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Linking the micro-structural properties of novel sound absorbing metallic foams to their macroscopic acoustic parameters

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Abstract [632] Recently, the Industrial Materials Institute (IMI) of the National Research Council of Canada (NRC) developed a new process to produce metallic foams. These foams have an interesting combination of properties, including good sound absorption qualities. A distinctive feature of the process is its ability to control some of the foam's final micro-structural properties such as the average pore D_p and window D_w diameters. With such a process, smart design of acoustical materials, namely optimization of the microstructure to obtain specific acoustical performances, can be deemed attainable. As a first step in this direction, the objective of this paper is to link the micro-structural properties of the metallic foams, mainly the pore and window diameters, to the thermal Λ' and viscous Λ characteristic lengths of the Johnson-Champoux-Allard model for rigid frame porous materials. The analysis of the metallic foams microstructures is based on measurements on micrographs taken by scanning electron microscopy (SEM). The macroscopic acoustic parameters are measured using a standing wave tube characterization method. It is shown that a direct link exists between the pore and window diameters and the thermal and viscous characteristic lengths for these particular materials, namely $\Lambda' \approx D_p/2$ and $\Lambda \approx D_w/2$.

1 INTRODUCTION

Smart design of acoustic materials is fast becoming one of the main research interest of the acoustic community. This is a necessary step in order to develop new and more efficient sound absorbing materials for tomorrow's applications. Two main approaches can be used to achieve this goal: a microscopic approach and macroscopic one. The microscopic approach consist in developing an acoustic wave propagation model which is directly based on the microstructure of the given material. The macroscopic approach involves establishing links, through either analytical or empirical methods, between the micro-structural properties of porous materials and their macroscopic acoustic properties. Once these links have been established, they are substituted in the macroscopic models and the necessary tools for optimizing the microstructure of an acoustic material are then available. In both approaches, the ability to produce the porous materials with the desired micro-structural properties is also an important part of this equation.

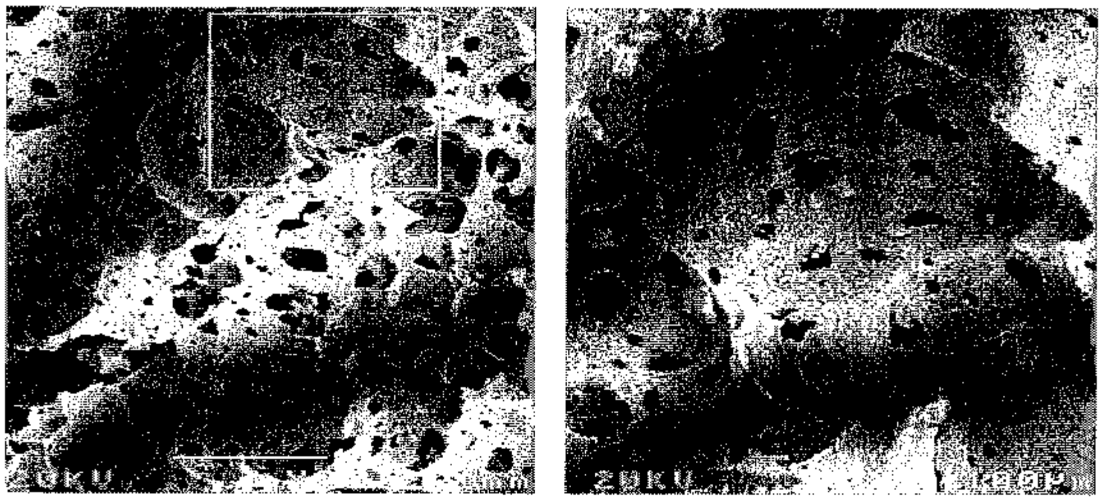
The materials evaluated in this study are newly developed metallic foams having an interesting combination of properties, including good sound absorption qualities [1, 2]. A distinctive feature of the process is its ability to control some of the foam's final micro-structural properties such as the average pore D_p and window D_w diameters. With such a process, the concept of smart design of acoustical materials can be deemed attainable. The main objective of the work presented in this paper is to establish links between the micro-structural properties of these metallic foams and their macroscopic acoustic properties.

Some models correlate wave propagation in porous media with some micro-structural parameters. Usually, they are only valid for simple pore geometries: cylindrical pores with constant circular, rectangular, triangular or slit section. In 1949, one of the first such model was developed by Zwikker and Kosten [3]. It allows for the study of acoustic wave propagation in cylinders with circular section. More recently, in 1991-1992, Stinson and Champoux developed exact solutions, based on Zwikker and Kosten's work, for porous materials with identical parallel cylinders with constant rectangular, triangular and slit sections trough the introduction of shape factors [4, 5]. Around the same time, more general models were developed by Johnson et al. and by Champoux and Allard [6, 7] which are valid for a wide range of porous materials with arbitrary pore geometry. They introduced two parameters, the viscous Λ and thermal Λ' characteristic lengths that are known to represent, from a macroscopic point of view, the radius of the small and large pores respectively [6, 7]. Generally speaking, these models are semi-phenomenological models and are not truly based on the microstructure of the studied materials. In 1999, Wang and Lu [8, 9] developed an analytical model for an acoustic material having an honeycomb structure. They optimized the microstructure of the material in order to maximize its acoustic sound absorption. In 2000, Lu et al [10] develop a theory based on the acoustic impedance of circular openings and of cylindrical cavities to model the acoustical behavior of an aluminum foam having this type of microstructure. They completed a parametric study to identify the influence of the micro-structural properties on the sound absorption of the foam.

The approach of developing a micro-structural model for a new type of material is quite interesting, but can be difficult for complex microstructure geometries. Hence, as a first step, the approach that will be used here is based on linking the acoustic parameters of the Johnson-Champoux-Allard models, mainly the viscous Λ and thermal Λ' characteristic lengths, to the window and pore diameters of the metallic foams. This should lead to the development of a semi-phenomenological model which takes micro-structural properties as input parameters. If successful, this approach could be applied to other types of acoustic materials in the future. This paper is structured as follows. First, the link between the micro-structural properties and the viscous and thermal lengths is shown analytically. Second, the procedures used to characterize the microstructure and the acoustical properties are detailed. The results are then presented and discussed. Finally, a short conclusion is made.

2 ANALYTICAL RELATIONS

The metallic foams studied here have an open-porosity structure featuring three levels of pore sizes [2]. The structure is characterized by large cells (1st level of pore size, referred to as the pores) with some openings (2nd level of pore size, also called windows) on the cell walls. The pores and windows can be seen in Fig. 1. The third level of pore size, visible at higher magnification, comes from the voids between the sintered metallic particles. This level of pore size is not considered in the present analysis. Hence, considering that the foams are homogeneous on a macroscopic scale, the basic topology of the foam, or metric, can be identified as a sphere (the pore) of diameter D_p with openings (the windows) of diameter D_w representing the intersections between the pores. The thickness of the pore wall is defined as $L_w/2$.



(a) pores (20X) (b) windows (50X)

Figure 1: *Typical SEM micrographs taken at different magnification for the pores and the windows.*

From this basic structure, it is possible to evaluate the analytical value of the thermal characteristic length Λ' using the following expression:

$$\Lambda' = \frac{2\int_V dV}{\int_S dS} = \frac{2(V_p + V_w)}{S_{pc} + S_{wc}}, \tag{1}$$

with

$$\begin{aligned} V_p &= \frac{4\pi(D_p/2)^3}{3}, \\ V_w &= N\pi(D_w/2)^2(L_w/2), \\ S_{pc} &= (1-\phi_p)S_p, \\ S_{wc} &= 2\pi N(D_w/2)(L_w/2). \end{aligned}$$

where V_p and V_w are the total volume of the pore and the windows respectively, S_p is the inner area of the pore of diameter D_p, S_{pc} is the contact area between the fluid and the pore wall, S_{wc} is the contact area between the fluid and all the windows walls, N is the average number of windows per pore and ϕ_p is the surface porosity of the pore. The terms related to the windows can be neglected, since L_w is very small. Hence, eqn. (1) reduces to:

$$\Lambda' = \frac{2V_p}{(1-\phi_p)S_p} = \frac{2(D_p/2)}{3(1-\phi_p)}, \tag{2}$$

where D_p is the pore diameter. By looking at Fig. 1 and considering that ϕ_p should be much smaller that the material total porosity ϕ, one can make the reasonable assumption that ϕ_p is relatively small, i.e. $0.3 \leq \phi_p \leq 0.4$, then eqn. (2) yields $0.95(D_p/2) \leq \Lambda' \leq 1.1(D_p/2)$, hence $\Lambda' \approx D_p/2$.

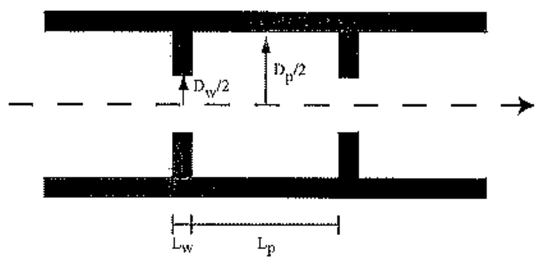


Figure 2: *Simplified 1D representation of the porous system for* Λ.

For the viscous characteristic length Λ, a similar relation can be developed. The expression of Λ writes:

$$\Lambda = \frac{2\int_V |\vec{v}_V|^2 dV}{\int_S |\vec{v}_S|^2 dS}, \tag{3}$$

where $|\vec{v}_V|^2$ and $|\vec{v}_S|^2$ are the norm of the squared microscopic velocity in a non viscous fluid in the volume and at the surface (of a pore or a window) respectively. Because of the velocity, it is more convenient to evaluate Λ for a simplified pore geometry than for the perforated sphere which is considered for the evaluation of Λ'. The pore geometry used for Λ is presented in Fig. 2 and is an idealized 1D cylindrical pore structure with a circular section having small openings (or windows) in the interconnecting walls. Considering this, eqn. (3) becomes:

$$\Lambda = \frac{2(\bar{v}_{Vp}^2 V_p + \bar{v}_{Vw}^2 V_w)}{\bar{v}_{Sp}^2 S_{pc} + \bar{v}_{Sw}^2 S_{wc}}, \tag{4}$$

where

$$V_p = \pi(D_p/2)^2 L_p,$$
$$V_w = \pi(D_w/2)^2 L_w,$$
$$S_{pc} = 2\pi(D_p/2) L_p,$$
$$S_{wc} = 2\pi(D_w/2) L_w.$$

It is important to point out that the thickness of the pore wall (or window length) L_w can not be neglected here, like it was the case for Λ'. This is related to the velocity which is more important in the smaller pores, i.e., in the windows. Considering that the fluid is inviscid in the porous system, then $\bar{v}_{Vp}^2 = \bar{v}_{Sp}^2 = \bar{v}_p^2$ and $\bar{v}_{Vw}^2 = \bar{v}_{Sw}^2 = \bar{v}_w^2$. Also, taking into account that they are no compressibility effects and that the volumetric flow is assumed constant through the pore and window, we get that the average velocity in the pore $\bar{v}_p$ is related to the velocity in the window $\bar{v}_w$ by $\bar{v}_p = \bar{v}_w(D_w^2/D_p^2)$. Therefore, eqn. (4) yields:

$$\Lambda = \frac{D_p D_w^3 L_p + D_w D_p^3 L_w}{2(D_w^3 L_p + D_p^3 L_w)}. \tag{5}$$

Assuming $D_w << D_p$, yields $\Lambda \approx (D_w/2)$.

3 MICRO-STRUCTURAL PROPERTIES

For the purpose of this research, five different metallic foams were produced. Various manufacturing parameters were used to obtain materials with different pore size distributions and densities. In the end, four disk shaped samples (diameter of 29 mm and thickness of 10 mm) were made for each metallic foam.

The micro-structural analysis of the metallic foams was done measuring the pores and windows on micrographs taken with a SEM (model JEOL JSM-6100). The pore and window diameters were evaluated by image analysis on the digitalized SEM micrographs. Figures 1 (a) and (b) show typical micrographs of the pore and window structures respectively. Figure 1 (b) present a magnification of the boxed section in Fig. 1 (a). As it can be seen, the foams are relatively heterogeneous at a microscopic scale. Each pore and window micrographs are taken at 20X and 50X magnification respectively. The large and small diagonals of the pores and windows were measured using an image analysis software. It is important to point out that windows smaller that 10 μm are not taken into account in the measurements, since they are too small to be measured on a 50X micrograph. Ten SEM micrographs have been taken (five at 20X and five at 50X) on one of the four samples for each metallic foam. Hence, a total of 50 SEM micrographs were taken for the purpose of this evaluation. The average pore and window diameter measurements are presented in Table 1.

Table 1: *Window (D_w) and pore (D_p) diameters - SEM measurements*

	Diameters	
Metallic foam	D_w (μm)	D_p (μm)
A	92 ± 51	363 ± 129
B	91 ± 63	305 ± 112
C	101 ± 77	389 ± 148
D	83 ± 40	256 ± 124
E	103 ± 78	676 ± 490

The most noticeable result in these measurements is the relatively important standard deviation. As it was pointed out before, this can be explained by the fact that the metallic foams are relatively heterogeneous at a microscopic scale, which leads to scattering of pore and window sizes. Hence, in the forthcoming analysis, only the average value of the diameters will be considered for comparison basis. The standard deviation will not be taken into account as it would yield a much wider range of validity, which in turn will reduce the accuracy of the present study.

4 MACROSCOPIC ACOUSTIC PROPERTIES

The acoustical properties of the 5 metallic foams are presented in Table 2. All measurements described here were performed on all four samples of each metallic foam. The flow resistivity (σ), the porosity (ϕ) and the bulk density (ρ_1) were measured using non-acoustical methods [11, 12], whereas the tortuosity (α_∞) and the viscous and thermal lengths (Λ and Λ') were measured using acoustical [13, 14] methods. The acoustical measurements were performed in a Bruel & Kjaer 29 mm diameter standing wave tube (model 4206). The specimen fit tightly inside the tube and were backed by the tube rigid termination, as described in the ASTM E1050-86 standard. The mechanical properties of the metallic foams (E, ν, and η) were not measured here since the rigid frame hypothesis was used to model the acoustic behavior of the foams. The metallic nature of the frame justifies the use of this hypothesis.

Table 2: *Macroscopic acoustic properties - acoustical measurements*

Metallic foam	Properties						
	ϕ	σ (Ns/m^4)	ρ_1 (kg/m^3)	α_∞	Λ (μm)	Λ' (μm)	Λ'/Λ
A	0.94	23181	516	1.15	43 ± 15	178 ± 42	4.1
B	0.94	25875	559	1.14	37 ± 16	149 ± 32	4.0
C	0.92	29518	759	1.50	42 ± 5	192 ± 4	4.6
D	0.89	62842	976	1.51	23 ± 1	119 ± 7	5.1
E	0.93	13652	666	1.36	38 ± 1	334 ± 9	8.7

Some remarks can be made regarding the macroscopic acoustic properties of these metallic foams. First, the Λ'/Λ ratio is relatively high compared to that of other foams: fibrous materials generally have a ratio close to 2 and the typical ratio for polymer foams is usually between 2 and 4. Second, the porosity ϕ is low compared to other acoustical porous materials, which usually have porosities between 0.95 and 0.98. Finally, the viscous length Λ is somewhat smaller than for other porous materials which can have a Λ as high as 200 μm. These various observations help one confirm some of the initial hypotheses that were made in the analytical justification: 1) $D_w << D_p$ since Λ'/Λ is high, and 2) the surface porosity ϕ_p of a pore can be very small since $\phi_p << \phi < 0.95$.

5 RESULTS AND ANALYSIS

The results obtained previously for the pore and window diameters were compared with the viscous and thermal characteristic lengths. The results are presented in Table 3.

The agreement between the measured average pore diameter D_p and $2\Lambda'$ is good for all five metallic foams (maximum error of 7%). The average value of the pore radius $D_p/2$ is within the standard deviation of Λ' for all materials except for material D, in which case the agreement is still satisfactory. From these results, it is also possible to deduce the average surface porosity ϕ_p of the pores using eqn. (2), which yields $\phi_{pA} = 0.32$, $\phi_{pB} = 0.32$, $\phi_{pC} = 0.32$, $\phi_{pD} = 0.28$ and $\phi_{pE} = 0.34$. This confirms the initial assumption that $0.3 \leq \phi_p \leq 0.4$ and that the thermal characteristic length is equivalent to the pore radius ($\Lambda' \approx D_p/2$). As for the viscous characteristic length Λ, the agreement is initially not as convincing (maximum error of 44%). Λ is

Table 3: *Comparison of acoustic and SEM measurements for the window and pore diameters*

Metallic foam	Window			Pore		
	2Λ (μm)	D_w (μm)	Δ_w (%)	$2\Lambda'$ (μm)	D_p (μm)	Δ_p (%)
A	87 ± 29	92 ± 51	5	357 ± 86	363 ± 129	2
B	74 ± 31	91 ± 63	19	297 ± 63	305 ± 112	3
C	83 ± 12	101 ± 77	18	384 ± 83	389 ± 148	1
D	47 ± 2	83 ± 40	44	238 ± 15	256 ± 124	7
E	77 ± 3	103 ± 78	25	667 ± 19	676 ± 490	1

smaller that the average window radius $D_w/2$, even when considering the standard deviation on Λ for materials C, D, and E. This result was nevertheless expected. Since windows smaller than 10 μm and the third level of porosity (voids in between the sintered metal particles) are not considered in the measurement of D_w, it is reasonable to assume that the actual average window diameter is smaller that the measured D_w. As explained previously, the expression of Λ is weighted by the average velocity and hence, tends to represent the smaller windows where the velocity is higher; the small windows and third level porosity are therefore taken into account when making the acoustical measurements of Λ, since it is a macroscopic measurement. Hence, when considering the aforementioned, it can be said that the viscous characteristic length Λ is a good indicator of the average window radius $D_w/2$, as the latter should be smaller than those measured on the digitalized micrographs.

6 CONCLUSION

It has been shown that a direct link exists between the thermal characteristic length Λ' of the Johnson - Champoux - Allard model and the average pore diameter D_p ($\Lambda' \approx D_p/2$) and between the viscous characteristic length Λ and the average window diameter D_w ($\Lambda \approx D_w/2$) in the studied open-cell metallic faoms. Considering that the metal foam production process used allows a good control of the final microstructural properties, smart design of acoustical materials, namely optimization of the microstructure to obtain specific acoustical performances, can be deemed attainable with these new materials. Furthermore, the direct link between Λ', Λ and the pore and window radii would allow to develop a non-destructive acoustical method to characterize the microstructural properties of these foams. This method would be less time consuming than the SEM image analysis method that is normally used.

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