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Ultrasonic characterization, simulation of porous metal in the interest of high frequency applications

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Abstract

Today, research is set up to carry out studies on the ultrasonic characterization of porous metals in the interest of ultrasonic applications. In this work, the acoustic properties of several porous metals were investigated to be used as a backing material in ultrasonic transducers. Results in terms of celerity, acoustic impedance and attenuation are reported for porosity ranging from 25 % to 50 % with pore size ranging from 1.7 µm to 60 µm. The acoustic impedance of the porous material depends linearly on the porosity and can be described by a simple model of the homogenization of a fluid in a solid matrix. Results show that the acoustic attenuation strongly depends on the porosity and can reach 4.3 $dB.mm^{-1}$ at 1 MHz which is suitable to be used as a backing material.

Keywords: Porous metal, ultrasonic characterization, simulation, acoustic impedance, acoustic attenuation, porosity.

1 Introduction

Ultrasonic non-destructive testing methods are particularly well adapted to the monitoring and control of structures. These methods are based on the use of single or multi-element ultrasonic transducers and allow the imaging of defects. An ultrasonic transducer (Figure 1) consists of an active piezoelectric element metalized on both sides on which a backing is bonded on the rear face. The role of this backing is to damp the vibration of the active element to improve the axial resolution and widen the bandwidth of the transducer. On the front side is bonded a matching layer whose role is to promote the transfer of energy to the propagation medium. [1]

Backing and adaptation layers are generally made of a polymer composite and a powder whose proportions are adjusted so that the acoustic properties meet the desired function [2]. In addition, the active element is in most cases a modified lead zirconate titanate (PZT) ceramic. As a consequence, conventional ultrasonic transducers cannot be used industrially at temperatures above 200 °C because of the polymer materials characteristics used and also because PZT ceramics have a Curie temperature below 450 °C. In practice, such transducers often have a maximum operating temperature below 200 °C [3]. However, there are many needs, especially in the nuclear sector where the control of structures at high temperatures (>500 °C) is required. In this case, PZT ceramics are replaced by Lithium Niobate with a Curie temperature above 1100 °C [3]. Thus, the laboratory has developed, manufactured and used for about thirty years ultrasonic sensors that can operate to temperatures higher than 600 °C for applications in sodium-cooled fast neutron reactors (SFR) [4]. Due to the lack of backing these transducers are used for telemetry applications. However, in the context of the improvement of high temperature ultrasonic transducers (HTUS) to develop high temperature imaging systems, the insertion of a backing bonded on the rear face of the active element is considered to improve the axial resolution of the transducers.

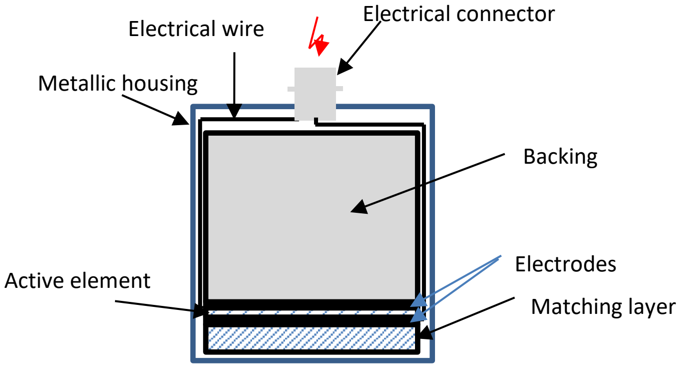

Figure 1: Schematic view of a transducer

In this context, porous metals in general and porous stainless steel (SS 316L) are relatively new classes of engineering materials that are possible candidates as high temperature backing materials. Thus, research is set up to carry out studies on ultrasonic characterization and the simulation of porous stainless steels. The introduction of pores in the material makes it possible to modify the properties of the initial material. These changes generate or reinforce desired properties, which are not observed or exhibited in a limited way in the original material. In particular, the variation of the structural properties of porous materials, such as the amount of porosity and the size of the pores, implies an evolution of the acoustic properties like the sound velocity, the acoustic impedance (given by the product of the density by the sound velocity) and the acoustic attenuation of these materials [5]. This fact explains why porous materials currently attract huge attention in the development of the acoustic field to absorb sound noises at low frequencies of the range of 2 - 6 kHz and to develop wideband ultrasonic transducers for high temperature applications.

In this work, the acoustics properties of porous stainless steel were determined from ultrasonic measurements in water using an insertion-substitution method. The transit time measurements of an ultrasonic wave and the frequency analysis are carried out considering the reflection and transmission coefficients at the interfaces to determine the ultrasonic celerity the acoustic impedance and the attenuation in stainless steel porous materials. Finally, the KLM equivalent scheme is used to model the electroacoustic response of a high temperature ultrasonic transducer.

2 Role of the backing

The propagation of ultrasonic waves through two materials and their energy transfer depends on the difference in the characteristic impedances, Z_1, and Z_2, of these materials. [2] If this difference is large, most of the energy of the incident wave is reflected while a small part of this energy is transmitted. The optimal energy transfer is obtained when the characteristic impedances are as close as possible. When the transducer is excited by a broadband electrical impulse, the piezoelectric element is put in resonance and around its central frequency given by $f_0 = c_p/2d$ where c_p is the celerity of the ultrasonic waves in the active element and d its thickness. An ultrasonic wave is emitted on the front and rear faces of the active element. A part of the acoustic energy is transmitted through the front face into the propagation medium and the other part to the backing. When the difference between the characteristic acoustic impedances of the piezoelectric element and the impedance of the backing is high, most of the energy is transmitted to the propagation medium through numerous round trips in the ceramic. These echoes increase not only the amplitude of the pulse-echo response but also its time duration.

The second characteristic to consider for backing is acoustic attenuation. [2] Acoustic attenuation quantifies the loss of acoustic energy mainly due to scattering and/or acoustic absorption mechanisms. For a given thickness, an attenuating backing avoids reflection echoes at the bottom of the backing that returns to the piezoelectric element. In the following, we discuss this mechanism in more detail to gain a deeper understanding of how a backing can damp acoustic probes and consequently improve the performance of the transducer.

3 Metallic porous materials for high temperature applications

3.1 Criteria for the choice of the material

The choice of backing material for a high-temperature ultrasonic transducer must, on one hand, meet a compromise between acoustic impedance and acoustic attenuation, and on the other hand, the chosen material must have physical and mechanical properties that ensure its operation at high temperatures.

The backing must, therefore, satisfy the following characteristics: [6]

- The ultrasonic attenuation coefficient must be high enough to reduce the acoustic energy returning to the piezoelectric material;
- The appropriate acoustic impedance must be a compromise between sensitivity and resolution;
- Physical and mechanical properties must be thermally stable in the conditions of the useful service;
- The coefficient of thermal expansion (CTE) should be close to that of the piezoelectric material so that thermomechanical stresses are minimized.

The possibility of assembling the backing and the active element must be ensured.

3.2 Porous steel

We have measured the acoustic properties (velocity attenuation and acoustic impedance) of different porous steels of type SS 316L manufactured by AMESPORE at room temperature. The average porosity and pore size characteristics measured on five samples of these steels are given in table I.

Material	Nominal thickness (mm)	Measured Thickness (mm)	Nominal density ($kg.m^{-3}$)	Measured density ($kg.m^{-3}$)	Nominal porosity (%)	Measured porosity (%)	Nominal Pore size (µm)
SSU02-10	10	9.98	5900 - 6300	6059	21 - 26	25.20	1.7
SSU05-10	10	10.30	5000 - 5600	5073	32 - 37	36.91	7.6
SSU10-10	10	10.13	4700 - 5100	5268	36 - 41	34.97	10.9
SSU15-10	10	9.92	4600 - 5000	4526	37 - 42	44.12	13.5
SSU25-10	10	9.88	4400 - 4800	4444	39 - 44	45.14	26.5
SSU40-10	10	10.34	4000 - 4400	3828	44 - 49	52.75	39.0
SSU60-05	5	5.05	3600 - 4000	3811	49 - 54	52.95	59.5
SSU60-10	10	9.89	3600 - 4000	3856	49 - 54	52.04	59.5

Table 1: Material density, porosity and pore size

4 Results and discussion

The acoustic properties of the samples were determined by transmission measurements using an insertion substitution method.

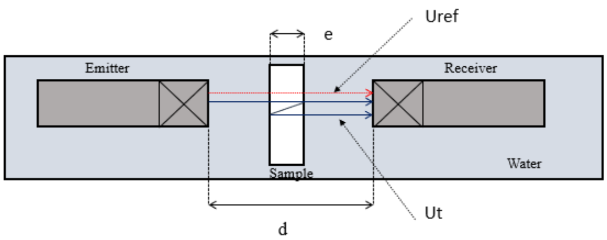

Figure 2: the principle of the insertion substitution method for the characterization of acoustic properties of materials

An electric pulse is sent to the emitting transducer using a wide band generator (Olympus- Panametric 1035 PR), and the signal is received after transmission either with or without the sample. It is digitized by an oscilloscope (Lecroy Wave runner 104Xi, Chestnut Ridge, NY, USA) and transferred to a computer for treatment. The time difference, Δt, between the transmitted signal in the reference medium, U_{ref}, (without that sample) and that when the sample is inserted, U_t, is related to the celerity of the ultrasonic wave in the material and to that of the reference medium.

$$\Delta t = e\left(\frac{1}{c} - \frac{1}{c_w}\right) \quad (1)$$

Where $c_w = 1500\ m.s^{-1}$ is the sound velocity in water, c is the propagation speed of ultrasound in the sample and e is its thickness.

Knowing the celerity and the attenuation, the transmission/reflection coefficient between the sample and water, then the attenuation in dB m^{-1} in the sample is given by

$$\alpha = -20log\left(\frac{\bar{P}_{t1}(f)}{T.\bar{P}_{Ref}(f)}\right) * \frac{1}{2e} \quad (2)$$

Where $\bar{P}_{t1}(f)$ is the modulus of the transfer function of the signal, U_t, transmitted through the sample, $\bar{P}_{Ref}(f)$ is the modulus of the transfer function of the signal, U_{Ref}, transmitted to in the water and T the energy transmission coefficient at the water-sample interface. In our case, this attenuation is measured at the center frequency of the transducer.

Table 2 presents the acoustic properties of the porous stainless steel. Measurements were made using 1 MHz transducers. For each nominal porosity, 20 samples were characterized which allow us to determine a standard deviation for the acoustic properties. Standard deviations are below 10 % for both celerity and acoustic impedance, however, it is around 20 % for the attenuation. Indeed, this measurement was made at the central frequency of the received signal which can change from one sample. In addition, as the attenuation coefficient depends on the transmission coefficient of the ultrasonic wave and thus the acoustic impedance this effect cumulates with the measurement of the amplitude ratio.

Material	Average porosity (%)	Average celerity ($m.s^{-1}$)	Standard deviation (%)	Average acoustic Impedance (MRayls)	Standard deviation (%)	Average attenua-tion ($dB.mm^{-1}$)	Standard deviation (%)
SSU02-10	25.20	4402	1.90	26.73	2.46	0.46	12.75
SSU05-10	36.91	3556	2.68	18.08	4.20	0.49	9.16
SSU10-10	34.97	3751	1.57	19.75	2.80	0.46	26.05
SSU15-10	44.12	2884	3.27	13.06	4.45	1.19	12.98
SSU25-10	45.14	2679	3.68	11.90	5.87	1.27	19.82
SSU40-10	52.75	2141	8.10	8.19	9.48	4.29	25.60
SSU60-05	52.95	2229	6.44	8.48	8.75	4.00	19.81
SSU60-10	52.04	2317	5.69	8.93	7.47	5.62	16.84

Table 2: Acoustic properties of porous stainless steel (SS 316L)

Figure 3 presents the evolution of ultrasonic celerity, acoustic impedance and attenuation as a function of the porosity.

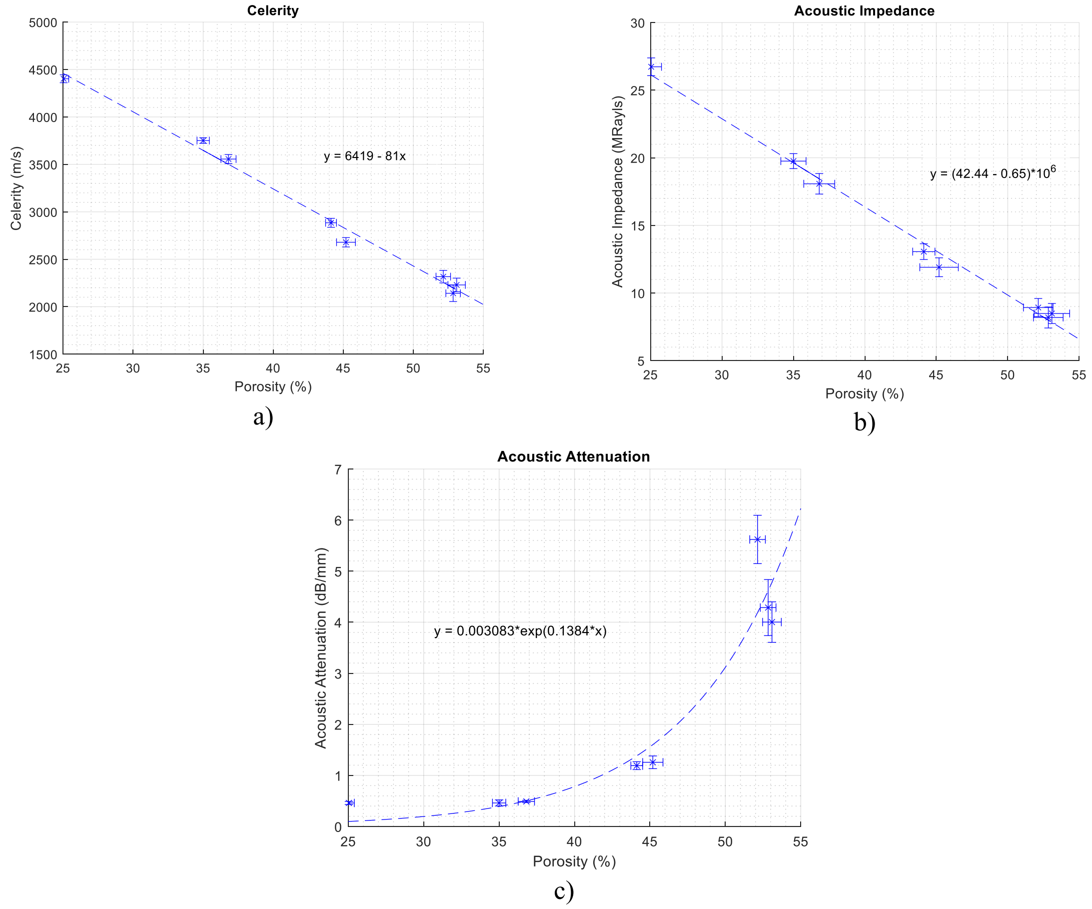

Figure 3: Acoustic properties of porous stainless steel as a function of the porosity. a) celerity of ultrasonic waves, b) acoustic impedance, c) acoustic attenuation.

Looking at the variation of the celerity as a function of the porosity (Figure 3a)), a linear dependence is observed. In the porosity range investigated it is possible to use a simple mix law to describe the behavior of celerity. As a consequence, acoustic impedance (Figure 3b)) has also a linear dependence. As a function of the porosity, it the possible to Taylor this value to fit the requirement for a specific application. For porosity below 37%, the attenuation is around 0.4 dB.mm^{-1} at 1 MHz, and rapidly increases to reach a value of 5 dB.mm^{-1} for a porosity of 52 %. Considering a transducer made with such a backing of 1 cm thick, attenuation at 1 MHz would be for a round trip in the backing of more than 100 dB which is largely sufficient for developing imaging systems.

5 Simulation of the transducer

In this part the electroacoustic response of a Lithium Niobate Z cut based transducer with backing is simulated using the one-dimensional KLM model that was developed in the laboratory. [1] For the simulations, we first simulated the impulse response of a reference lithium niobate based transducer whose configuration is given in table 3. Then porous steels whose characteristics were measured previously replaced the rear face. Figures 4, 5 and 6 present the pulse-echo response of the reference transducer and those obtained by replacing the rear face with a 25 % (SSU10) and 45% (SSU25) porosity stainless steel.

Cristal	**$LiNbO_3$ Z-cut**	**Front layer / rear layer**	
Diameter (mm)	40	Thickness (mm)	1.2 / 2
Thickness (mm)	0.78	Velocity (m.s^{-1})	5900
Density (kg.m^{-3})	4650	Acoustic impedance Z (MRayl)	45.4
Velocity (m.s^{-1})	7140		
Z (MRayls)	33,2		
Relative dielectric constant	29,16		
Coupling coefficient	0.17		

Table 3: Transducer simulation input parameters

Figure 4 the pulse-echo response of the reference transducer presents a very long time response. This can be explained by the multiple reflections that exist in the structure. Indeed, the active element the rear face and the front face are coupled resonators that present multiple resonance spectra. The half-width pulse duration measured on the envelope of the pulse-echo response is around 40 ms. When a porous backing is used instead of the rear layer, the pulse duration reduces to less than 1 μm when SSU02 material is used and 2 μm when SSU25 material is used. However, the pulse shape still presents round-trip echoes that is due to the presence of the front layer

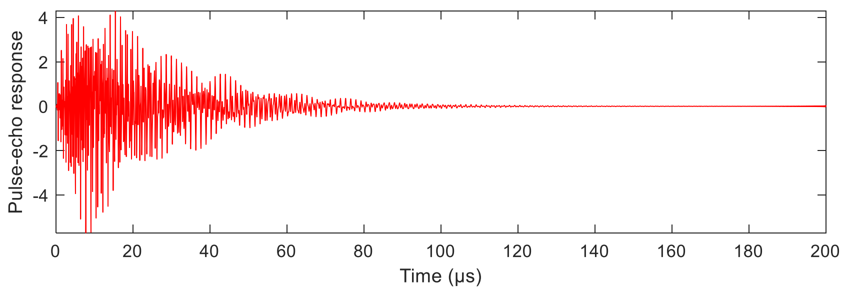

Fig.
Figure 4: pulse-echo response of the reference transducer for high temperature applications

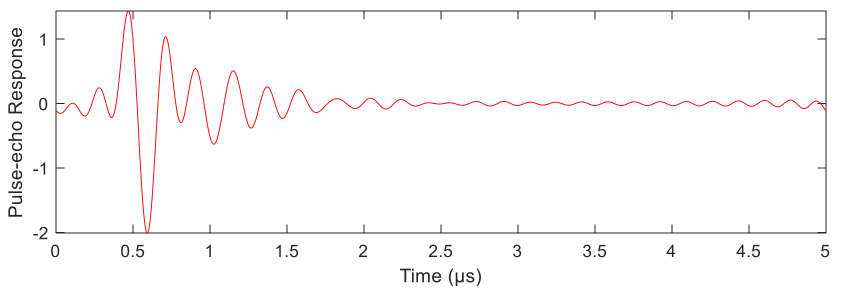

Figure 5: pulse-echo response of a transducer with a 25 % of porosity backing SSU02

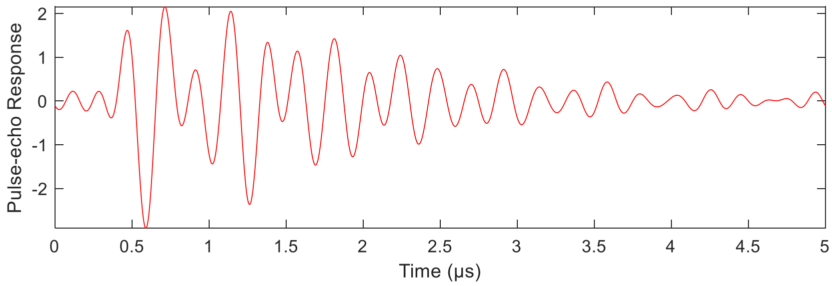

Figure 6: pulse-echo response of a transducer with a 45 % of porosity backing SSU25

6 Conclusion

In this work, the acoustic properties of porous stainless steel have been investigated. Celerity, acoustic impedance and attenuation were determined for porosity ranging from 25 to 52 % in the MHz range. Experimental results show that the celerity and the attenuation vary linearly with the porosity rate. Attenuation measurements at 1 MHz demonstrate that these materials are good candidates to be considered as backing materials for high temperature applications. Simulations of a Lithium Niobate based transducer with such backing, show a significant improvement in the pulse-echo response of the transducer. However, careful attention must be paid to the compromise that needs to be reached between the sensitivity and the bandwidth of the transducer as well as geometrical dimensions that restrain the use of certain porous materials in reason of their relatively low attenuation.

Future work will focus on the thermal characterization of these porous materials and on the modeling of the attenuation as a function of the porosity level and pore size.

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