Density dependence of acoustic characteristics of silica nanofoam

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(Received 30 September 2010, Accepted for publication 27 January 2011)

Abstract: In this study, we experimentally estimated the sound speed of silica nanofoam as a function of the density through acousto-optic measurements. He–Ne laser light at the wavelength of 632.8 nm was emitted through the sample in the direction perpendicular to the propagation of the ultrasound. The diffraction of the light wave by the ultrasonic longitudinal waves with frequency in the range of 500–2,000 kHz agreed with the Raman-Nath theory. The sound speed estimated from the Raman-Nath diffraction angle varied in the range of 55–178 m/s for the sample density of 100–300 kg/m$^3$. The measured sound speed almost agreed with the sound speed calculated from the density, bulk Young’s modulus and Poisson’s ratio. This implies that the low sound speed might be attributed to the reduced bulk elastic constant owing to the structure and might not be affected much by air confined in the porous structure.

Keywords: Aerogel, Porous silica, Sound speed, Raman-Nath diffraction

PACS number: 43.35.Cg [doi:10.1250/ast.32.132]

1. INTRODUCTION

Silica nanofoam [1] is a porous material with a nanometer structure produced through a sol-gel process, and has been considered a thermal insulator [2]. The nanofoam can work as a good acoustic matching layer for airborne ultrasonic transducers [3,4] for highly sensitive and wideband ultrasound transmission/detection since it has an extremely low acoustic impedance. The nanofoam may also have a possibility as an acousto-optic device [5] because of its very low sound speed and optical transparency [6]. The density and elastic properties of nanofoam in conjunction with the production process were investigated in previous studies [7–11]. Gross et al. measured mechanical behavior through ultrasonic and static compression experiments [7].

We have precisely estimated the sound speed and acoustic attenuation of silica nanofoam with a density of 250 kg/m$^3$, through acousto-optic measurements [12]. The sound speed and the acoustic attenuation constant were in the range of 140–150 m/s and $4.3 \times 10^{-11}$ dB/(mm-Hz)$^{1/2}$, respectively. It was observed that the change rate of the optical refractive index of the nanofoam with changing sound pressure was in the range of $1.2–1.6 \times 10^{-8}$ 1/Pa. It was found that Raman-Nath diffraction [13–16] occurs at a relatively low frequency since the sound speed is very low. In the previous studies, the relationship between the acoustic characteristics and the density of nanofoam was not clarified.

In this work, we experimentally studied the sound speed of the nanofoam as a function of the density through Raman-Nath diffraction analysis. Diffraction angles of the light wave for ultrasonic waves with frequency in the range of 500–2,000 kHz agreed with the Raman-Nath theory. The measured sound speed almost agreed with the sound speed calculated from the averaged density, bulk Young’s modulus and Poisson’s ratio. Young’s modulus and Poisson’s ratio were measured by a static compression experiment and the correction using the finite element analysis.

2. EXPERIMENTAL SETUP FOR SOUND SPEED MEASUREMENT

Figure 1 shows the experimental setup for measuring light diffraction patterns to estimate sound speed. A 510-kHz ultrasonic transducer was attached to a silica nanofoam sample with the dimensions of $10 \times 10 \times 5$ mm. The diameter of the radiation surface of the transducer was 12.3 mm. We prepared five samples with different densities ranging from 100 to 300 kg/m$^3$. Let us define, throughout this paper, the mass of the sample divided by the volume calculated using the outer dimensions as the average or
apparent density. The light of the He–Ne laser ($\lambda = 632.8$ nm) travels through the sample in the direction vertical to that of ultrasound propagation. The silica nanofoam is an optically transparent material, and its optical power transmission is 80% for a 5-mm-thick sample with the density of 200 kg/m$^3$ at the optical wavelength of 633 nm. We adjusted the intensity of light using an ND filter. As an example, Fig. 2 shows a photograph of the diffracted light pattern for the sample of the density with 150 kg/m$^3$.

Figure 3 shows the intensity distributions of the diffracted light for a 150-kg/m$^3$ sample when the vibration velocities of the ultrasonic transducer were 0, 67, 83, and 96 mm/s. The diffracted light distribution is measured with a photodetector scanned transversally to the direction of the laser light. The distance between the sample and the photodetector was 750 mm. A diameter of the light-receiving surface of the photodiode was 1.0 mm. Here, the received signal was detected by a lock-in amplifier with the frequency of a light chopper. The vibration velocities of the transducer were measured using a laser Doppler velocimeter. It is seen that diffracted light intensity increases with the vibration velocity of the transducer. The intensity ratio of the first-order diffracted light to the fundamental light was 1/4 when the input ultrasonic intensity was 9 W/m$^2$ for a 200-kg/m$^3$ sample. This shows that the nanofoam has higher acousto-optic efficiency than those of other conventional materials.

We measure the diffraction angle $\theta$, and then, the sound speed $c$ is calculated the product of the ultrasonic frequency and the ultrasonic wavelength $\Lambda$. $\Lambda$ is calculated from the relationship

$$\sin \theta = \frac{\lambda}{\Lambda},$$

where $\lambda$ is the light wavelength (632.8 nm). From these results, the sound speed of silica nanofoam varied in the range of 57–179 m/s with density.

3. STANDING WAVE MEASUREMENTS

To verify the results presented in the previous section, we measured standing waves in the silica nanofoam, using an optical interferometer [12]. In this measurement, we employed a laser Doppler velocimeter (LDV) as an optical interferometer. The light of the LDV was transmitted through the nanofoam sample in the direction perpendicular to the propagation direction of the ultrasound, and was reflected back to the LDV head by a mirror located outside the sample. The optical path length was modulated by the ultrasound via the acousto-optic effect of the sample, and the modulation was decoded at the output of the LDV as if...
the mirror had vibrated. The LDV light was scanned along the propagation direction of the ultrasound to plot the sound field distribution in the sample. The ultrasonic frequency is limited to the lower region, since it is difficult to reduce the beam diameter of the light smaller than the ultrasonic wavelength. Then, a 130-kHz ultrasonic transducer was employed in this experiment. Figure 4 shows an example of the measured standing waves in the silica nanofoam with a density of 250 kg/m$^3$. Sound speed can be estimated from the ripples of the standing waves, and was found to be 57, 67, 100, 127, and 178 m/s for the samples with the densities of 100, 150, 200, 250 and 300 kg/m$^3$, respectively. The results agreed well with the data measured from the diffraction at 510 kHz.

4. STATIC COMPRESSION EXPERIMENT FOR SOUND SPEED CALCULATION

We measured Young’s modulus and Poisson’s ratio of a sample to calculate sound speed. We applied a static force to the sample using a force gauge with a plate of 25 mm$^2$, as shown in Fig. 5. Stress-strain characteristics and the relationship between longitudinal deformation and transverse deformation are measured. It is impossible to estimate Young’s modulus from only the stress-strain relationship because the static compression experiment conducted here was not an ideal case. In the experiment, the top and bottom surfaces are fixed to the pressing plate the stage without slip. We measured the longitudinal deformation $x$ and the lateral deformation $y$, as indicated in Fig. 6, by changing the vertical force. Here, let us define the apparent Poisson’s ratio $\sigma_a$ as the ratio of the longitudinal strain to the lateral strain,

$$\sigma_a = \frac{2y}{10 \times 10^{-3} \text{[m]}} / \frac{x}{5 \times 10^{-3} \text{[m]}} = \frac{y}{x},$$

and the apparent Young’s modulus $E_a$ as

$$E_a = \frac{F}{10 \times 10^{-6} \text{[m$^2$]}} \left / \frac{x}{5 \times 10^{-3} \text{[m]}} \right..$$

Here, $x$ was measured using a micrometer installed in the $z$-axis stage, while $y$ was measured using optical microscope. On the other hand, on the basis of the model shown in Fig. 6, the relationship between the apparent Poisson’s ratio and true Poisson’s ratio is calculated by the finite element method (FEM). Figures 7 and 8 show the relationships between the apparent Poisson’s ratio and the ratio of apparent Young’s modulus to true Young’s modulus and true Poisson’s ratio, respectively. Using these plots, the true Poisson’s ratio and the Young’s modulus are found from the measured $\sigma_a$ and $E_a$, and the results are summarized in Figs. 9 and 10 as functions of density. Young’s modulus varied 0.13–3.0 MPa for the density of 100–300 kg/m$^3$, while Poisson’s ratio varied in the range of 0.20–0.38. These values are substituted into the equation for the longitudinal sound speed,

$$c = \sqrt{\frac{E}{\rho \left(1 + \sigma \right) \left(1 - 2\sigma \right)}}.$$

where $E$ is Young’s modulus, $\rho$ is the density, and $\sigma$ is the Poisson ratio of the silica nanofoam. Since the width of the path of the ultrasonic waves was much larger than their

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**Fig. 4** Standing wave distribution in the silica nanofoam with density of 250 kg/m$^3$.

**Fig. 5** Experimental setup for measuring Young’s modulus and Poisson’s ratio.

**Fig. 6** Silica nanofoam deformed by press test.
wavelength, Eq. (4) can be used instead of the sound speed of a rod. The resultant sound speed varies in the range of 38–136 m/s.

5. DISCUSSION

Figure 11 summarizes the sound speed of silica nanofoam measured by the three methods as well as the sound speed of a bulk sample of silica glass (SiO$_2$). Figure 12 shows the relationship between the sound speed of silica
nanofoam and frequency. Sound speed changes negligibly in the range of 0.1 to 2 MHz.

The sound speed measured as described in Sect. 2 using the Raman-Nath diffraction angle can be fitted by the curve $47 + 0.00008\rho^{2.5}$ as a function of density. The results agreed with the ones measured from the 130-kHz standing waves. A lower density sample has lower sound speed. These values agreed with ones estimated from the bulk Young’s modulus, Poisson’s ratio and the density with the error of less than 43 m/s. This implies that the low sound speed might be attributed to the reduced bulk elastic constant owing to the structure and might not be greatly affected by air confined in the porous structure in the density range of our experiments.

6. CONCLUSIONS

In this study, we experimentally estimated the sound speed of silica nanofoam as a function of the density through acousto-optic measurements. The sound speed was estimated, from the Raman-Nath diffraction angle, to be 55–178 m/s for the apparent density of 100–300 kg/m$^3$. The measured sound speed almost agreed with the sound speed calculated from the bulk Young’s modulus and Poisson’s ratio. This implies that the low sound speed might be attributed to the reduced bulk elastic constant owing to the structure, and might not be greatly affected by air confined in the porous structure. Theoretical considerations with appropriate modeling of the nanofoam structure will be left for future studies. The experimental data given in this paper may provide basic references for such theoretical work.

ACKNOWLEDGMENT

The authors would like to thank Mr. M. Hashimoto of Panasonic Corporation for providing the silica nanofoam sample.

REFERENCES