1-3 piezocomposite autoclavable transducers for medical and industrial applications

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Abstract—Both medical and industrial fields require ultrasound transducers able to withstand high temperature (>100°C) and harsh environment (high pressure, chemical resistance). Such probes can be used as sterilizable equipment by autoclave for the medical applications and can perform in-situ characterization of materials and in-service inspection in non-destructive testing (NDT) applications. This article will focus on the development of specific 1-3 piezocomposite configurations to address these applications in the 5-8MHz frequency range (single element and array transducers). Adequate piezocomposite configurations are integrated into complete transducers The electro-acoustical performances will be reported after more from 20 to 85 sterilization cycles. For NDT applications, the transducers will be characterized at high temperatures up to 110°C.

Index terms—autoclavable medical probe, NDT, Piezocomposite.

I. Introduction

NDT market and application required ultrasound arrays able to withstand high temperatures (>100°C) harsh environments (high pressure, chemical resistance) to perform the in-situ characterisation of materials, process monitoring and in-service inspection [1].

In medical area, lots of decontaminating solutions were used to sterilize medical ultrasound arrays, like ethylene oxide, peracetic acid, aldehydic solutions. According to the high resistance and the multiplicity of pathogen agents and microbes, most of the time the clinician has to use several decontaminating solutions. A sterilisation by an autoclave equipment would be the solution : vapour treatment at high temperature (134°C during ten minutes) and on pressure (about 2 bars) leads us to remove a great part of microbes and thus pyrolysis treatment of the post decontaminating solutions is not necessary with this autoclave equipment.

Therefore, it is necessary to develop robust and high temperature transducers that offer high sensitivity, broadband response [2] and minimum performance degradation through thermal cycles or autoclave cycles: it is a real challenge for the transducer manufacturer.

In this paper we will first describe the acoustical design of a 32 element 5MHz centre frequency ultrasound array, used in NDT application. Electroacoustical performances of this array are displayed for temperature range from 20°C to 110°C.
For medical probes, the electro-acoustical performances of a single-element 7MHz centre frequency will be reported from 1 to 85 autoclave cycles.

II. Material and Characterisation

Both single element and arrays configurations were investigated in this paper. At first, a 32 element 5MHz centre frequency probe was manufactured for NDT applications. Piezocomposite configuration was defined with piezoceramic Curie temperature of above 200°C.

The matching layer was previously described [3] and modified with 46%w of thermally conductive additive of aluminium oxide (Aldrich, 99.7%) with a particle size less than 10 microns. Finally a backing material modified with 15%w of glass bubbles was used. Polymeric phases we have investigated to manufacture this ultrasound array are all based on a thermosetting phenolic resin with a glass temperature transition at 150°C. Finally all acoustic configurations were post-cured in order to avoid delaminating of each acoustic component.

Acoustic properties of matching layer were reported in Table 1 and were measured using a through transmission inter-correlation technique. The longitudinal acoustic wave velocity (V_l) and longitudinal attenuation values (α_l) were measured at 3.5MHz. In addition, thermal conductivity (λ) was determined by the Guarded Hot Plate Apparatus [4]. Three measurements were expected on each sample. The thermal conductivity of piezocomposite material was reported on table 2.

Matching layer	
V_l (m/s)	2700
Z (MRayls)	4.99
α_l **(dB/mm/MHz)**	0.7
λ (W/mK)	1.65

Table 1 : Acoustic and thermal characteristics of manufactured matching layers.

Piezocomposite	
λ (W/mK)	0.251

Table 2 : Thermal conductivity of piezocomposite plate.

The piezocomposite configuration was chosen among the configurations detailed in a previous work [3]. For these transducer and array, the main criteria was optimum electrical impedance matching as compared to 50 Ohms, and thermal behaviour [5].

The influence of temperature on electroacoustic parameters was studied on discs with a diameter of 10mm. Real part and imaginary part of electrical impedance measurements were obtained with impedance analyser, for each temperature step between room temperature to 140°C. Electroacoustic parameters (kt, V_l, permittivity and loss) were extracted and demonstrate the very good thermal behaviour of piezocomposite material

Of course polymer phase and piezocomposite kerf widths are chosen in order to push the lateral mode far away from the operating bandwidth range.

III. ARRAY PERFORMANCES AS A FUNCTION OF TEMPERATURE IN NDT APPLICATION

In order to assess the performances of the described piezocomposite and acoustic stack materials, an array transducer was carried out. Specifications of the array are disclosed as follows :

Application :	NDT
Nb elements :	32
Center frequency :	5 MHz
Pitch :	1mm
Elevation aperture :	10 mm
Focus :	NA
Temperature range :	[-20°C, 110°C]

Figure 1 : Photo of the final array packaged and interconnect for harsh environment.

To manufacture this array, specific packaging and process for high temperature and harsh environment were developed. The acoustic stack assembly was obtained by bonding using a high temperature glue. Electrical interconnections were performed with flexible circuits and a 32 elements high temperature micro-coaxs shielded cable, with external jacket connected to the elements. A stainless steel housing was used for external protection of the array combined with encapsulation using chemical resistance and low thermal expansion potting.

The transducer array was measured in a thermally regulated silicone oil bath within the 20°C-110°C range. Transducer is connected to the 5072PR pulser-receiver via a 192 channel multiplexer. The measurements start with the recording of individual impulse response of the 32 elements of the array.

The figure 2 shows a typical impulse response obtained on transducer array immersed in water at 23°C . From impulse response and frequency spectrum, electroacoustic performances are determined: center frequency is 4.9MHz, -6dB bandwidth 73 % and axial resolution 462ns @ -20dB.

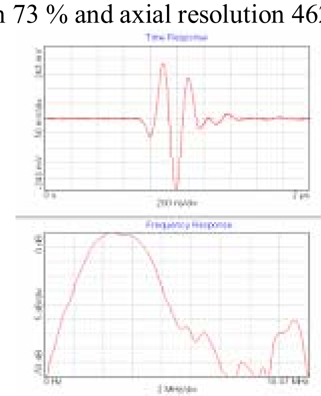


Figure 2 : Typical pulse and spectrum response for a single element of transducer array

For each temperature step all impulse responses from all array elements are acquired and then electroacoustic performances calculated. On the figure bellow is displayed average sensitivity and center frequency of the array elements as a function of temperature. All measurements were realized with in oil with agitation stopped. We limited the measurement at 110°C just before the boiling point of silicone oil, that induced strong modification of acoustic properties of propagation medium.

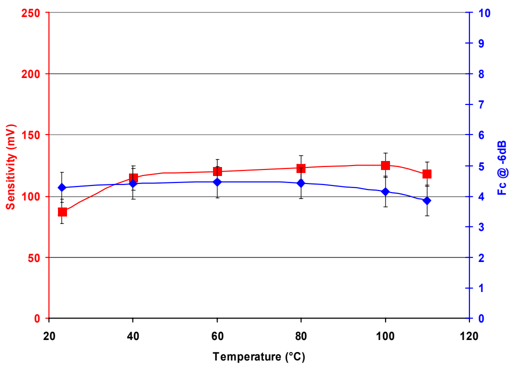


Figure 3 : (□) Sensitivity and (◊) center frequency as function of temperature for NDT transducer array.

On the figure 3, one can observe that the overall performances of array elements through the temperature range are very stable and homogeneous. The lower decrease of sensitivity at high temperature is mainly due to slight modification of bath oil acoustic properties (Impedance and attenuation). That demonstrates the good thermal stability of the acoustic stack. This array will then be very adequate on this large temperature range in NDT applications. Furthermore an acoustic control was performed @ 23 °C in water with the same previously described protocol and no changes were observed as compared to initial performances showing a non hysteretic behavior.

IV. PERFORMANCES AS A FUNCTION OF AUTOCLAVE AGEING IN MEDICAL APPLICATION

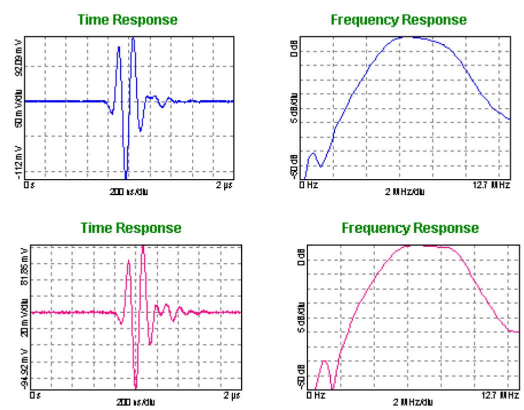
To demonstrate the autoclavable ultrasound transducer technology, we choose a simple design as prototype. The transducer is a single active element probe for superficial A-mode monitoring. The center frequency is 7 MHz and the active diameter is 5mm.

The acoustic stack is composed of the same 1-3 piezocomposite material than the previous NDT probe, with corrected thickness to target the good center frequency. Lateral mode is far away from bandwidth of interest and will not degrade the electroacoustic performances. The matching layer is set of the same material, but for the medical application an acoustic lens is cast on the transducer surface. The lens material is a specific in-house prepared silicone rubber.

After the final assembly in order to stabilize the configuration the transducer is undergone through a post-curing process in autoclave during 5 "equivalent" cycles (i.e. 134°C during 10 minutes).

Figure 4 : Photo of single element transducer integrating autoclavable compatible technology.

The procedure to qualify the purpose technology is to cycle the probe in the autoclave and to verify electroacoustic performances at each step. Number of undergone cycles is respectively: 5, 15, 35, 55, 75 and 85. Electroacoustic characterization is performed each time in water using the same characterization setup and the transducer cooled at room temperature. The figure bellow shows a typical transducer response before the first cycle and after the 75^{th} one.



(a

(b

Figure 5 : Pulse and time response of the single element medical probe 7 MHz center frequency for : (a) initial measurement, (b) after 75 autoclave cycles

One can observed that no major changes are induced between the two measurements, calculated electroacoustic performances confirm this point : Vpp = 204.1mV ; Fc = 6.9MHz ; BW(@-6dB) = 66% ; AxR(@ -20dB) = 361ns before any cycle and Vpp = 176.8mV ; Fc = 6.9MHz ; BW(@-6dB) = 68% ; AxR(@ -20dB) = 371ns after 75 cycles.

Figure 6 and Figure 7 display the fractional bandwidth, center frequency and sensitivity for each autoclave cycle.

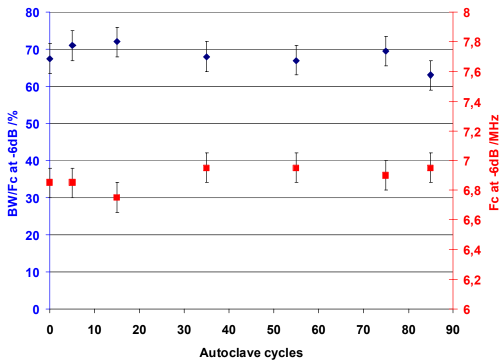


Figure 6 : (□) Bandwidth and (◊) center frequency as function of autoclave ageing for single element medical probe

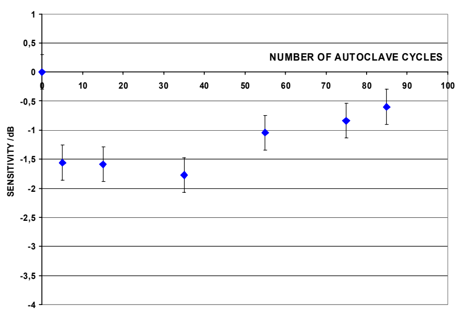


Figure 7 : Variation of sensitivity as a function of autoclave ageing for single element medical probe

During autoclave cycles minimum deviation of center frequency and bandwidth is induced. Furthermore, a very low sensitivity variation lower than 2dB is observed. This slight modification of sensitivity might be due to material ageing.

These results demonstrate the capability of this technology to handle such a large number of autoclave cycles and then to be compatible with sterilization process in medical applications.

Stable performances between cycles will allow a good reproducibility of the transducer performances as compared to the application.

We successfully applied this design to 5.0 MHz 128 element linear array for superficial applications. After 20 autoclave cycles no discrepancies on performances were observed as compared to initial control. This demonstrates the possibility to design and manufacture both single element and array transducers compatible with autoclave sterilization

V. Conclusion

This study has demonstrated that high temperature NDT transducers can reach electro-acoustic performances of their medical counterparts when properly designed.
For the medical probe, the electro-acoustic performances are conveniently stable in sensitivity, bandwidth and center frequency after more than 80 autoclave cycles (134°C, 10 min, 2 bars).
This design is applicable to specific array probes for medical application such as intraoperative ones that need high decontamination and sterilization.

References

[1] Q. Xue, M. Stanton, and G. Elfbaum, *"A high temperature and broadband immersion 1-3 piezocomposite transducer for accurate inspection in harsh environments"* in IEEE-UFFC Proceedings, pp : 1372-1375, 2003.
[2]N. Felix, L. Ratsimandresy and R. Dufait, *"High Bandwidth, High Density Arrays for Advanced Ultrasound Imaging"*, IEEE-UFFC Proceedings, 2001.
[3] C. Devallencourt, S. Michau, C. Bantignies, N. Felix, *"A 5 MHz piezocomposite ultrasound array for operations in high temperature and harsh environment" "*, IEEE-UFFC Proceedings, 2004.
[4] International standard ISO 8302.
[5] A.C.S. Parr, R.L. O'Leary, G. Smillie, A. Rice and P.T. Smith, *"Experimental and theoretical evaluation of the thermal behavior of 1-3 piezoelectric composite transducers",* IEEE-UFFC Proceedings, pp : 1041-1044, 2000.