# Interest of optimizing the response of a high-temperature ultrasonic transducer by integrating a porous aluminium backing element for the detection of structures immersed in liquid sodium

G. Chabanol[1], F. Baudry[1], E. Rosenkrantz[1], D. Laux[1], A. Paveyranne[1,2], JY. Ferrandis[1*]

[1] IES, Univ Montpellier, CNRS, Montpellier, France
[2] CEA-DES-IRESNE, Cadarache, Saint-Paul-Lez-Durance, France
(*) jean-yves.ferrandis@umontpellier.fr

*Abstract*—**With the emergence of major applications in harsh environments (such as the new generation of nuclear reactors and power plants, under sodium visualization reactors...), the scientific and industrial community expresses a real need for developing a range of instrumentation dedicated to monitor, control, and check resistance to ageing and damage of a large panel of structures. Ultrasonic transducers are particularly well adapted to address this issue. Up to date, there are no commercial solutions for this type of application and only a few prototypes of ultrasonic transducers exists. Thanks to the use of a specific backing material produced by uniaxial pressing of an aluminium powder containing a small amount of wax followed by sintering, we designed two ultrasonic prototypes transducers dedicated to continuous high temperature experiments. The first one is a PZ27 based 2 MHz piezo-element and the second one a Cerium-modified NBT based 10 MHz. These sensors, with a thickness of 5 mm, tested on a steel sample from room temperature to 140°C (for PZ27) and 335°C (for NBT), turned out to be entirely consistent with what one might expect for echographic time-resolved measurements. Furthermore, temperature-dependent velocity propagation relationships obtained on steel were consistent with the literature. Given their small thickness, they might be easily integrated into various experiments in harsh environments, where space is limited: measurements in sodium reactors, nuclear fuel assemblies, narrow zones in aeronautics or petrochemical industry etc.**

*Keywords* — **High temperature, Ultrasounds, Pulse echo, Thin transducers, Harsh environment**

## I. Introduction

In order To carry out ultrasonic measurements on thin samples when it is impossible to use very high frequencies (for instance because of sample attenuation), one solution is to optimize the backing, a material added on the rear face of the piezo-element. This material has a damping effect and therefore reduces the duration of ultrasonic echoes in the studied material, thus increasing the temporal resolution of A-scans. However, it is important to avoid any round trip in the backing which could interfere with the echoes in the studied sample. The backing must therefore be highly attenuating. Finally, the backing must have a well-chosen impedance with respect to the impedance of the piezo-element. If its impedance is too low, it is useless. On the contrary, if its impedance is too high, the backing dampens the signals too much, ultimately rendering the transducer ineffective. For the classic piezo-elements used in high-temperature applications an impedance between 5 and 15 MRayl is suitable [1]. The subject is widely discussed in literature [2,3]. For example, factory-made porous steels with a thickness of 2 cm have been proposed [4]. In our previous paper [1], we proposed an experimental protocol using uniaxial pressing of aluminium powder containing a very small amount (2-4 %) of wax, to produce highly attenuating 4 mm backings with an impedance that is perfectly acceptable for the use with classical piezo-elements used in industry. Thanks to the pressing method and the addition of wax, the backing is actually lamellar and highly anisotropic, leading to the desired mechanical properties. In this new paper, we coupled such backing materials to a simple 2 MHz-PZ27 piezo-element and to a Cerium-modified NBT (Na0.5 Bi(4.5−x)Ce(x)Ti4015) screen printed 10 MHz piezo-element settled on a 760 µm alumina substrate manufactured in our team dedicated to high temperature tests. All details concerning these Cerium-modified NBT piezo-element manufacturing can be found in [5]. Ultrasonic velocity measurements were then carried out on a 1 cm 304 steel sample up to 140°C for PZ27 sensor and up to 335°C in the NBT case in order to check the capital role of our backings, their temperature resistance and the quality of the ultrasonic signals during the temperature increase. After a detailed presentation of the piezo-elements coupling to backing, heating procedure, experimental high temperature test benches, signal acquisition and data processing, the law obtained between ultrasonic velocity in steel and temperature will be discussed regarding literature data to validate the potentialities of our transducers in hostile environments.

## II. Experimental benches, data acquisition, and signal processing

To achieve the bond between the piezo-element and the backing, the characteristics of the adhesive must be precisely chosen, particularly in terms of acoustic impedance. Indeed, if the impedance of the adhesive is too different from that of the backing, the expected effect of the backing may be strongly impacted. Ideally, an adhesive material having a high attenuation and an impedance equal to those of the backing has to be used. In this case, the adhesive layer behaves like an extra-layer of backing. Obviously, the adhesive material has to be temperature-resistant and must have a thermal expansion coefficient close to that of the backing and the piezo-element. Ceramic bonding cements or epoxy like adhesives can fill this role. To guide our choice, several ceramic cements adhesives (Resbond 940, 989, 919, 907GF) and a high expansion epoxy like (Thermeez 7030) produced by Cotronics were characterized. For each adhesive, we manufactured disks with a diameter of 16 mm and a thickness of 5.5 mm. These disks were characterized with a transmission method at 5 MHz using the measurement bench described in reference [6] and validated in the framework of fine ultra-wideband characterization of poly(methyl metacrylate) (PMMA). The results in terms of acoustic impedance are given in Table 1.

TABLE I
ACOUSTICAL IMPEDANCE OF SOME RESBOND AND THERMEEZ HIGH TEMPERATURE ADHESIVES

| Cotronics adhesive type | Acoustical impedance (MRayl) ± 0.5 |
|---|---|
| Resbond 940 | 5.1 |
| Resbond 989 | 9.1 |
| Resbond 919 | 9 |
| Resbond 907GF | 5.9 |

The aluminium backing disks used in our experiments had an acoustical impedance equal to 6 MRayl. So, considering the results presented in Table 1, all the adhesives can be used because their acoustical impedance is in the same order of magnitude of backing impedance. Rigorously, the adhesives to be chosen are, in order of preference (if acoustical impedance is the major criterion): Resbond 907RF, Resbond 940, Thermeez 7030, Resbond 919 and Resbond 989. Finally, Thermeez 7030 adhesive was chosen not only for its impedance, but also for its thermal characteristics and ease of use: it can withstand temperatures up to 980°C (1800°F), and is easily applicable to small surfaces at room temperature. Furthermore, its preparation is very simple compared to the other adhesives. It only consists in mixing adhesive powder with water. At last, the attenuation of this ceramic paste has been estimated at around 40 dB/cm at 5MHz which is a perfectly acceptable value as mentioned in our previous work [1]. In practice, 100 doses of 7030 powder were mixed 20 doses of water. The obtained paste was then applied between the piezo-element and the backing disk. The assembly, firmly tightened with a 200 grams mass was heated 4 hours at 65°C.

The final thickness of these probes was estimated at 5 mm using a caliper. Before temperature measurements, the (backing+piezo-element) assembly was then coupled to the steel sample using a high-temperature (100°C-520°C) coupling paste supplied by Action-NDT. To ensure that the sample-transducer coupling remained stable throughout the test, a small device with a screw was used for the two sensor's tests and is displayed in Fig. 1 for PZ27 system. For PZ27 based sensor, temperature-dependent measurements up to 140°C we used a PID-controlled hot table. Concerning higher temperature tests for NBT based sensor, a Carbolite RWT 100 furnance (up to 1100 °C) was employed (See Fig. 2). In both cases, even if a temperature is imposed by the heating device, a thermo-couple was added in the vicinity of the ultrasonic sensor to obtain the real temperature. Furthermore, after any temperature change we followed the echoes arrival time until they reached a plateau. Indeed, as ultrasonic velocity is time dependant, if echoes do not temporally move this means that a stable temperature has been reached.

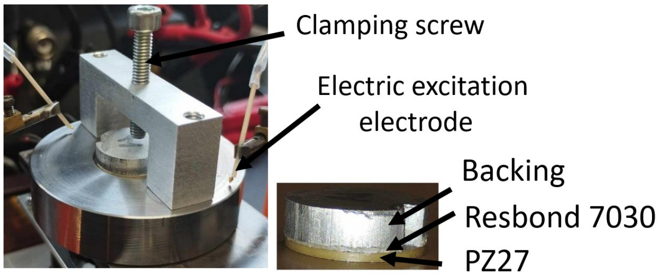


Fig. 1. PZ27 piezo-elements coupled to aluminium backing and steel sample before heating

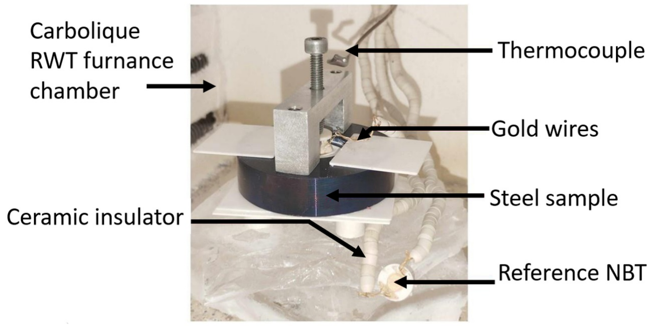


Fig. 2. NBT piezo-element coupled to aluminium backing and steel sample after heating.

## III. Experimental bneches, data acquisition, and signal processing

### *A. Effect of backing*

In order to illustrate the effect of backing on echoes duration and temporal resolution, echograms with and without backing are displayed in Fig. 3 and Fig. 4.

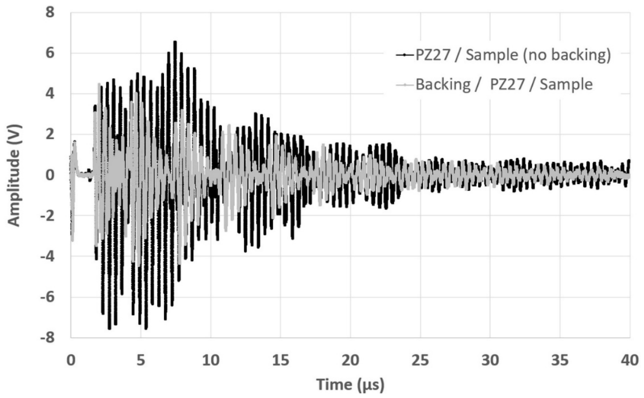


Fig. 3. Echograms for PZ27 device with and without backing at room temperature

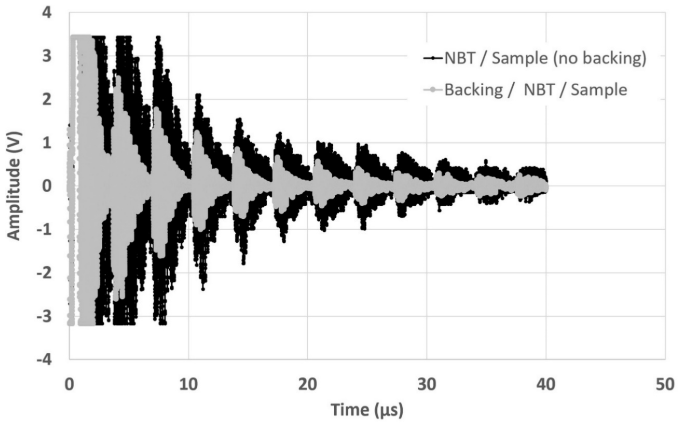


Fig. 4. Echograms for NBT device with and without backing at room temperature

As expected and clearly demonstrated in our previous work [1] with simulations, the presence of backing lead to echoes duration reduction and consequently to temporal resolution increase, overlapping between round-trips being reduced. Piezo-element coupling lead to echoes amplitude reduction which could have a deleterious effect for attenuating samples investigation. Nevertheless, the choice of an impedance around 5 MRayl limits this effect and in fine, the echograms are not impacted a lot in term of amplitude.

### *B. Ultrasonic velocity in steel versus temperature*

Ultrasonic velocity, measured as described in [7-9] versus temperature with an accuracy of ± 30 m/s is displayed (in the range 25°C-140°C) for PZ27 device in Fig. 5 and for NBT device (in the range 30°C-330°C) in Fig. 6. Error bars are not plotted in these figures for more clarity. In both cases a linear trend was observed an led to the regressions (1) and (2). The mean behaviour law (3) can be given for ultrasonic velocity in steel sample versus temperature :

$$V_{STEEL(PZ27)} = 5913 - 0.636.T(°C) \quad (1)$$

$$V_{STEEL(NBT)} = 5926 - 0.623.T(°C) \quad (2)$$

$$V_{STEEL(MEAN)} = 5919.5 - 0.629.T(°C) \quad (3)$$

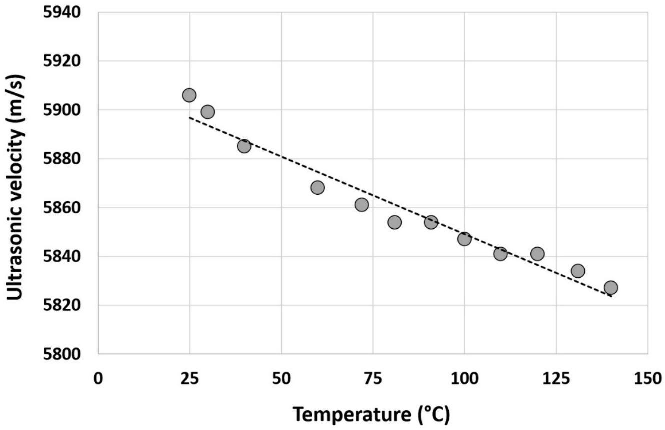


Fig. 5. Ultrasonic velocity in steel sample obtained with PZ27 device up to 140°C

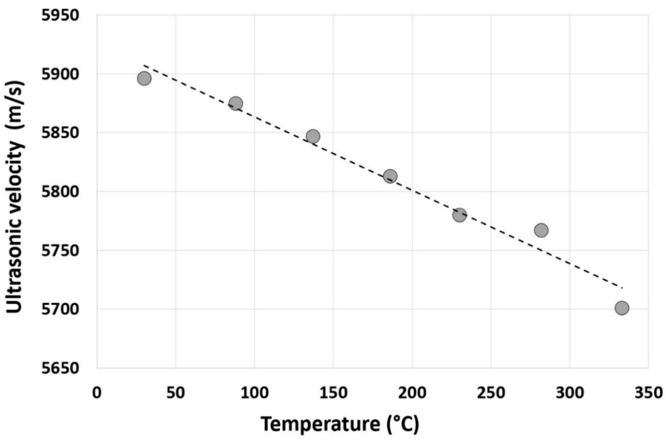


Fig. 6. Ultrasonic velocity in steel sample obtained with NBT device up to 335°C

Our results are in line with literature [10,11] in which linear trends are also reported with slopes between -0.28 and -0.68 m/s/°C. Our value of velocity at room temperature (5919 m/s) is also in line with values reported in the previous references. Regarding Curie's temperature of both PZ27 (350°C) and Cerium-modified NBT (600°C), results up to 250°C in PZ27 case and 450°C for NBT could have been expected. Indeed, it is generally admitted that piezo-elements are enough efficient up to 0.75TCurie. After experiments and return to room temperature signals have recovered the amplitudes measured before test. So, no degradation of piezo-elements occurred and no electrical connections were damaged. So, the integrity of sensors is not responsible for the temperature limitations observed. But one has to bear in mind that with temperature increase the mechanical quality factor of the piezoelement decreases and that the ultrasonic attenuation in steel increases [11, 12] leading to smaller amplitude echoes during heating.

## IV. Conclusions

Results obtained in this communication clearly demonstrate the capital role of the backing material and that aluminium backings produced by uniaxial pressing of an aluminium powder containing a small amount of wax followed by sintering are perfectly adapted for high temperature time resolved measurements. Nevertheless, measurements were limited to 140°C for PZ27 device and 334°C for NBT system which is a little bit under what could have been expected regarding Curies temperature. These limitations, attributed to piezoelement quality factor and to ultrasonic attenuation in steel is perhaps also induced by the degradation of the coupling between piezo-element and the sample. Indeed, in the framework of these experiments we used a coupling paste. Even if it is theoretically given to ensure a coupling up to 520°C nothing indicates that its performance in term of coupling quality are constant during temperature elevation. It could be imagined to couple the sensor to the sample with the Thermeex 7030 adhesive but, in this case, it would not be possible to use the sensor for other samples, the sensor being definitively glued to the sample. In this communication, ultrasonic velocity measurement in steel was just used to test our system and to demonstrate the potentialities of our transducers. For practical investigation in hostile media and in particular for ultrasonic investigations under Sodium for RNR reactors study, these transducers are particularly adapted to evaluate distance between metallic components, estimate metallic components thicknesses… during maintenance operations for instance when reactor is stopped but remains hot. Indeed, their very small thickness compared to recent works using porous steel backings [13] is very promising to operate in reduced volumes. Further works will be dedicated to reach temperatures up to 500°C-600°C thanks to the use of a best coupling agent.

## Acknowledgements

This work was supported by "La Region Occitanie - Pyrénées - Mediterranée" as part of a PhD grant.

## References

[1] Chabanol G, Laux D, Rosenkrantz E, Ferrandis JY. Uniaxial pressing of aluminium powder to design thin lamellar high damping backing materials for high-temperature ultrasonic probes. Applied Acoustics 2024;221. https://doi.org/10.1016/j.apacoust.2024.110027

[2] Rymantas K, Vaskeliene V. High temperature ultrasonic transducers: a review. Sensors2021;21(9). https://doi.org/10.3390/s21093200.

[3] Dong Y, Yue Q, Cheng D, Zhou Z, Liang R, Dong X. Ultrasonic transducer with BiScO3-PbTiO3-based ceramics of operating temperature over 400° C. Sensors and Actuators A: Physical 2022;340. https://doi.org/10.1016/j.sna.2022.113528.

[4] Nguyen DC, Navacchia F, Tran-Huu-Hue LP, Feuillard G. Ultrasonic characterization, simulation of porous metal in the interest of high frequency applications. e-Journal of Nondestructive Testing 2022;27(12). https://dx.doi.org/10.58286/27525

[5] Baudry F, Rosenkrantz E, Combette P, Fourmentel D, Destouches C, Bonzon PV, Paumel K, Ferrandis JY. Design, manufacture and temperature characterization of screen-printed acoustic sensors for monitoring the release of fission gases in experimental fuel rods of the Jules Horowitz reactor. IEEE Transactions on Nuclear Science 2024;71(5). https://doi.org/10.1109/TNS.2024.3368618

[6] Laux D, Chabanol G, Sapey G, Ferrandis JY, Rosenkrantz E. Shear and Longitudinal attenuations and quality factors of poly(methyl metacrylate) (PMMA) from 20 kHz to 12 MHz investigation with ultrasonic spectroscopy. Ultrasonics 2023;134. https://doi.org/10.1016/j.ultras.2023.107104

[7] Rosenkrantz E, Ferrandis JY, Lévêque G, Baron D. Ultrasonic measurement of gas pressure and composition for nuclear fuel rods. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 2009;609(3). https://doi.org/10.1016/j.nima.2009.02.028

[8] Sinha DN, Kaduchak G. Noninvasive determination of sound Speed in liquids. In: Levy M, Bass H, Stern R (Eds.). Published in Modern Acoustical Technics for the Measurement of Mechanical Properties. Academic Press 2001.

[9] Laux D, Gibert O, Ferrandis JY, Rosenkrantz E, Mograme MA, Prades A. In-pipe coconut water rheological characterization with ultrasonic waves. Journal of Food Engineering 2018;235. https://doi.org/10.1016/j.jfoodeng.2018.04.030

[10] Ginzel E, Ginzel R. Approximate dV/dT values for some materials. e-Journal of Nondestructive Testing 2017;22(9). https://www.ndt.net/?id=21545

[11] Tai JL, Sultan MTH, Łukaszewicz A, Shahar FS, Tarasiuk W, Napiórkowski J. Ultrasonic Velocity and Attenuation of Low-Carbon Steel at High Temperatures. Materials. 2023; 16(14). https://doi.org/10.3390/ma16145123

[12] Kube CM. Attenuation of laser generated ultrasound in steel at high temperatures;
comparison of theory and experimental measurements. Ultrasonics 2016;70. https://doi.org/10.1016/j.ultras.2016.05.009

[13] Feuillard G, Nguyen DC, Lethiecq M, Jean M, Navacchia F. Porous Metal Backing for High-Temperature Ultrasonic Transducers. Acoustics. 2024; 6(4). https://doi.org/10.3390/acoustics6040058