of the pipes easily (Fig. 1(b)).

In this study, we investigated the effect of the experimental conditions to establish this method. To maintain the shape of

Fig. 1 Schematic illustration of the porous aluminum alloy fabricated by this method. (a) Full view. (b) Cross section in the radial direction of the pipes. (c) Alignment of the pipes.

the pipes, melting point of the pipes should be higher than that of the base metal. From these reason, we selected industrial pure aluminum and Al–13 mass%Si as the pipe material and the base metal, respectively. Both of them are practically used light-weight materials. Dipping experiments were performed to elucidate the following points using these materials. First, the holding time of pipe in the melt was investigated to maintain the internal shape of the pipes without melting by the experiment with a thick pipe. Second, the penetration of the melt among the pipes was investigated as well as the microstructure and the distribution of Si in the vicinity of the boundary between the pipe and the base metal by the experiment with multiple pipes. From these results, the bonding mechanism and the possibility of fabrication of porous aluminum alloys were discussed.

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Table 1 The composition of 99.99 mass% Al ingot and Al–24.9 mass% Si ingot used to prepare the base metal.

	(mass%)			
	Si	Fe	Cu	Al
99.99 mass% Al	0.004	0.003	0.001	bal.
Al–24.9 mass% Si	24.9	0.20	0.00	bal.

Table 2 The composition of the A1070 pipe and A1050 pipe.

	(mass%)							
	Si	Fe	Cu	Mg	V	Ti	Remains	Al
A1070	0.03	0.11	0.01	0.02	0.01	0.01	≤0.03	bal.
A1050	0.10	0.33	0.00	0.00	0.01	0.01	0.00	bal.

2. Experimental Procedures

2.1 Investigation of the optimum holding time

Base metal ingots of Al–13 mass% Si were prepared by melting 99.99 mass% Al together with Al–24.9 mass% Si (Table 1). During the solidification of the alloy melt in a mold, a cooling curve was obtained by thermal analysis. The cooling curve showed a region of thermal arrest at the eutectic temperature, which followed after just a small region of temperature drop caused by the proeutectic solidification. The content of Si in the base metal ingots was confirmed to be in the range between 13.61 and 15.22 mass% by gravimetric analysis, which was performed by Sumitomo Metal Technology, Inc. From these results, the composition of the base metal was confirmed to be almost eutectic, including a small fraction with hyper eutectic composition. A pure aluminum pipe (A1070, Table 2) with internal diameter of 18 mm and wall thickness of 1 mm was prepared. The bottom end of the pipe was capped with alumina cement in order to prevent the entry of melt into the inner side of the pipe.

The base metal ingots of 70 g were set in a crucible (Fig. 2) and the pipe was set over the crucible fixed under the pipe holder, which was movable vertically. After setting the apparatus with the ingots and the pipe into an electric furnace, it was heated and the base metal was melted. The temperature was kept at 873 ± 5 K with the feedback controlling by measurement of the temperature of the melt. The atmosphere was air. At 873 K the pipe was dipped into the melt by shifting the pipe holder downwards. The temperature 873 K was selected because it is higher than the liquidus temperature of Al–13 mass% Si and is lower than the melting point of pure aluminum.⁶⁾

After a given holding time up to 600 s, the crucible was

Fig. 2 Schematic illustration of the experimental apparatus.

taken out of the furnace and cooled down in the air. Furthermore, the temperature change of the melt during this experiment was measured.

The solidified specimen was cut along the central axis of the pipe. The change of the pipe wall thickness was investigated across different holding times by observing around the pipe wall with an optical microscope. Another specimen fabricated under the same condition was sliced in the radial direction of the pipe with an interval of 5 mm. The wall thickness was measured at more than 12 points on the radial cross-section by image analyzer WinROOF (Mitani Corporation, Tokyo, Japan). The average thickness was obtained from the measured values.

2.2 Investigation of penetration of melt among pipes, microstructure and Si distribution

Thirty-seven pure aluminum pipes (A1050, Table 2, internal diameter 3 mm, wall thickness 0.5 mm) were aligned with an interval s (Fig. 1(c)) of 0.5 and 1 mm and fixed under the pipe holder. The base metal ingots of 110 g were set in the crucible. Dipping experiments were carried out with holding time of 0 s in the same procedure as shown in the section 2.1.

The porosity of a porous metal is defined as the volume fraction of pores in the porous metall. Since the structure of the porous metal in this study was considered not to vary significantly in the longitudinal direction, the porosity was calculated as follows:

$$\text{Porosity } p (\%) = \text{Area of the pores } A_p / \text{Area of cross section of the specimen } A \times 100 \quad (1)$$

The value of A was measured as the hexagonal area drawn with the dotted lines in Fig. 1(b).

The concentration distribution of Al and Si in the radial direction of the pipe was then determined as shown in Fig. 3 by EPMA (JXA8100, JEOL Ltd., acceleration voltage 15 kW,

2000 μm square). The EPMA analyses were carried out by Sumitomo Metal Technology, Inc. Then, a concentration profile of Si was obtained through normalization of the values of Al and Si concentrations under approximation that this system was considered as Al–Si binary system.

R: Radial direction of the pipe.

Fig. 3 Schematic illustration of scanning area of EPMA analysis.

3. Results and Discussion

3.1 Change of pipe wall thickness by holding time

Figure 4 shows the cross-sections of the fabricated samples using one pipe with internal diameter of 18 mm. There was not a remarkable gap between the pipe and the base metal at any holding time. Although the pipe retained its internal shape at short holding times, the pipe melted and the base metal melt flowed into the pipe at holding time 600 s. The pipe retained its internal shape at holding times 420 s, because the melt was held by the alumina cement to cap the bottom end of the pipe although the pipe was melted. Figure 4 also shows that the pipe wall thickness decreased with increasing holding time. These results showed that the

holding time should be brief enough and the pipe wall should be thick enough to prevent melting the internal wall of the pipe. Furthermore, it was realized that the pipe and the base metal seemed to bond even at holding time of 0 s.

Figure 5 shows the temperature change of the melt during the experiment with holding time 120 s. Even at the holding time of 0 s, the thickness of the pipe decreased from that of the original one, because it took about 420 s to solidify the specimen after the crucible had been taken out from the furnace.

In previous study, Kosaka, *et al.* investigated the rate of dissolution of the Al into Al–13 mass% Si at 873 K.⁷⁾ Their data showed the rate of dissolution M to be $1.35 \times 10^{-3} \text{ mm}^2/\text{s}$. Substituting the value M and time t into the following equation, the erosion depth x from the pipe surface can be estimated:

$$x = \sqrt{Mt} \quad (2)$$

In this study, the time t can be interpreted as the period from the time of dipping the pipe into the melt to the end of the solidification. The erosion depth from the pipe surface was estimated to be about 0.7 mm at holding time 0 s with the time t of 420 s. However, Fig. 4 shows that the pipe was eroded by only 0.1 mm. This discrepancy was considered to be caused by difference in the conditions, because temperature and phase change took place during solidification in this study. The convection in the melt may be different between in this study and in the previous study. Furthermore, the rate of dissolution of the pipe during holding the pipe in the

Fig. 4 Specimens fabricated by the experiment using a thick pipe at different holding times.

Fig. 5 Temperature change of the melt during the experiment.

Fig. 6 Specimens of different interval of the pipes fabricated by the experiment using thin pipes.

melt was not able to be decided because of the inhomogeneous dissolution of the pipe. However, the rate of the dissolution of the pipe during holding time can be applied to a rough estimation of the erosion depth in the process of this study.

3.2 Fabricated porous aluminum alloy

Figure 6 shows the specimens fabricated with 37 pipes. The position and diameter of the pipes were almost the same as the original ones. These results show that the melt flowed among the pipes aligned with interval s of 0.5 and 1 mm. Some cavities are observed between the pipes on the cross sections. It was confirmed that these were formed by alumina particles. These particles appeared when the specimen was cut. These particles are considered to have fallen from the fixation cement during the experiment. Thus, those cavities were not continuous in the longitudinal direction of the pipes.

The porosity of the specimens measured by the image analyzer was 39 and 30% for the interval of 0.5 and 1 mm, respectively. Note that the cavities observed in the cross section of the specimen were not included in the porosity. On the other hand, the ideal porosity was calculated under

Fig. 7 Fabricated porous aluminum with interval between pipes 0.5 mm by the experiment using thin pipes. (a) Cross sectional view. (b) Microstructure of the part marked in (a). (c) Microstructure of the part marked in (a). (d) Microstructure of the part marked in (b).

assumption that the pipes with exact dimensions were aligned at an exact interval. As a result, the porosity was 40 and 33% for the interval of 0.5 and 1 mm, respectively. These results show that the porosity and the pore diameter of porous aluminum alloys can be controlled by this method.

Figure 7 shows microstructures of the specimen with pipe interval s of 0.5 mm. In Fig. 7, no remarkable gap between the pipe and the base metal was observed and the microstructures were continuous from the pipe to the base metal. These results show that the pipe and the base metal bonded metallurgically. The arrows illustrated in Figs. 7(b) and 7(c) represent the growth directions of primary α dendrite. Under this condition, the specimen was cooled from outer wall of the pipes and inner wall of crucible in the radial direction of both of the pipes and the crucible. In Fig. 7(b), pure Al of the pipe remained around the pores, and was covered by the base metal. Furthermore, an intermediate layer is observed as a white ring around the

Fig. 8 Color mapping images of Al and Si obtained from the EPMA analysis in the vicinity of the bonding boundary.

pure Al. This part was supposed to be a layer with an intermediate composition between pure Al and the base metal, and defined as the bonding boundary.

The dotted line in Fig. 7(d) represents the initial position of the outer wall of the pipe, and the solid line in Fig. 7(d) represents the bonding boundary. As shown in Fig. 7(d), the bonding boundary migrated inward in the radial direction of the inner wall of the pipe.

Figure 8 shows the color mapping images obtained from EPMA analysis of the bonding section between the pipe and the base metal of Al and Si. The dotted lines in Fig. 8 represent the initial position of the outer wall of the pipe. The dashed lines in Fig. 8 represent the bonding boundary. The Si content measured by the EPMA analysis was less than

0.5 mass% near the inner surface of the pipe and 10.3 mass% (average) in the base metal. There was some Si inside the initial position of the outer wall of the pipe even at a holding time as short as 0 s. These results showed that the pipe bonded with the base metal metallurgically by the following mechanism. First, Si contained in the base metal melt diffused into the pipes through the outer wall. Then, the outer side of the pipe melted due to the decrease in the liquidus temperature by the alloying.

4. Conclusion

In this study, a new method for fabricating porous metals was proposed and the efficiency of the method was examined by dipping multiple pure aluminum pipes into a base metal melt of an Al–Si alloy. The following conclusions were obtained.

- (1) The fabrication of porous metals with aligned unidirectional pores is possible by dipping aligned pipes into a base metal melt and solidifying them.
- (2) The pipes and the melt can bond metallurgically while maintaining pipe internal geometry at short holding times if the pipe thick enough to prevent the melting of the internal pipe wall.
- (3) The pipes are bonded with the base metal due to the decrease in the liquidus temperature of the outer walls and the diffusion of elements from the base metal.
- (4) The porosity, pore size, pore shape and pore distribution can be controlled easily by the initial pipe size and position.

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