Influence of Porosity and Pore Size on Electrical Resistivity of Porous Aluminum Produced by Spacer Method

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Porous Al specimens with a pore size range from 212–300 to 850–1000 µm and a porosity range from 77 to 90% were produced by the powder-metallurgical spacer method, and their electrical properties were experimentally investigated. The electrical resistivity increased with an increase in porosity; on the other hand, it was negligibly affected by the pore size when the pore size was sufficiently small. The experimental results agreed with the theoretical results obtained using the unit-cell model in which size of apertures at cell walls are taken into consideration. However, at the maximum pore size in the range investigated, the measured value was much higher than the calculated one. This is likely to be related to the large variation in the local density of the cross section.   [doi:10.2320/matertrans.48.32]

1. Introduction

Porous metals are of practical interest in many applications because they show unique behaviors in a variety of properties such as mechanical, acoustic, electrical, damping and heat transfer capacity.[1,2] Understanding the unique behavior in porous metals promotes the development of high-performance porous metals. Among these properties, the electrical resistivity of porous metals is one of the most interesting ones. Besides, the electrical resistivity of porous metals can be used to characterize the porous structure. For example, Harte *et al.*[3] measured the electrical resistance of conventional porous aluminum during its monotonic and cyclic compression tests and successfully verified that the cyclic compression behaviors of the porous aluminum significantly differ from the monotonic ones. To date, several studies on electrical resistivity of porous metals have been conducted.[4–10] For further understanding of the electrical resistivity of porous metals, it is important to properly investigate the influence of the porous structure, such as the porosity and pore size, on the electrical resistivity.

Thus far, many processing techniques for porous metals have been developed.[1] In particular, porous metals with high porosity (to 95%) and small pore size (less than 1 mm) have been fabricated by the spacer (or replication) method.[11–20] Through this method, the pore size and porosity can be uniformly controlled, and formation of structural defects such as missing cell walls, coupled pores and irregularly elongated pores *etc.* can be successfully suppressed. Porous aluminum has been fabricated via the powder-metallurgical spacer method comprising the sintering of mixed (Al/NaCl) powder and dissolution of the NaCl particles in water.[14,17–20] The spacer method having good adjustability of porosity and pore size makes it possible to properly evaluate the effect of the porosity and pore size on the electrical properties of porous metals. In the present study, porous Al specimens with pore size range from 212–300 to 850–1000 µm and

porosity from 77 to 90% are produced by the spacer method, and their electrical resistivities are experimentally investigated. Furthermore, a simple theoretical model in which the influence of the porosity and pore size is taken into consideration is developed and the theoretical results are compared with the experimental ones.

2. Experimental

Commercially available 99.9% pure Al powder with the average particle diameter of approximately 3 µm and carefully sieved NaCl particles with sizes of several hundred micrometers were prepared. The Al powder and NaCl particles were thoroughly mixed in a given volume ratio and put in a cylindrical graphite die. Spark plasma sintering was conducted by applying an on-off DC pulse current through the mixture compacted between graphite punches. The sintering temperature, sintering pressure and sintering time were 843 K, 20 MPa and 10 minutes, respectively.[19,20] The sintered compact was then placed in running water to remove NaCl particles. Mass and dimension measurement confirmed that the desired porosities were successfully achieved, leaving no NaCl residues behind in the water-washed specimens. The pore size of porous Al produced by the spacer method agreed with the spacer size. In the present investigation, seven specimens with different pore sizes and porosities were fabricated. The pore sizes and porosities of the specimens are listed in Table 1.

The electrical resistivities of the porous Al specimens were measured at room temperature by the four-probe method. Due to the low electrical resisitivity of the porous Al specimens, the aspect ratio of the specimens must be enough large for accurate measurement. Therefore, square-columnar specimens with the dimension of $2 \times 2 \times 20$ mm^3 were prepared. Measurements of the electrical resistivity of each specimen were carried out three times and the value of electrical resistivity was taken to be their average. Deviations of the values were enough low to assure the validity of the measurement.

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Table 1 Pore sizes, porosities and average aperture sizes of porous Al specimens fabricated by spacer method.

| Specimen ID	Pore size (μm)	Porosity (%)	Aperture size (μm)
A	425–500	90.3	105
B	425–500	85.6	76
C	425–500	80.7	59
D	425–500	76.5	41
E	212–300	85.4	69
F	610–700	85.0	131
G	850–1000	85.9	178

Fig. 1 Pore characteristics of porous Al specimens observed with scanning electron microscope: (a) specimen B (porosity = 85.6%, pore size = 425–500 μm), (b) specimen D (porosity = 76.5%, pore size = 425–500 μm) and (c) specimen E (porosity = 85.4%, pore size = 212–300 μm).
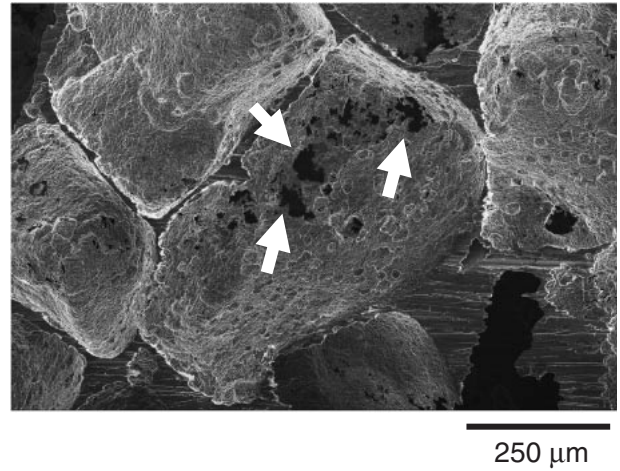
Fig. 2 Apertures at cell walls of porous Al specimen (specimen A, porosity = 90.3%, pore size = 425–500 μm) observed with scanning electron microscope.

3. Model

The cell structure of porous materials is generally classified into two types: open-cell structure and closed-cell structure. However, porous Al produced by the spacer method often has the features of both open-cell and closed-cell structures. Scanning electron microscopy images of the porous Al specimens produced by the spacer method are shown in Fig. 1. It can be seen that each pore is surrounded by cell walls; but there are apertures (or small opening windows) at the walls, as shown by arrows in Fig. 2. These apertures allow the spacing NaCl particles to be leached out during the water-washing, interconnecting the pores. Thus, the porous structure is open-cell in principle, but consists of cell walls with apertures, rather than cell struts which are typical of open-cell porous materials. This was observed in all the specimens investigated. The average aperture sizes of porous aluminum specimens produced by the spacer method are shown in Table 1, where the aperture sizes were calculated from the total area of apertures at each cell wall. The aperture size tended to increase as porosity or pore size increases.

To date, many models of the electrical properties of porous metals have been developed;[4–10] for example, Dharmasena and Wadley[6] analyzed the electrical conductivity of typical open-cell metallic foams using a tetrakaidecahedral unit-cell approach. Another example is the study of Feng et al.[7] where the electrical conductivity of the typical closed-cell aluminum alloy foams is evaluated. However, these models cannot be applied to the analysis of the electrical resistivity of the present porous Al produced by the spacer method because the influence of the aperture sizes is not taken into consideration. That is to say, the conventional models cannot be applied to evaluate the electrical resistivity of the present porous Al because of the unique cell structure. For the analysis of the electrical resistivity of the porous Al produced by the spacer method, not only the porosity and pore size, but also the aperture sizes must be taken into consideration.

A schematic illustration of a cubic unit-cell model for the porous Al produced by the spacer method is shown in Fig. 3.
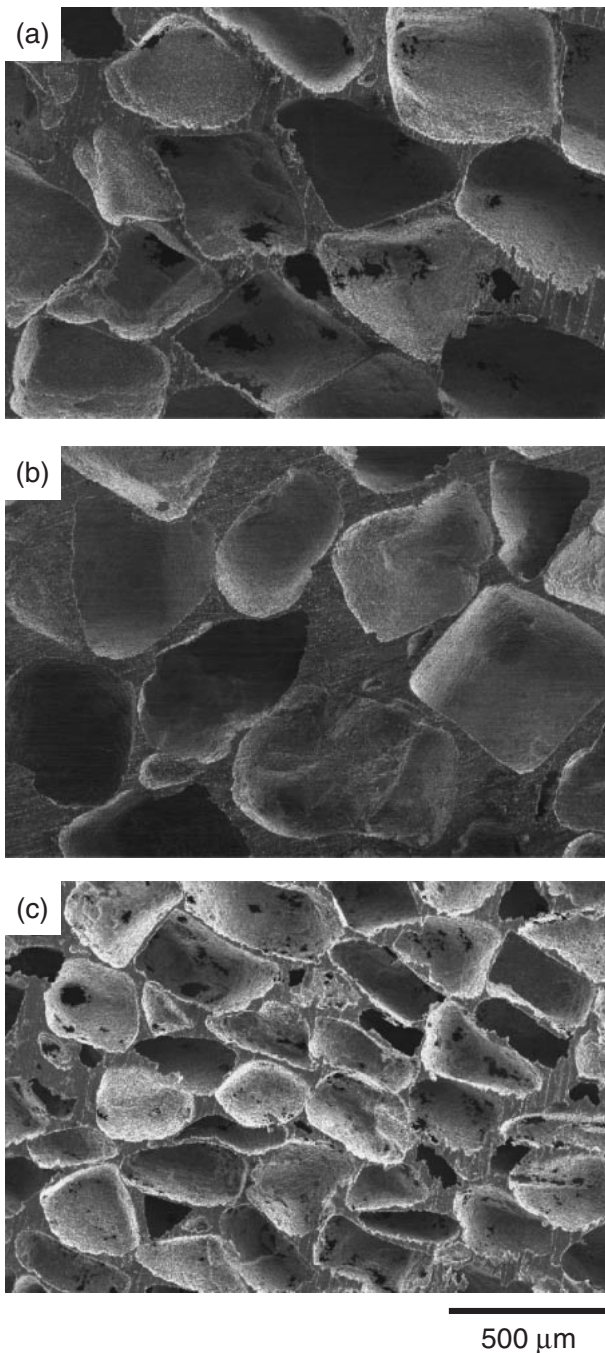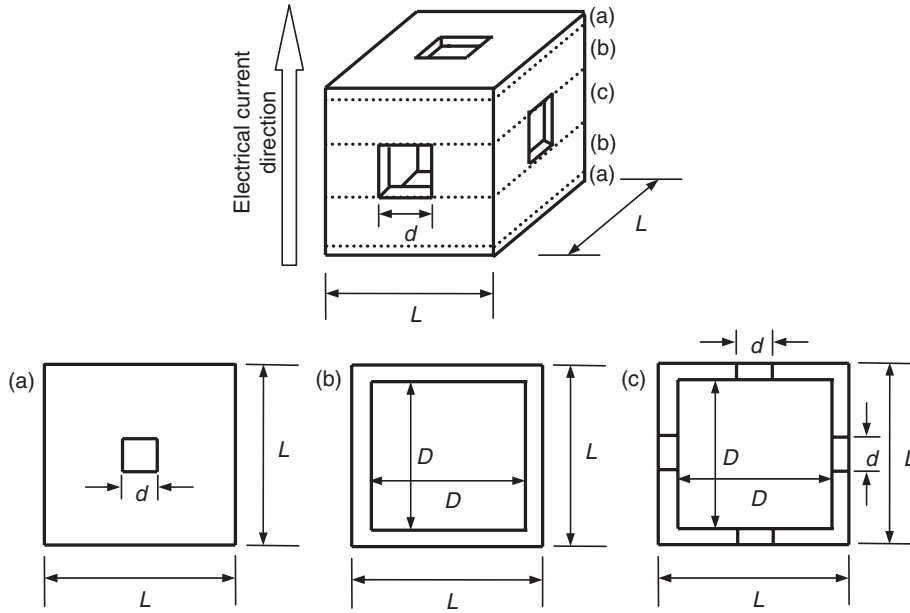
Fig. 3   Schematic illustration of a cubic unit-cell model for porous Al produced by spacer method.

For simplicity, it is assumed that the pore and aperture are rectangular and the thickness of the cell wall is constant. The unit cell consists of three types of cross section: (a), (b) and (c) shown in Fig. 3. Based on the unit cell, the electrical resistance of the porous Al is given by

$$R = K\rho_{\mathrm{M}}\left(\frac{L-D}{L^2-d^2} + \frac{D-d}{L^2-D^2} + \frac{d}{L^2-D^2-2d(L-D)}\right),$$
(1)

where R is the electrical resistance of the porous Al, ρ_{M} is the electrical resistivity of the matrix, L is the length of the unit cell, D is the pore size, d is the aperture size, and K is a constant and defined as a correction factor for matching the unit cell with a real cell because the real cell generally has higher electrical resistance than the ideal one due to its curved or thinner cell walls and residual porosity and oxides in its matrix. Also, the relationship between the electrical resistance and the electrical resistivity of the porous Al is given by

$$R = \frac{\rho_{\mathrm{P}}}{L},$$
(2)

where ρ_{P} is the apparent electrical resistivity of the porous Al. Hence, from eqs. (1) and (2), the electrical resistivity of the porous Al is given by

$$\rho_{\mathrm{P}} = KL\rho_{\mathrm{M}}\left(\frac{L-D}{L^2-d^2} + \frac{D-d}{L^2-D^2} + \frac{d}{L^2-D^2-2d(L-D)}\right).$$
(3)

In the present paper, the length of the unit cell was calculated from

$$D^3 + 6d^2\left(\frac{L}{2} - \frac{D}{2}\right) = \theta L^3,$$
(4)

where θ is the porosity. In the present investigation, the aperture sizes were experimentally measured, as shown in Table 1.
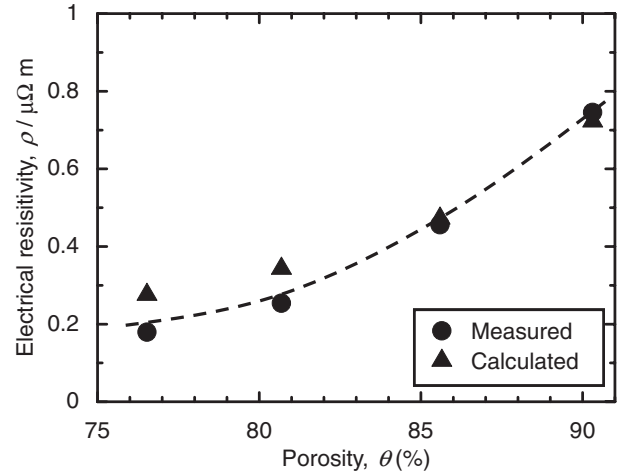

Fig. 4   Variation in electrical resistivity as a function of porosity, where pore size is constant (= 425–500 μm).

4. Results and Discussion

The variation in electrical resistivity as a function of porosity is shown Fig. 4, where the pore size is constant (= 425–500 μm). In Fig. 4, the experimental data for specimens A, B, C and D are plotted. The electrical resistivity increased with increasing porosity. This agrees with the results in the previous works.[4–10] In particular, the electrical resistivity of specimen D, having a high porosity of 90%, was much higher than those of the other specimens.

The values of electrical resistivity calculated from eq. (3) for specimens A, B, C and D are also plotted in Fig. 4, where ρ_{M} is 2.66×10^{-4} μΩ m and K is determined to be 1.83 by fitting the calculated results with the experimental results. It should be noted that the calculated values are in agreement with the experimental ones. This indicates that the electrical resistivity of the porous Al can be properly represented by the unit cell model.
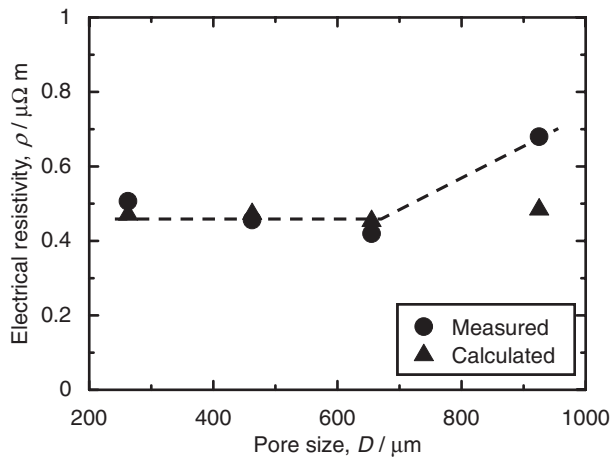
Fig. 5   Variation in electrical resistivity as a function of pore size, where porosity is constant (= 85%).

2 mm

Fig. 6   Scanning electron microscopy image of specimen G with pore size from 850 to 1000 μm and porosity of 85%.

The variation in electrical resistivity as a function of pore size is shown Fig. 5, where the porosity is constant (= 85%). In Fig. 5, the experimental and calculated results ($K = 1.83$) for specimens B, E, F and G are plotted, where the pore size is assumed to be 462.5 μm for specimen B, 256 μm for specimen E, 655 μm for specimen F and 925 μm for the specimen G, respectively. It is of interest to note that there is little difference between the experimental results and calculated results in a small and middle pore size range; however, the experimental value is much higher than the calculated one at the maximum pore size (= 925 μm) in the range investigated. Except for the experimental data at the maximum pore size, the electrical resistivities were nearly constant and independent of the pore size in both the experimental results and calculated results. Therefore, it is likely that the electrical resistivity is negligibly affected by the pore size, at least in the range investigated.

The higher experimental value of electric resistivity at the maximum pore size, compared to the calculated one, may be explained from the viewpoint of *size effect*, namely, the ratio of the cross-sectional dimension to pore size. The size effect in the mechanical properties of porous metals has been reported in the literatures;[21–23] the plateau stress is decreased when the ratio of the cross-sectional dimension to pore size is small. This is related to the reduced constraint of cell walls at the free surface.[21,22] On the other hand, the size effect in electrical resistivity for porous metals is considered to be related to the variation in the local density of the cross section, because the electrical resistivity is increased when there is, locally, a cross section with a density lower than the overall density, due to a nonuniform cell structure. When the pore size is comparable to the cross-sectional dimension, the variation in the local density of the cross section is large, because only one or two cell walls are involved in a cross section and the cross-sectional area (and thus, the electrical resistivity) sensitively depends on the individual inhomogeneity of those one or two cell walls. On the other hand, when the pore size is much smaller than the cross-sectional dimension of a specimen, the variation in the local density of the cross section is negligible, because the cross section contains many cell walls.
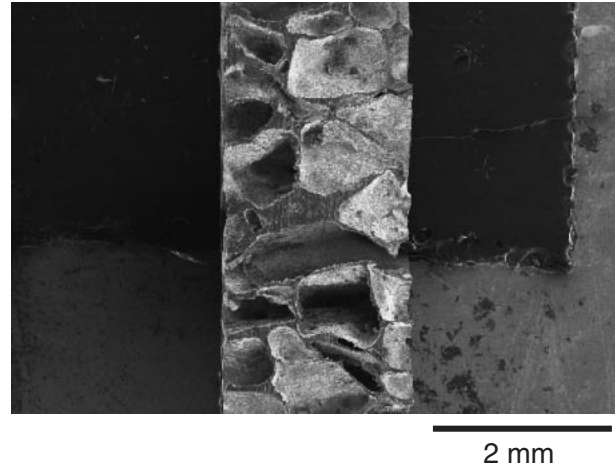
The microstructure of specimen G is shown in Fig. 6, where specimen G has the maximum pore size (= 850–1000 μm) in the range investigated. It can be seen that there is a large variation in the local density of the cross section, because the ratio of the cross-sectional dimension to pore size is small. Therefore, it is suggested that the high electrical resistivity for specimen G having the maximum pore size can be attributed to the large variation in the local density of the cross section. The present results imply that at least three pores across the specimen dimension are needed for the proper evaluation of the electrical resistivity of porous metals.

5.   Conclusions

Porous Al specimens with a pore size range from 212–300 to 850–1000 μm and a porosity range from 77 to 90% were produced by the powder-metallurgical spacer method, and their electrical properties were experimentally investigated. In addition, a simple model taking porosity, pore size and aperture size into consideration was developed and compared to the experimental results. The results are as follows.

(1) The electrical resistivity increased with an increase in porosity. On the other hand, it was negligibly affected by the pore size when the pore size was sufficiently smaller than the specimen dimension.

(2) The theoretical results obtained using the unit-cell model in which size of apertures at cell walls are taken into consideration agreed well with the experimental results.

(3) However, at the maximum pore size in the range investigated, the measured value was much higher than the calculated one. This is likely to be related to the large variation in the local density of the cross section. It is suggested that at least three pores across the specimen dimension are needed for proper measurement of electrical resisitivity.

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