AIP | Journal of Applied Physics

Sound absorption characteristics of aluminum foam with spherical cells

Yunjie Li, Xinfu Wang, Xingfu Wang, Yuelu Ren, Fusheng Han et al.

Citation: J. Appl. Phys. **110**, 113525 (2011); doi: 10.1063/1.3665216

View online: http://dx.doi.org/10.1063/1.3665216

View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v110/i11

Published by the American Institute of Physics.

Related Articles

Acoustic properties of Kel F-800 copolymer up to 85 GPa
J. Chem. Phys. 137, 014514 (2012)

Dual beam photoacoustic infrared spectroscopy of solids using an external cavity quantum cascade laser
Rev. Sci. Instrum. 83, 064901 (2012)

Photoexcitation of gigahertz longitudinal and shear acoustic waves in BiFeO3 multiferroic single crystal
Appl. Phys. Lett. 100, 212906 (2012)

Defect-free localized modes and coupled-resonator acoustic waveguides constructed in two-dimensional phononic quasicrystals
J. Appl. Phys. 111, 104314 (2012)

Response to “Comment on ‘Observation of anomalous acoustic phonon dispersion in SrTiO3 by broadband stimulated Brillouin scattering’”[Appl. Phys. Lett. 100, 206101 (2012)]
Appl. Phys. Lett. 100, 206102 (2012)

Additional information on J. Appl. Phys.

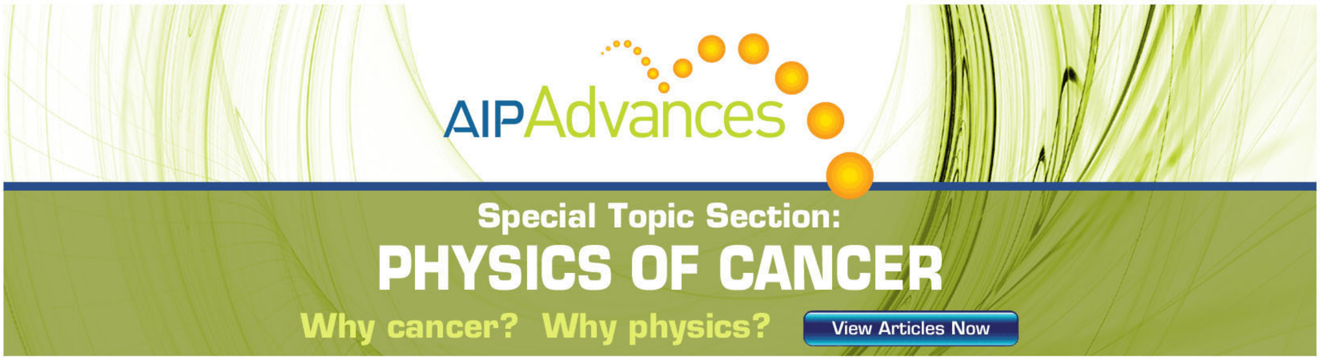
Journal Homepage: http://jap.aip.org/

Journal Information: http://jap.aip.org/about/about_the_journal

Top downloads: http://jap.aip.org/features/most_downloaded

Information for Authors: http://jap.aip.org/authors

ADVERTISEMENT



AIP Advances

Special Topic Section:

PHYSICS OF CANCER

Why cancer? Why physics?

View Articles Now

Downloaded 08 Jul 2012 to 202.127.206.173. Redistribution subject to AIP license or copyright; see http://jap.aip.org/about/rights_and_permissions

JOURNAL OF APPLIED PHYSICS **110**, 113525 (2011)

Sound absorption characteristics of aluminum foam with spherical cells

Yunjie Li,[1] Xinfu Wang,[1] Xingfu Wang,[1] Yuelu Ren,[1] Fusheng Han,[1,a)] and Cuie Wen[2]
[1]*Key Laboratory of Materials Physics, Institute of Solid State Physics, Chinese Academy of Sciences, Hefei, Anhui 230031, China*
[2]*Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Hawthorn, Victoria 3222, Australia*

(Received 23 June 2011; accepted 29 October 2011; published online 13 December 2011)

Aluminum foams were fabricated by an infiltration process. The foams possess spherical cells with a fixed porosity of 65% and varied pore sizes which ranged from 1.3 to 1.9 mm. The spherical cells are interconnected by small pores or pore openings on the cell walls that cause the foams show a characteristic of open cell structures. The sound absorption coefficient of the aluminum foams was measured by a standing wave tube and calculated by a transfer function method. It is shown that the sound absorption coefficient increases with an increase in the number of pore openings in the unit area or with a decrease of the diameter of the pore openings in the range of 0.3 to 0.4 mm. If backed with an air cavity, the resonant absorption peaks in the sound absorption coefficient versus frequency curves will be shifted toward lower frequencies as the cavity depth is increased. The samples with the same pore opening size but different pore size show almost the same absorption behavior, especially in the low frequency range. The present results are in good agreement with some theoretical predictions based on the acoustic impedance measurements of metal foams with circular apertures and cylindrical cavities and the principle of electroacoustic analogy. © *2011 American Institute of Physics*. [doi:10.1063/1.3665216]

I. INTRODUCTION

Porous metals or metal foams show many interesting properties and thus are drawing much attention in a variety of industry fields.[1] Sound absorption is one of the most important functional properties of porous metals. Recently, there has been an increasing demand for materials that can reduce noise, even in severe environments such as high temperature and corrosive surroundings. Many authors have proposed that porous metals are a promising candidate in such applications due to their relatively higher specific mechanical strength and stiffness, and their resistance to heat, corrosion, and climatic conditions than nonmetallic porous materials such as urethane foam and glass wool, etc.[2–10] Sound absorption means that an incident sound wave is neither reflected nor transmitted but absorbed by the material.[5] The sound absorption behavior of porous metals is determined by the cell structure, which can be roughly divided into two types, i.e., open-celled and closed-celled structures. Generally, porous metals with a closed-celled structure are poor sound absorbers, owing to the difficulty of sound penetrating to the interior of the material; on the contrary, open-celled porous metals show excellent sound absorption properties, due to the sound wave propagating easily into the material.[2,3,5–8] Among the other porous metals, aluminum foam would be currently one of the most important porous metals used for sound absorption.

Han *et al.*[9] conducted a study on the sound absorption behavior of a closed-celled aluminum foam, and concluded that the sound absorbing performance can be improved by introducing an air gap behind the foam or conducting a compression on the Al foam. Lu *et al.*[5] reported that the sound absorbing ability of closed-celled aluminum foam can be enhanced by partially fracturing the cell walls via rolling. They also studied the sound absorption characteristics of semi-open-cell foams,[3] and concluded that the sound absorption increased upon decreasing the pore opening size. A peak absorption coefficient of 0.8 was obtained for this aluminum foam in the frequency range of 800–2000 Hz. Wang *et al.*[4] analyzed the sound absorption of aluminum alloy foams and honeycombs using a point-matching method. They found that the pore sizes for the optimal sound absorption were on the order of $\sim$0.1 mm. However, structural parameters such as sample thickness and open porosity were not considered in Wang's study. Han *et al.*[2] noted that aluminum foam with an open-celled structure, which is manufactured using an infiltration process, shows a significant improvement in sound absorption capacity compared with that with a closed-celled structure. Hakamada *et al.*[6,7] studied the sound absorption of aluminum foam fabricated via a spacer method. They indicated that the air gap and the pore opening size have significant effects on the sound absorbing performance of metal foams. The importance of pore openings in the sound absorption of aluminum foams have been also pointed out by many other authors.[2,3,6]

However, to date, there is very little information on the relationship of sound absorption performance with the pore opening size and pore opening density of metal foams. Accordingly, the sound absorption performance of aluminum foams with spherical cells[1,11–14] was investigated in the present study focusing on the effect of the pore opening diameter, the density on the incidence surface, the air gap, and the specimen thickness. In addition, the experimental results were discussed in accordance with the theoretical model

---

[a)] Author to whom correspondence should be addressed. Electronic mail: fshan@issp.ac.cn.

0021-8979/2011/110(11)/113525/7/$30.00

proposed by Lu *et al.*[3] to disclose the effect of the pore opening on the sound absorption behavior of metal foams and relevant mechanisms.

II. EXPERIMENT

A. Sample preparation

The porous samples were fabricated using an air pressure infiltration process consisting of the following stages. First, spherical sodium chloride (NaCl) particles were prepared by sintering NaCl powders to the required sizes. Second, the spherical NaCl particles were compacted in a mold using an appropriate pressure to form a porous framework. A pure aluminum melt was then poured into the mold and infiltrated into the interstices of the porous framework under compressed air, yielding an aluminum/NaCl composite. Finally, the composite was washed by water to remove the NaCl particles, leaving an aluminum-based porous structure. The reason for choosing the spherical NaCl particles is that it is easy to control the size of the pore openings by adjusting the diameter of the spherical NaCl particles and the infiltration pressure.[3,15] Three sizes of NaCl particles or pores were selected in the present study; that is, 1.3, 1.6, and 1.9 mm, respectively.

The porosity, P, of the resultant aluminum foam can be determined by,

$$P = \left(1 - \frac{\rho_f}{\rho_s}\right) \times 100\%, \tag{1}$$

where ρ_f is the apparent density of the foam, which is obtained by measuring the dimensions and weight of the foam, and ρ_s is the density of the aluminum matrix. The pore opening density, γ, is calculated by,

$$\gamma = \frac{N}{S_{surf}}, \tag{2}$$

where S_{surf} is the surface area of the samples that faces the sound wave, and N is the number of pore openings in the area.

The typical pore structure of the present aluminum foams is shown in Fig. 1. It is seen that the small spherical pore openings exist on the pore walls that form the connection tunnels among the pores. The pore opening diameter can be calculated by the method proposed by Chen *et al.*[15] As shown in Fig. 2, there are two rigid spherical particles denoted as O_1 and O_2 having an identical radius, R, and contacting at the point O. When liquid metal tries to enter the interstices of the two particles under an infiltration pressure, ΔP, the pore opening radius ($=OA$) is given by the pressure, ΔP, the spherical particle radius, R, the wetting angle, θ, between the liquid metal and the spherical particles and the surface tension, σ_{Al}, of the liquid aluminum.[16] Based on this principle, the infiltration pressure, ΔP, was adjusted from 0.1 to 0.3 MPa to lead to the corresponding pore opening diameter to range from 0.31 to 0.39 mm, while the porosity and pore diameter were kept unchanged, i.e., 65% and 1.3 mm, respectively. The mean pore opening density γ was between $49.3/\text{cm}^2$ and $73.7/\text{cm}^2$, as shown in Table I.

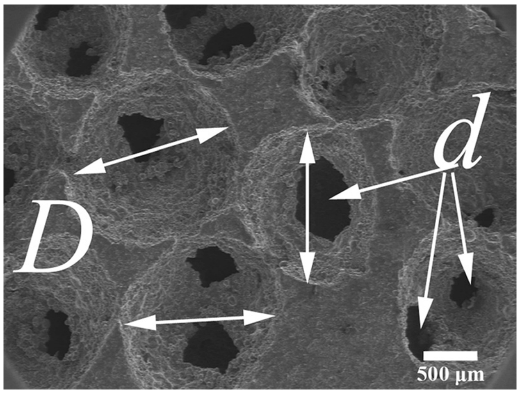


FIG. 1. Typical pore morphology of sample C, where *D* denotes the pore diameter and *d* denotes the pore opening diameter.

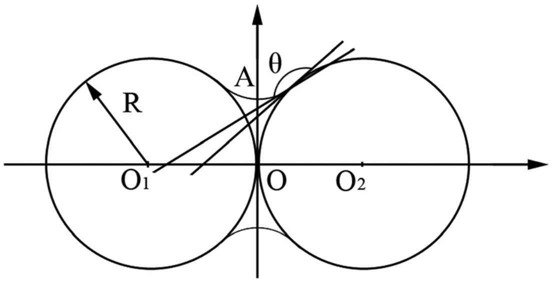


FIG. 2. Schematic illustration of interaction of two particles during the infiltration process.

B. Sound absorption coefficient measurement

There are mainly two methods to measure the sound absorption coefficient of materials, i.e., the reverberation room method and the impedance tube method, both of which provide the sound absorption coefficient of materials against frequency. The measurement principles of the impedance tube method can be divided into two types: a method using the standing wave ratio and the transfer function method. In this investigation, the latter was used since it is relatively quick and easy, and fully reproducible measurements of sound absorption coefficients require only small samples of the absorbing material, which is useful in basic research and product development. The schematic drawing for the transfer function method is shown in Fig. 3. In this method, a broadband stationary random sound wave is generated by the loudspeaker of the tube, and the sound absorption coefficient is determined by measuring the sound pressure of a standing

TABLE I. Structure parameters of aluminum foam samples in the present study.

Sample	Pore size, *D* (mm)	Pore opening diameter, *d* (mm)	Pore opening density (cm^{-2})	Infiltration pressure (MPa)
A	1.30	0.32	49.3	0.3
B	1.30	0.32	57.8	0.3
C	1.30	0.32	73.7	0.3
D	1.30	0.31	71.1	0.3
E	1.30	0.35	71.1	0.2
F	1.30	0.39	71.1	0.1

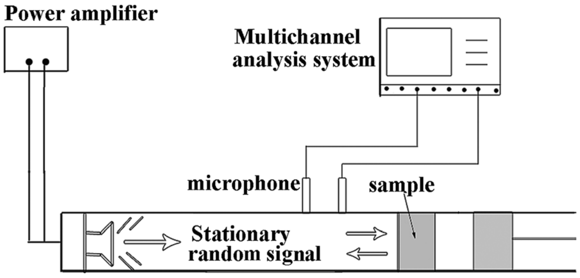


FIG. 3. Schematic illustration of the fundamental transfer function measurement.

wave with two fixed microphones and calculating the complex transfer function using a two-channel digital frequency analyzer.

The transfer function technique is based on the fact that the sound reflection factor at normal incidence, r, can be determined from the measured transfer function, H_{12}, between the two microphone positions in front of the material being tested. The complex acoustic transfer function, H_{12}, is defined as,

$$H_{12} = \frac{p_2}{p_1} = \frac{e^{ik_0 x_2} + re^{-ik_0 x_2}}{e^{ik_0 x_1} + re^{-ik_0 x_1}}, \tag{3}$$

where p_1 and p_2 are the complex sound pressures at the two microphone positions, x_1 and x_2 are the distances of the two microphone positions from the reference plane ($x = 0$), and k_0 is the wave number defined by $k_0 = 2\pi f / c_0$, where f is the frequency and c_0 is the speed of sound.

The transfer functions for the incident wave, H_I, and for the reflected wave, H_R, can be calculated by,

$$H_I = e^{-ik_0(x_1 - x_2)}, \tag{4}$$

$$H_R = e^{ik_0(x_1 - x_2)}. \tag{5}$$

Combining Eqs. (3), (4), and (5), the normal incidence reflection factor, r, can be calculated using,

$$r = \frac{H_{12} - H_I}{H_R - H_{12}} e^{2ik_0 x_1}. \tag{6}$$

The sound absorption coefficient, α, can be determined in terms of r by,

$$\alpha = 1 - |r|^2 = 1 - r_r^2 - r_i^2, \tag{7}$$

where r_r and r_i are the real and imaginary components of r, respectively.

The diameter of the impedance tube used in this investigation is 29 mm, the frequency range investigated is from 500 to 6400 Hz, and the samples to be measured were placed against a rigid wall with varied cavity depths in between.

III. RESULTS

Figure 4 gives the changes of the normal sound absorption coefficient against the frequency range from 500 to 6400 Hz for the aluminum foams with varied pore opening densities. It is seen that the sound absorption coefficients increase with increasing frequency until about 3200 Hz, where the sound absorption coefficients reach the peak values, and after that the sound absorption coefficients decrease with a further increase in frequency. As the pore opening density increases, the peak value was elevated and meanwhile shifted toward lower frequencies. Sample C shows the highest sound absorption peak at the lowest frequency because it has the greatest pore opening density among the three samples.

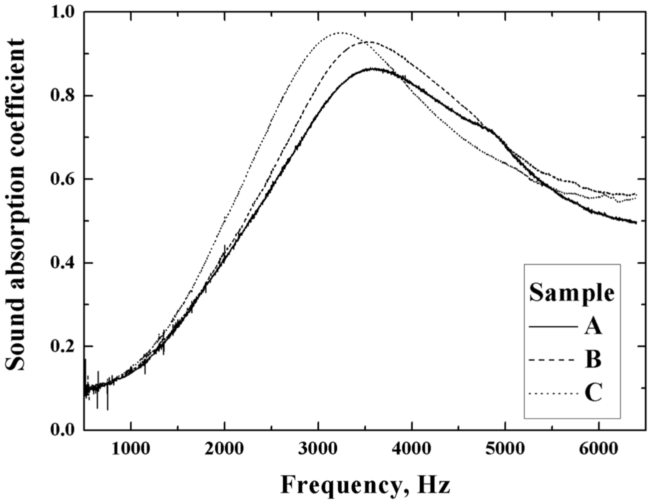


FIG. 4. Sound absorption coefficient vs frequency for samples A, B, and C with varied pore opening densities of 49.3, 57.8, and $73.7/\mathrm{cm}^2$, respectively, and with a fixed thickness of 15 mm.

The influence of the pore opening diameter, d, on the sound absorption coefficient is shown in Fig. 5. It is obvious that, as the pore opening diameter increases, the sound absorption coefficient decreases and sample D, with the smallest pore opening diameter (0.31 mm), shows the highest sound absorption coefficient peak among the three samples. This tendency is consistent with those observed in common open or semi-open celled aluminum foams.[2,3,6]

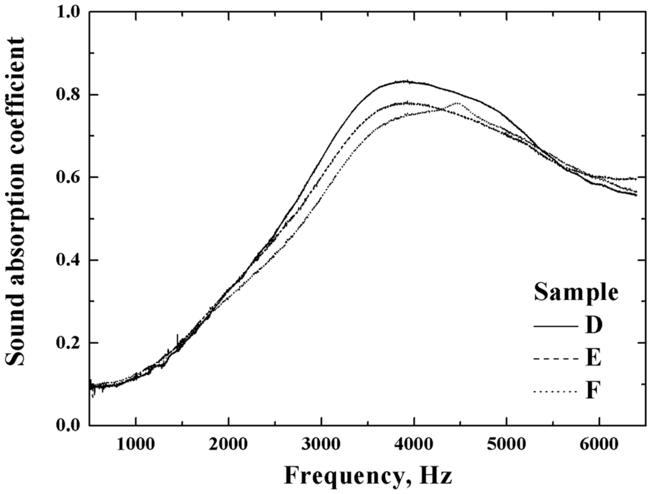


FIG. 5. Sound absorption coefficient vs frequency for samples D, E, and F with different pore opening diameters of 0.31, 0.35, and 0.39 mm, respectively.

There have been a number of studies on the effect of the cavity between the specimen and rigid wall on the sound absorption behavior of porous materials.[2,3,5,7] It is generally accepted that the deeper the cavity is, the lower the peak location frequency is, while the height of the sound absorption peak remains the same. However, it is seen from Fig. 6 that the maximum sound absorption coefficient decreases although the peak location is shifted toward lower frequencies with an increase in the cavity depth from 0 to 30 mm. Figure 7 shows the relationship of the sound absorption coefficient with the porosity, pore size, and pore opening size. It is found that even if the samples have varied pore sizes, for example, 1.3, 1.6, and 1.9 mm, they show almost the same sound absorption peak value, especially in the frequency range of 500 to 3000 Hz because they have the same pore opening diameter of 0.3 mm. Figure 8 compares the results obtained from the experimental measurements and theoretical prediction proposed by Lu *et al.* for the samples with different thicknesses of 10, 15, and 20 mm.[3] They both show a good agreement in the low frequency range and the deviation in the high frequencies is less than 8%.

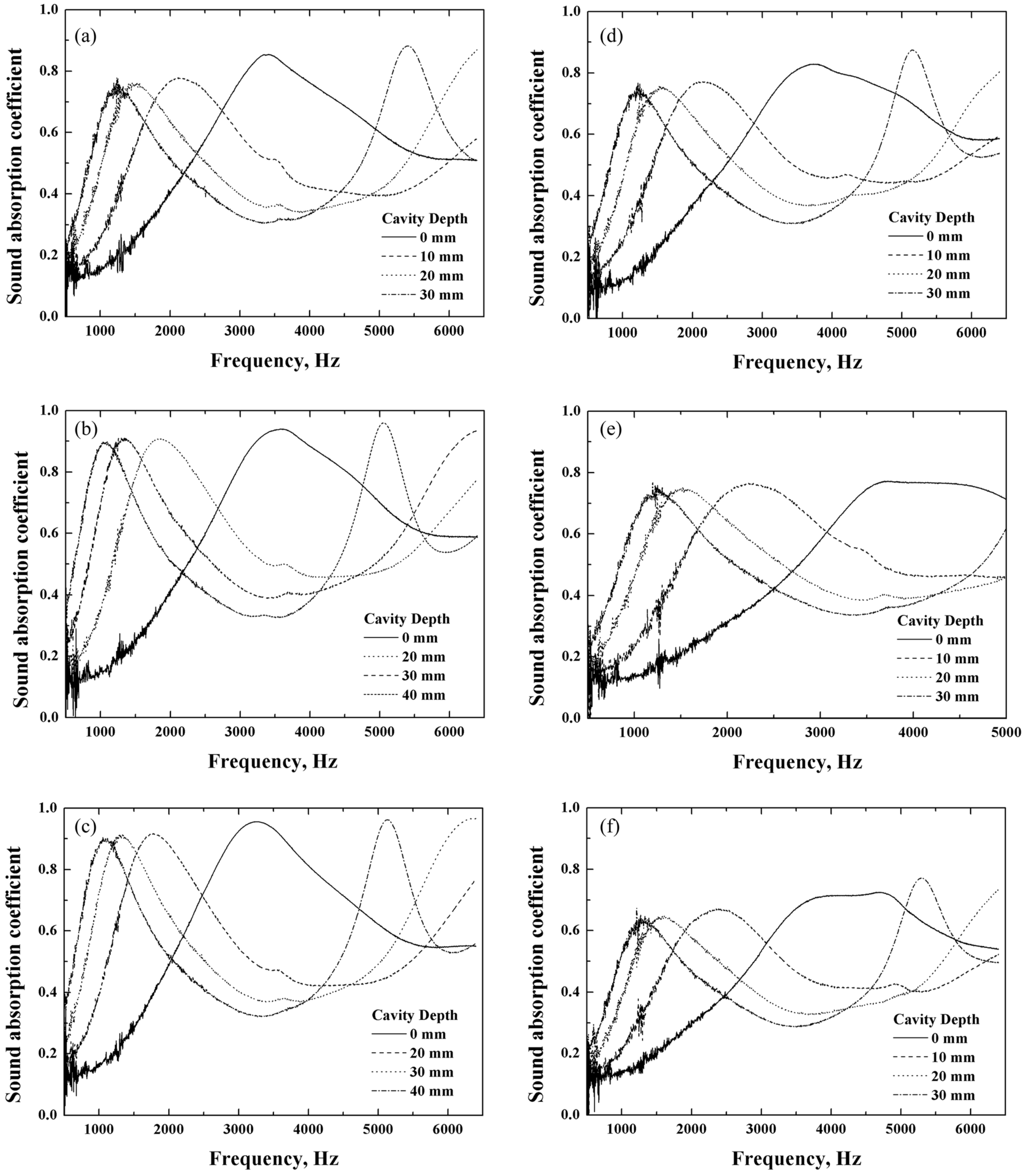


FIG. 6. (a)–(f) Sound absorption coefficient vs frequency for samples A-F at different cavity depths of 0, 10, 20, and 30 mm, respectively, with a fixed thickness of 15 mm.

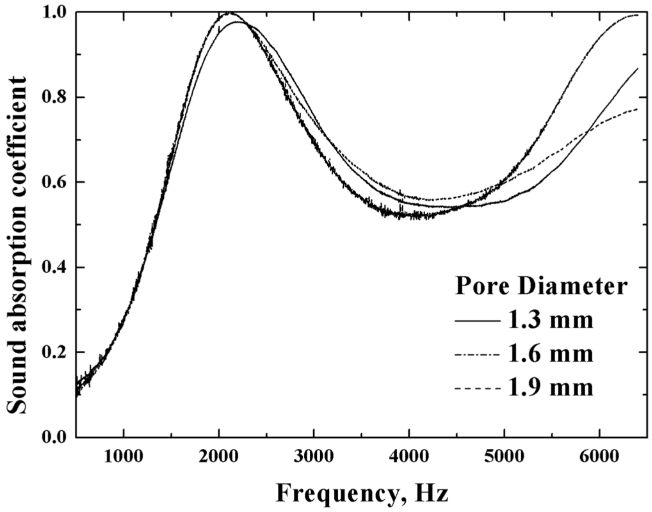


FIG. 7. Sound absorption coefficient vs frequency for samples with a porosity of 65% and a pore opening diameter of 0.3 mm, but varied pore sizes of 1.3, 1.6, and 1.9 mm.

IV. DISCUSSION

The sound propagation and attenuation in porous materials have been extensively studied for several decades and the related theories developed for the explanation of sound absorption mechanisms and for the prediction of acoustic behavior are well documented.[2,9,16–21] The matrices in rigidly-framed porous materials such as Al are of low intrinsic damping compared with fibrous polymeric materials. The loss of acoustic energy due to the structural damping is on the order of 10^{-3}. Therefore, if only the materials themselves are considered, the sound absorption of aluminum foams depends mainly upon the pore structures including the pore size, the connectivity of the pore opening, the surface topography, etc.

As is seen in Fig. 1, there are several small spherical pore openings on the wall of each pore, which guarantees the connections and forms a complex network of interlinking air channels among the pores. This pore structure is obviously different from those closed-celled[5,8] or open-celled aluminum foams with irregular pores[2,6,7] howver, very similar to those used in the study by Lu *et al.*[3] The small pore openings connecting the large pores allow considerable sound waves to enter the pore structure and to be dissipated via increased friction with the pore surface because of increased air velocity when the air travels from the large pores into the much smaller pore openings.

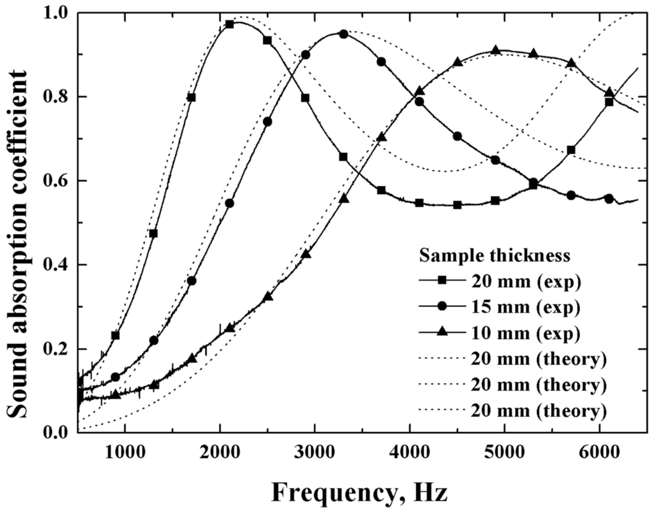


FIG. 8. Measured and theoretically predicted sound absorption coefficient vs frequency for sample C with different thicknesses of 10, 15, and 20 mm.

Figure 4 shows the relationship between the surface pore opening density and the sound absorption performance of aluminum foams. As expected, the high sound absorption corresponds to the high surface pore opening density, which is easy to understand because the greater the number of the surface pore openings, the greater the dissipation of the sound energy due to viscous and thermal losses. In addition to the pore opening density, the pore opening size also has a significant influence on the sound absorption performance of aluminum foams, as shown in Fig. 5. It is seen that the sound absorption coefficient increases as the pore opening size decreases in the range of 0.3 to 0.4 mm, being in good agreement with previously reported results;[2,3,6,15] for instance, Wang *et al.*[4] suggested that the optimum cell size for the best sound absorption is on the order of around 0.1 mm, and other researchers reported that the foam with a smaller aperture size of 0.034 mm showed a higher sound absorption than that with a larger aperture size of 0.088 mm.[6] Obviously, when the pore opening size is too large, the velocity of air flow will change a little when passing through the pores and thus, the resulting dissipation from the friction will not be high.[7] On the contrary, if the pore opening size is too small, the flow resistance of air will be too high and most of the sound waves will not come into the interior of the materials but will be reflected from the specimen surface, also leading to poor sound absorption.[3,4,6] For aluminum foams with similar porosity and pore shape, the air flow resistance is dependent upon the pore opening diameter and sample thickness.[2] It is seen from Fig. 5 that sample D has the smallest pore opening size but the highest sound absorption capacity, which is most probably related to its highest flow resistance.

As previously mentioned, introducing a cavity between the samples and rigid wall will significantly change the sound absorption behavior of porous materials. From the vibroacoustic viewpoint, the sound absorption of porous materials equipped with a cavity is dominated by the resonance of the air mass in both the pores and the back cavity, and the absorption efficiency is limited to the resonance frequency region. This combination is, in principle, equivalent to a Helmholtz resonator that is composed of a cavity with a small neck. For a Helmholtz resonator, there is a definite absorption peak at the resonant frequency of the enclosed air mass in the resonator. The resonant frequency, f_r, can be calculated by,

$$f_r = \frac{c_0}{2\pi}\sqrt{\frac{S_{nek}}{LV}}, \tag{8}$$

where c_0 is the velocity of sound, S_{nek} is the cross-sectional area of the neck, L is the neck length, and V is the volume of the cavity.

In the present study, the combination of each pore opening with the back cavity can be regarded as a Helmholtz resonator in which the opening channel forms the neck. As is seen in Fig. 6, the resonator peaks shifted to lower frequencies as the cavity depth increased, suggesting that the longer cavities correspond to the lower resonant frequencies. These results are consistent with the prediction of Eq. (8).

Figure 7 shows the sound absorption coefficient against the frequency for the samples with varied pore sizes of 1.3, 1.6, and 1.9 mm, but with the constant porosity and pore opening size, i.e., 65% and 0.3 mm, respectively. The three samples show almost the same absorption behaviors although they have different pore sizes. This phenomenon further demonstrates that the contribution of friction enhanced by the pore openings to the dissipation of the sound wave energy is more significant than those of viscous and thermal losses by the large pores.[2,5] In other words, there is no definite correlation between the pore size and the sound absorption coefficient of aluminum foams with spherical cells.

Recently, Lu *et al.*[3] proposed a model to describe the sound absorption behavior of aluminum foams with spherical cells. According to the model, the specific acoustic impedance of air inside a cell, Z_D, the acoustic specific impedance of the pore opening, Z_0, the specific acoustic resistance, R_0, and the reactance of the pore opening between the pores, M_0, have the following relationships:

$$Z_{\mathrm{D}} = -\,\mathrm{i}\rho_0 \mathrm{c}_0 \cot(0.806D\omega/\mathrm{c}_0), \tag{9}$$

and

$$Z_0 = R_0 + iM_0 = \left(32\eta t/d^2\right)\left(\sqrt{1+\beta^2/32} + \sqrt{\beta d/4t}\right) + i\omega\rho_0 t\left(1 + 1/\sqrt{9+\beta^2/2} + 0.85d/t\right), \tag{10}$$

where ρ_0 is the density of air, η is the viscosity of air, c_0 is the speed of sound in air, D is the pore size, d is the pore opening size, ω is the angular frequency ($\omega = 2\pi f$, where f is the frequency of the sound wave), and t is the thickness of the cell walls ($t = (1 - \Omega)D/[3.55 - 6(d/D)^2]$, and Ω is the porosity), and $\beta = (\Omega\rho_0\eta)^{1/2}d/2$. The acoustic impedance of an acoustic system, Z_1, is given by,

$$Z_1 = z_0 + Z_D, \tag{11}$$

where $\mathrm{z}_0 = \mathrm{Z}_0((0.909D)^2/d^2)$ is the relative specific acoustic impedance of the pore openings. When the number of cells in the direction of the sound propagation, n, is greater than 1, the acoustic impedance of the acoustic system, Z_{n}, is given by,

$$Z_n = z_0 + \frac{Z_D Z_{n-1}}{Z_D + Z_{n-1}} = R_n + iM_n. \tag{12}$$

From Eq. (12), the sound absorption coefficient, α, is given by,

$$\alpha = \frac{4R_n/\rho_0 c_0}{(1 + R_n/\rho_0 c_0)2 + (M_n/\rho_0 c_0)}. \tag{13}$$

Figure 8 gives the measured and calculated sound absorption coefficients for sample C with varied thicknesses of 10, 15, and 20 mm, respectively. Calculations were performed using the following parameters: $\Omega = 65\%$, $D = 1.3$ mm, and $d = 0.32$ mm, respectively. It is seen from Fig. 8 that the absorption peak tends to rise and shift toward lower frequencies as the sample thickness increases and the experimental measurements are in good agreement with the theoretical predictions. The effect of the sample thickness on the sound absorption is easy to understand due to the lengthened propagation distance in relatively thick samples that leads to the enhanced interaction of sound wave with the pore walls. However, a slight discrepancy between the experimental data and the predicted results can also be found. This would be due to the assumption that the pore opening has a spherical shape and a single diameter of 0.32 mm, which is, in fact, different from the real situations. Besides, the model assumed that the apertures are circular and the cavities are cylindrical, and considered only the viscous effect without taking into account the thermal losses. These limitations should be responsible for the discrepancies.

V. CONCLUSIONS

Aluminum foams with a porosity of 65%, pores sizes ranging from 1.3 to 1.9 mm, pore opening diameters ranging from 0.3 to 0.4 mm, and pore opening densities ranging from 49.3 to 73.7 cm^{-2} were fabricated by an infiltration method using spherical soluble particles. The sound absorption behaviors of the resultant samples were investigated in the present study using the transfer function method and the following conclusions are summarized.

1. The sound absorption coefficient increases upon increasing the pore opening density or decreasing the pore opening diameter.
2. The sound absorption performance of the foams at low frequencies can be significantly improved by introducing an air cavity behind the foams, due to the Helmholtz resonance effect. The location of the sound absorption peak is shifted toward lower frequencies however, the height is slightly decreased as the cavity depth increases.
3. Samples with varied pore sizes but constant pore opening size show almost the same absorption behavior in the frequency range of 500–6400 Hz, suggesting that the pore opening plays a more important role in dissipating the sound wave energy than large pores.
4. The peak of the sound absorption coefficient increases and shifts toward lower frequencies with an increase in the sample thickness. The experimental measurements are in good agreement with those predicted by the theoretical model if the pore opening size is considered.

ACKNOWLEDGMENTS

This work is jointly supported by the National Basic Research Program of China (Grant No. 2011CB610300), the

National Natural Science Foundation of China the Knowledge Innovation Program of the Chinese Academy of Sciences (Grant No. 50871107). The authors would also like to thank Dr. Xiaolin Wang from the Institute of Acoustics, Chinese Academy of Sciences, for help in conducting the sound absorption measurements and valuable discussion of the results.

[1] J. Banhart, Prog. Mater. Sci. **46**, 559 (2001).

[2] F. S. Han, G. Seiffert, Y. Y. Zhao, and B. Gibbs, J. Phys. D: Appl. Phys. **36**, 294 (2003).

[3] T. J. Lu, F. Chen, and D. P. He, J. Acoust. Soc. Am. **108**, 1697 (2000).

[4] X. L. Wang and T. J. Lu, J. Acoust. Soc. Am. **106**, 756 (1999).

[5] T. J. Lu, A. Hess, and M. F. Ashby, J. Appl. Phys. **85**, 7528 (1999).

[6] M. Hakamada, T. Kuromura, Y. Q. Chen, H. Kusuda, and M. Mabuchi, J. Appl. Phys. **100**, 114908 (2006).

[7] M. Hakamada, T. Kuromura, Y. P. Chen, H. Kusuda, and M. Mabuchi, Appl. Phys. Lett. **88**, (2006).

[8] F. S. Han, Z. G. Zhu, and C. S. Liu, Acta Acustica/Acustica **84**, 573 (1998).

[9] F. S. Han, Z. G. Zhu, and J. C. Gao, Metall. Mater. Trans. A **29**, 2497 (1998).

[10] X. F. Wang, X. Wei, F. S. Han, and X. L. Wang, Mater. Sci. Technol. **27**, 800 (2011).

[11] Y. Y. Zhao, F. S. Han, and T. Fung, Mater. Sci. Eng., A **364**, 117 (2004).

[12] A. Jinnapat and A. R. Kennedy, J. Alloys Compds. **499**, 43 (2010).

[13] R. Goodall and A. Mortensen, Adv. Eng. Mater. **9**, 951 (2007).

[14] R. Goodall, A. Marmottant, L. Salvo, and A. Mortensen, Mater. Sci. Eng., A **465**, 124 (2007).

[15] F. Chen, A. W. Zhang, and D. P. He, J. Mater. Sci. **36**, 669 (2001).

[16] H. K. Kim and H. K. Lee, J. Sound. Vib. **329**, 866 (2010).

[17] X. H. Zhang, H. B. Li, C. M. Cao, and S. L. Wang, *2009 3rd International Conference on Bioinformatics and Biomedical Engineering* (IEEE, New York, 2009), Vols. 1–11, p. 6441.

[18] M. J. Brennan and W. M. To, Appl. Acoust. **62**, 793 (2001).

[19] M. R. Stinson and E. A. G. Shaw, J. Acoust. Soc. Am. **77**, 2039 (1985).

[20] J. P. Arenas and M. J. Crocker, J. Sound Vib. **44**, 12 (2010).

[21] K. Sakagami, K. Matsutani, and M. Morimoto, Appl. Acoust. **71**, 411 (2010).