Effects of Pore Characteristics Finely-Controlled by Spacer Method on Damping Capacity of Porous Aluminum

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The room-temperature damping properties of porous aluminum fabricated by the spacer method were investigated using the method of lateral resonant vibration in cantilever holding. In particular, the effects of the porosity and pore size, which are the representative parameters of porous metals and can be controlled well by spacer method, on the damping properties were focused on. The damping capacity increased with increasing porosity and pore size. Local stress concentration arising from the heterogeneity of porous structures seems responsible for the enhanced damping capacity under the condition in which the main damping mechanism is amplitude-dependent dislocation damping. The present results point out the importance of the porous structure control in damping properties. [doi:10.2320/matertrans.MRP2008389]

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1. Introduction

Porous metals are receiving considerable attention as engineering materials for a wide variety of applications.1) Recently, it has been reported that the damping capacities of porous metals are enhanced, compared with those of dense materials.2–10) Although pure Al or Al alloy is essentially a low damping material,11–13) porous Al is of considerable practical interest as a damping material in severe conditions because of its lightweight and good corrosion resistance as well as its excellent damping capacity. In general, pore characteristics, such as porosity, pore size and pore shape, of the porous structure influence the damping capacity of cellular metallic materials. However, there are some discrepancies in the dependence of the damping capacity on the pore characteristics.3–9) Past relevant studies have mostly focused on the mechanical damping of foamed Al.3–5,7) Foamed Al often suffers from heterogeneous pore characteristics because control of bubble expansion in liquid or semisolid metal is difficult. Hence, it has been difficult to properly evaluate the pore characteristic effects. In addition, the porous Al in the previous studies often had pores as large as millimeters.3–8)

The spacer method (or replication method), which has been employed since the 1960s, is one of the methods for fabricating porous Al.14–19) Features of the spacer method are: (1) strict control of the porosity and pore size, and (2) distribution of homogeneous pores and small pores. Hence, porous metals fabricated by the spacer method have been used for investigations of the effects of the porosity and pore size on various properties of porous metals.20–22) Also, small pore sizes of approximately 100 μm can be attained by the spacer method.14–19) In the present study, porous Al specimens with porosities ranging from 55.7 to 68.2% and pore sizes ranging from 53–106 to 425–500 μm are fabricated by the spacer method, and the damping capacity is examined in order to understand the effect of the porosity and pore size.

2. Experimental

99.9 mass% pure aluminum powder with a diameter of approximately 3 μm and 99.5 mass% pure, carefully sieved NaCl particles were prepared as starting materials. They were thoroughly mixed with zinc stearate (0.5 mass%) at specific ratios depending on the desired density. The mixed powder was uniaxially pressed at a pressure of 200 MPa into a compact. The compact was then sintered at 883 K for 3 h in a tubular furnace under an Ar + 5 vol% H2 atmosphere, followed by furnace cooling. Subsequently, porous Al was obtained by sinking the sintered compact into running water to remove the space-holding NaCl particles. Mass and dimension measurements revealed that all NaCl particles were removed by the water washing. Two levels of porosity are introduced by the present method, as shown later in Fig. 1(b); replicated pores produced by removing the spacer-holding NaCl particles, and fine residual pores remaining in the cell walls. The total porosity of the specimens was calculated by summing the replicated porosity and residual porosity.

In the present study, six types of specimens were used. The characteristics of the specimens tested are listed in Table 1. For reference, specimens with no replicated pores (specimen F) were also prepared. Typical structures of the porous Al fabricated by the spacer method are shown in Fig. 1 for (a) specimen B and (b) specimen E.

Room-temperature damping behavior was measured by the method of lateral resonant vibration in cantilever holding. The specimens had dimensions of 60 × 10 × 1.6 mm3. The damping capacity was specified by the load factor of free vibration, \( \eta (= A/\pi, \text{where } A \text{ is the logarithmic decrement}) \). For each specimen grade, two nominally identical specimens were prepared, and the damping test was performed twice for
The specimens for measuring the damping capacity were measured at room temperature by the free resonance vibration method and by compression tests, respectively. Both the dynamic and static Young’s moduli were measured using a universal testing machine, where the crosshead velocity was 1 mm/min. The cylindrical specimens for compression tests had dimensions of 10 mm in diameter and 12 mm in length.

In contrast to previous works, the loss factor increased with increasing porosity particularly in the high-strain-amplitude range. This trend agreed with the results in previous works. Also, specimen F with a residual porosity of 13.4% showed a higher damping capacity than dense Al when measured under similar testing conditions.

It has been pointed out that the amplitude of porous Al is inversely proportional to the pore size, although a very weak sensitivity of pore size dependence has also been reported for porous steel. Figure 2(b) shows the effect of the pore size on damping capacity for specimens B, D, E and F. In contrast to previous works, the loss factor increased with increasing pore size for the present materials.

The reason for this trend may be explained by the local stress concentration due to cell wall thickness heterogeneity. Average values and standard deviations of cell wall thicknesses were analyzed for specimens B and E and found to be 72 ± 66 μm and 8.9 ± 4.5 μm, respectively. These analyses revealed that the porous structure in specimen B with a larger pore size of 425–500 μm was more heterogeneous than that of specimen E with a smaller pore size of 53–106 μm. This trend in the cell wall thickness homogeneity is mainly because the minimum cell wall thickness is generated around the contact points between the spacer NaCl particles and thus not dependent on spacer particles’ size (close to pore size),

### Table 1 Characteristics of the specimens investigated.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Pore size, ( D_{μm} )</th>
<th>Porosity, ( ρ (%) )</th>
<th>Replicated</th>
<th>Residual</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>425–500</td>
<td>57.7</td>
<td>10.5</td>
<td>68.2</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>425–500</td>
<td>52.0</td>
<td>12.9</td>
<td>64.9</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>425–500</td>
<td>43.9</td>
<td>11.8</td>
<td>55.7</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>212–300</td>
<td>53.0</td>
<td>11.7</td>
<td>64.7</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>53–106</td>
<td>53.0</td>
<td>11.3</td>
<td>64.3</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>—</td>
<td>0</td>
<td>13.4</td>
<td>13.4</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2  Loss factor versus strain amplitude for porous aluminum fabricated by spacer method. Effects of (a) porosity and (b) pore size on amplitude dependence of damping capacity are shown. Error bars indicate standard deviations.

### 3. Results and Discussion

Figure 2(a) shows the relationship between the porosity and loss factor for specimens A, B, C and F. The loss factor increased with strain amplitude for all materials. Amplitude-dependent damping in porous metals and alloys is often related to dislocation-related damping. If the strain amplitude of the specimen is sufficiently low, the dislocation line is held by weak pinners and undergoes damped motion. This type of dislocation damping is amplitude-independent. However, at higher strain amplitudes, the dislocation can be broken away from the weak pinning points. The breakaway and sweeping motion dissipates energy. This results in a hysteresis-type decrement that is amplitude-dependent. Higher strain amplitude also causes local microplastic deformation in the porous structure.

Thus, the main damping mechanism of the present materials may be amplitude-dependent dislocation damping.

It is well known that the presence of pores enhances damping capacity due to stress concentration and mode conversion around pores. It can be seen from Fig. 2(a) that the loss factor of the present materials also increased with increasing porosity particularly in the high-strain-amplitude range. This trend agreed with the results in previous works. Also, specimen F with a residual porosity of 13.4% showed a higher damping capacity than dense Al when measured under similar testing conditions.

It has been pointed out that the amplitude of porous Al is inversely proportional to the pore size, although a very weak sensitivity of pore size dependence has also been reported for porous steel. Figure 2(b) shows the effect of the pore size on damping capacity for specimens B, D, E and F. In contrast to previous works, the loss factor increased with increasing pore size for the present materials.
whereas maximum cell wall thickness is determined by that geometric configuration of initial NaCl particle-Al powder mixture which varies with the size of spacer particles. When the variation in cell wall thickness becomes inhomogeneous, higher local stress concentration is expected at some microzones. The local stress concentration will enhance the damping capacity under the condition in which amplitude-dependent dislocation damping is the dominant mechanism. This is perhaps because the higher stress concentration facilitates dislocation breakaway from weak pinning points. Another possible mechanism for the enhanced damping capacity is microplastic deformation where the porous structure gradually and locally becomes unstable due to the heterogeneity. \(^8,9\) Anyway, the governing effect of local stress concentration is supported by the fact that the damping capacity of specimen B with a larger pore size was higher than that of specimen E with a smaller pore size.

The existence of local stress concentration can also be confirmed from the initial loading response during compression tests. Gibson and Ashby\(^ {25} \) proposed that the Young’s modulus of porous materials is independent of the pore size. However, it has been demonstrated that the Young’s modulus measured from the slope of the initial loading curve is appreciably smaller than that measured from the slope of the unloading curve after deformation due to local yielding caused by the stress concentration. \(^{26,27} \) Figure 3 shows compressive stress-strain curves for specimens B, D and E with different pore sizes. The Young’s moduli measured from the slopes of the initial loading lines, where each is given as an average of three measured values of the steepest slope, were calculated to be 449, 757 and 860 MPa for specimens B, D and E, respectively. It is of interest to note that the Young’s modulus measured from the slope of the initial loading lines increased with decreasing pore size. Alternatively, there was little difference in Young’s modulus measured by the free resonance vibration method among specimens B, D and E; the Young’s moduli measured by this method were 6.1, 6.2 and 6.1 GPa for specimens B, D and E, respectively. Therefore, the discrepancy in the slope of the initial loading line observed during compression tests implies the difference in the degree of stress concentration around the pores.

4. Summary

The effects of the porosity and pore size on the damping behavior of porous Al produced by the spacer method were investigated. Amplitude-dependent damping was observed, indicating that the main damping mechanism is dislocation-related damping. The damping capacity increased as the porosity and pore size increased. Microstructural observation showed that the porous structure in the specimen with a larger pore size was more heterogeneous than that in the specimen with a smaller pore size. Therefore, it is suggested that local stress concentration owing to the heterogeneity of structures facilitates dislocation breakaway from pinning points and microplastic deformation, resulting in higher damping capacity for the specimen with a larger pore size. The present results point out the importance of the porous structure in damping capacity.

REFERENCES