Short Communication

Measurement of tortuosity in aluminum foams using airborne ultrasound

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Article history:
Received 18 April 2009
Received in revised form 29 May 2009
Accepted 28 July 2009
Available online 7 August 2009

PACS:
81.70.Cv
43.20.Hq
43.20.Jr
43.20.Ye

Keywords:
Tortuosity
Ultrasound
Porous medium
Dispersion
Attenuation

Abstract

The slow compressional wave in air-saturated aluminum foams was studied by means of ultrasonic transverse transmission method over a frequency range from 0.2 MHz to 0.8 MHz. The samples investigated have three different cell sizes or pores per inch (5, 10 and 20 ppi) and each size has three aluminum volume fractions (5%, 8% and 12% AVF). Phase velocities show minor dispersion at low frequencies but remain constant after 0.7 MHz. Pulse broadening and amplitude attenuation are obvious and increase with increasing ppi. Attenuation increases considerably with AVF for 20 ppi foams. Tortuosity ranges from 1.003 to 1.032 and increases with AVF and ppi. However, the increase of tortuosity with AVF is very small for 10 and 20 ppi samples.

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1. Introduction

Bone is a composite material composed of organic and inorganic phases and mainly consisted of two main anatomical types: cancellous (or spongy) bone and cortical (or compact) bone. Cancellous bone is more complicated than cortical bone in terms of structure. Cancellous bone is inhomogeneous, anisotropic and porous with the trabeculae forming a supporting honeycomb-shaped microstructural framework. The spaces between the trabeculae are filled with bone marrow. The presence of trabecular makes cancellous bone a highly scattering medium. Osteoporosis is a bone disease characterized by significant change in cancellous bones: decrease in bone mass and deterioration of bone microstructures. Trabecular bone spacing is considered an important parameter to detect change in bone tissue microstructures. Some researchers have attempted to use ultrasonic techniques to estimate mean trabecular bone spacing, which is the average distance between regular trabeculae [1–3]. Interaction of ultrasound with cancellous bone is complicated because the received transmitted or reflected signals are influenced by many factors such as material absorptive characteristics, scattering mechanism, porosity, to name a few. Recently, some bone tissue-mimicking phantoms [3–7] have been designed to systematically study the effect of the influencing factors upon the amplitudes, phase velocities and attenuation of the ultrasonic signals. However, these phantoms do not adequately account for the microstructures of the cancellous bones.

Biot developed an effective medium theory for an isotropic and macroscopically homogeneous fluid-saturated porous solid [8–10]. The theory predicts two compressional waves. The fast wave corresponds to the solid and fluid components moving in phase while the slow wave corresponds to the two components moving out of phase. The slow wave always travels at speed slower than the compressional wave speed in fluid. Plona [11] was the first to observe the slow compressional wave at ultrasonic frequencies and Berryman [12] confirmed the agreement between Biot's theory and Plona's results. Below a critical frequency, the slow wave is diffusive and strongly attenuated. Above the critical frequency, the slow wave propagates with low attenuation. The theory predicts...
the phase velocities better than the attenuation of the transmitted signals [13]. Tortuosity is an intrinsic property of the solid frame relating to the pore space and geometry [12,14] and is an important parameter to predict phase velocities of porous materials. The resistivity method and airborne ultrasound technique have been used to measure tortuosity of some porous materials [14,15]. Nagy et al. [16] was the first to propose a simple method to measure tortuosity in air-filled porous materials and natural rocks. The airborne ultrasound method is appealing because of the following reasons. Firstly, air has a low dynamic viscosity $\eta$ (or high kinematic viscosity $\eta_0 = \eta/\rho_f$, where $\rho_f$ is the density of air) and, thus, saturates the samples quickly. This is prescribed by the condition that the viscous skin depth $\delta = (2\eta/\rho_f\omega)^{1/2}$ at angular frequency $\omega$ be less than the pore size while the wavelength is greater than the grain size [16]. Secondly, though high attenuation is expected, the slow waves can be observed without interference from the fast waves. Leclaire et al. [17] provided a description of slow wave generation in air-filled porous material. Vibrations in air cannot generate vibrations of the frame because the frame is heavy while vibrations of the frame can generate displacement in air. They are known as airborne and frame-borne compressional waves respectively. The airborne wave, which is strongly damped at low frequencies, is known as slow wave. Stretziki et al. [18] studied ultrasonic slow waves in air-saturated cancellous bone.

The commercial DUOCEL open-celled aluminum foams have an irregularly interconnected network of solid ligaments. Ji et al. [19] studied aluminum foams and obtained some agreement between experiments and Biot's theory. Studies using the aluminum foams are very limited [19–23]. The foams are attractive because they mimic the porous microstructures of cancellous bone. Our ultimate goal is to evaluate aluminum foams as potential cancellous bone-mimicking phantoms for osteoporosis studies. The present work discusses the results of using airborne ultrasound technique to measure tortuosity of aluminum foams.

2. Materials and methods

The DUOCEL aluminum foams were manufactured by the ERG Materials and Aerospace Corporation (Oakland, CA) and the metal skeleton is aluminum 6101 alloy. A foam sample is shown in Fig. 1. The foam has an open-celled structure and the aluminum ligaments form an interconnected network. The matrix of pores and ligaments is completely repeatable. The foam properties are characterized by the number of cells or pores per inch (ppi) and the aluminum volume fraction (AVF). There are four available ppi: 5, 10, 20, and 40 and each ppi has three available AVF: 5%, 8% and 12%.

The samples have high porosities (95%, 92% and 88%), which are calculated by \((1 - \text{AVF})\). The mean cell size (in mm) is calculated by 25.4/ppi; the mean pore size is mean cell size \(\times (1 - \text{AVF})\); the mean ligament thickness is mean cell size \(\times\) AVF or \((1 - \text{mean pore size})\). For our purpose, we chose to study 3 cell sizes excluding 40 ppi. The cell size ranges from 1.27 mm to 5.08 mm and the pore size from 1.11 to 4.82 mm. There were nine samples together and the sample dimension were 12.7 mm thick with a 50.8 mm \(\times\) 50.8 mm square surface. Table 1 summarizes the cell and pore sizes of the samples. The ligament thickness, pore size and AVF of the 20 ppi foam samples are quite similar to the trabecular thickness, trabecular separation and bone volume fraction of the human calcaneus [3,24].

Fig. 2 depicts the schematic diagram of the transverse transmission experimental setup. The apparatus has a pair of 19-mm-diameter 0.5 MHz unfocused broadband transducers (Olympus V318-SU, Waltham, MA) co-aligned linearly with each other at 29.2 ± 0.5 mm separation. At 0.5 MHz, the skin depth (3.1 mm) is much less than the pore size and the wavelength (0.68 mm) is larger than the ligament thickness. The transmitter was pulsed by a Olympus 5800 computer controlled pulser/receiver (Olympus, Waltham, MA) and the signals was received and stored by a LeCroy waverefer 422 oscilloscope (LeCroy, Chestnut Ridge, NY). The signals were digitized at 2 Gigasamples per second at 8 bit resolution and were averaged over 256 acquisitions to increase signal-to-noise ratio. The time window consisting of the waveform was selected and the corresponding time series was later decimated 100 times to reduce data samples to 400 points, which were then padded with zeros for FFT. For each sample, eight measurements were made and the samples were shifted slightly (~2 mm) parallel to the transducer faces between measurements. Tortuosity values were calculated for all eight measurements and the average was reported.

According to Ref. [25], there is a preferred elongation of the pore structures during the forming process of aluminum foam due to the primary expansion directly from the balance between gravitational and pneumatic forces. This phenomenon mimics a similarly orienting trabecular bones in a direction of primary load stress [26]. The anisotropy of the structural behavior in the elongated direction is around 5–15% greater than the other two orthogonal directions. This may have an influence on acoustical behavior. In our experiment, the ultrasonic beam is along the thinnest dimension (12.7 mm) and perpendicular to the pore elongation.

3. Results and discussion

Fig. 3 shows the time signals for all samples. Fig. 3a is the signal through air without sample in the traveling path. The total acoustic travel time is 85.4 \(\mu\)s. Thus the velocity of sound in air is 342 m/s at room temperature (22 °C). Fig. 3b–d show the signals through nine samples. Each signal is the average of eight measurements. The signals are attenuated and the amplitudes are reduced by a factor of 10 as compared to the air pulse. Pulse broadening is obvious and increases with the increase of ppi. For the same ppi, AVF has very small influence upon the pulse shape and amplitude as shown in Fig. 3b–d. Fig. 4 shows the corresponding phase velocity curves. Phase velocities were calculated by the substitution method [19]:

$$PV(\omega) = \frac{\omega L}{\omega L/c_{\text{air}} - \Delta \phi(\omega)}$$

where $\omega$ is angular frequency, $L$ thickness of the foam, $c_{\text{air}}$ acoustic wave speed in air and $\Delta \phi(\omega)$ is the unwrapped phase difference between the air pulse and the sample signal. Dispersion is described by the slope of phase velocity versus frequency curve. Small dispersion is shown in all samples at low frequencies. The phase velocities...
at 0.5 MHz were measured and tabulated in Table 1. All phase velocities are less than the acoustic wave speed in air and decrease with the increase of ppi. By assuming a stiff solid frame, the tortuosity, $a_1$, can be approximated by the phase velocity $c$ of the signal at high frequency (phase velocity method):

$$a_1 = \frac{n_2}{r} = \frac{c_{air}}{c}$$

where $n_2$ is the refractive index. At frequencies higher than 0.7 MHz, the phase velocity reaches a constant value for each sample and no dispersion was further observed. Using the slow wave phase velocity at 0.7 MHz as the asymptotic value for all high frequencies, the tortuosity can be calculated. Table 1 lists the tortuosity values for all samples. The values range from 1.003 ± 0.001 for 5 ppi and 5% AVF to 1.032 ± 0.003 for 20 ppi and 12% AVF. For 5 ppi, tortuosity increases with AVF; for 10 and 20 ppi, tortuosity increases moderately with AVF. However, tortuosity increases with increasing ppi. Tortuosity values for 20 ppi are very similar to those reported for cancellous bone samples. Stretitzki et al. [18] obtained a mean of 1.037 for repeated measurements of one sample and a mean of 1.041 for all samples. Fellah et al. [27] obtained a value of 1.059 for tortuosity of water-saturated human cancellous bone by optimization of an inverse problem using reflected waves. Instead of using the phase velocity at high frequency, the signal velocity of aluminum foam, $v$, can also be used to determine the tortuosity as [16]:

$$a_1 = \frac{c_{air}}{v}$$

where $a_1$ is the tortuosity and $v$ is the signal velocity. For example, for 20 ppi and 12% AVF, the signal velocity is 336 m/s, the same as the asymptotic phase velocity value. Leclaire et al. [17] suggested a method to determine tortuosity using the ordinate

<table>
<thead>
<tr>
<th>AVF (%)</th>
<th>5 ppi</th>
<th>10 ppi</th>
<th>20 ppi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell size (mm)</td>
<td>5.08</td>
<td>5.08</td>
<td>5.08</td>
</tr>
<tr>
<td>Pore size (mm)</td>
<td>4.82</td>
<td>4.67</td>
<td>4.47</td>
</tr>
<tr>
<td>$PV$ (m/s)$^a$</td>
<td>341</td>
<td>339</td>
<td>338</td>
</tr>
<tr>
<td>Attenuation (dB)$^b$</td>
<td>17.5 ± 0.5</td>
<td>18.6 ± 0.5</td>
<td>18.9 ± 0.5</td>
</tr>
<tr>
<td>Tortuosity$^c$</td>
<td>1.003 ± 0.001</td>
<td>1.015 ± 0.007</td>
<td>1.022 ± 0.002</td>
</tr>
<tr>
<td>Tortuosity$^d$</td>
<td>1.003 ± 0.002</td>
<td>1.014 ± 0.007</td>
<td>1.022 ± 0.002</td>
</tr>
</tbody>
</table>

$^a$ Measured at 0.5 MHz. The standard deviations of the measurements are very small and can be neglected.

$^b$ Measured at 0.5 MHz.

$^c$ Estimation provided by the phase velocity method based on Eq. (2).

$^d$ Estimation provided by the intercept method [17].

Fig. 2. A schematic diagram of the experimental setup.

Fig. 3. The ultrasound signals: (a) through air, (b) through 5 ppi samples, (c) through 10 ppi samples, and (d) through 20 ppi samples. (5% AVF: solid line; 8% AVF: dashed line with crosses; 12% AVF: dashed line with circles.)

Fig. 4. Phase velocities: (a) 5 ppi samples, (b) 10 ppi samples, and (c) 20 ppi samples. (5% AVF: solid line; 8% AVF: dashed line with crosses; 12% AVF: dashed line with circles.)
The tortuosity values obtained by the intercept method are very close to the best-fitted line with the ordinate yields the tortuosity. The intercept of the best-fitted line with the ordinate yields the tortuosity range from 1.003 ± 0.002 to 1.032 ± 0.003 and increases with AVF and ppi. The increase of tortuosity with AVF is quite small for 10 and 20 ppi samples. Tortuosity values are obtained by the phase velocity method and the intercept method respectively and are in good agreement. With the increase of ppi, phase velocities decreases but attenuation increases. The 20 ppi foam samples bear much resemblance to the cancellous bone in terms of ligament thickness, pore size, solid volume fraction and tortuosity. Our future work will be focused on studying the foam samples further as a potential cancellous bone-mimicking phantom for osteoporosis study.

Acknowledgments

The research was supported by Natural Sciences and Engineering Research Council of Canada.

References


