A 5MHz piezocomposite ultrasound array for operations in high temperature and harsh environment

Christine Devallencourt, Stéphane Michau, Claire Bantignies and Nicolas Felix
VERMON, Tours - FRANCE ; http://www.vermon.com
c.devallencourt@vermon.com

Abstract—In non-destructive testing (NDT) applications, ultrasound transducer arrays capable of withstanding high temperatures and harsh environment (high pressure, chemical resistance) are required to perform the in-situ characterisation of materials, process monitoring and in-service inspection.

Index terms—High performance, Piezocomposite, NDT.

I. INTRODUCTION

Nowadays, NDT ultrasound imaging requires ultrasound arrays having acoustic performances (bandwidth and sensitivity) equivalent to those of medical imaging transducers [1,2]. Furthermore, some NDT markets and applications require the transducers to withstand high temperature operating conditions and harsh environment (high pressure, chemical resistance) to perform the in-situ characterisation of materials, process monitoring and in-service inspection. This article relates to the development of a novel 32-element 5MHz transducer specifically designed for harsch condition applications.

For this study, we have developed suitable acoustic stack components (piezocomposite, matching layer and backing) [4,5], transducer housing and assembly techniques which are compatible with the aforementioned environmental specifications.

Five configurations of 1-3 piezocomposite with improved performances have been developed and systematic study on the thermal behaviour of the different layers of transducer was conducted. The composite structures were optimised through fine adjustment of volume fraction, piezoelectric material and matrix resin.

New measurement protocols were established taking into account the intrinsic parameters of composite material as the function of temperature and thermal conductivity. Based on the results, two composite configurations have been retained for transducer designs in combination with selected passive components as matching layers and backing.

Finally, the transducer is connected to a 32-element coaxial cable and integrated in a stainless steel housing. Electro-acoustical performances versus temperature are reported.

II. MATERIAL AND CHARACTERISATION

Five configurations of piezocomposite samples, C1 to C5, were defined among 3 types of piezoceramics: one low ε_{33}^T and two high ε_{33}^T respectively designated as high ε1 and high ε2. The highest values of permittivity were obtained for the high ε1 ceramic type. The piezocomposites were manufactured using a dice and fille technique. Each piezocomposite sample had a thickness about 300µm, in manner to exhibit targeted 5 MHz resonant frequency. Kerf was chosen to provide lateral modes out of operating bandwidth range. Filler resins are designated as F1 and F2 corresponding respectively to thermosetting and epoxy resins. All details on piezocomposite configurations were reported on Table 1. The piezocomposite configurations C1 to C4 were filled with the resin F1, (a polymer with a glass temperature transition at 150°C). And the C5 was filled with the resin F2 (exhibiting a glass transition temperature at 70°C, used classically in medical arrays).

	C1	C2	C3	C4	C5
Ceramic type	highε1	lowε	high ε2	lowε	high ε2
Filler type	F1	F1	F1	F1	F2
Volume fraction	56%	66%	56%	56%	56%

Table 1 : Piezocomposite configuration details.

We also developed five preparations of matching layers (A to E) containing thermally conductive additives such as mineral particles having diameter less than 10 microns. Samples A and C were modified respectively with 46% weight and 57.8%w of aluminium oxide (Aldrich, 99.7%); sample B contained 50.6%w aluminium nitride (Aldrich, 98%), sample D contained 21.0%w silicon dioxide (Aldrich, 99%) and sample E was modified with 7.9%w of glass bubbles (3M, 99%). It is noticed that sample D is manufactured with epoxy resin F2 while the others are obtained from resin F1.

Acoustic properties of the matching layers were reported in Table 2 and were measured using a through transmission inter-correlation technique. The longitudinal velocity (V_l), and longitudinal attenuation (α_l) were measured at 3.5MHz. In addition, thermal conductivity (λ) was determined by the

Guarded Hot Plate Apparatus [3]. Three measurements were performed for each sample and the average values were reported. The whole thermal conductivity values were reported in the tables 2 and 3 corresponding respectively to matching layers and piezocomposite types.

	A	B	C	D	E
Vl (m/s)	2700	2890	2844	2668	2440
Z (MRayls)	4.99	5.14	5.64	3.49	2.24
α_l (dB/mm/MHz)	0.7	0.8	0.75	0.95	1.15
λ (W/mK)	0.165	0.236	0.175	0.095	0.178

Table 2 : Acoustic and thermal characteristics of matching layer sets.

The results above demonstrate that combination of good acoustic properties and thermal conductivity can be achieved by making optimal selection of resin and associated particles. F2 resin based matching layer exhibits lower thermal conductivity than those of F1 resin. The required acoustic impedance for matching layers was defined at 5Mrayls in order to match the impedance of Plexiglass, low acoustic attenuation and good thermal conductivity are others requirements of the design. With respect to results of table 2, type A matching layer set has been selected for their acoustic and thermal properties. However, the competing matching layer definitions can also be used in certain designs where particular characteristics are emphasized.

	C1	C2	C3	C4	C5
λ (W/mK)	0.167	0.251	0.140	0.112	0.120

Table 3 : Thermal conductivity of piezocomposite plates.

Data of conductivity measured on piezocomposite plates give information on the behavior of the material in temperature conditions. We may note by comparing results of C2 and C4 composites that thermal conductivity is directly a function of volume fraction. High dielectric piezoceramic based piezocomposites (C1 and C3) exhibit higher thermal conductivity than 5H based type due to their higher density and lower porosity.

III. INFLUENCE OF TEMPERATURE ON ELECTROACOUSTIC PARAMETERS

From the manufactured piezocomposite batch, three discs of 10mm of diameter were provided in each reference to evaluate influence of temperature on electroacoustic parameters.

Samples were then placed on a Präzitherm hotplate (accuracy about 0.5°C) having its temperature controlled by a surface temperature probe TESTO 925 (accuracy of 0.7°C between – 40 to 900°C). Electrical impedance of each sample was recorded with impedance analyzer from room temperature: 20°C to 140°C with increments every 15°C. Figure 1 illustrates real part and imaginary part of electrical impedance measurements obtained from sample C5 at 20°C and 100°C.

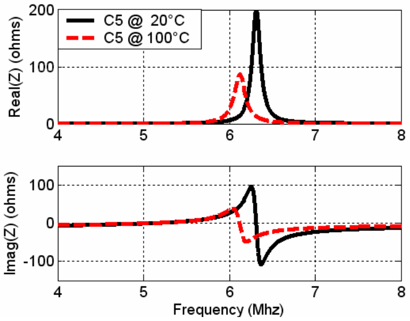
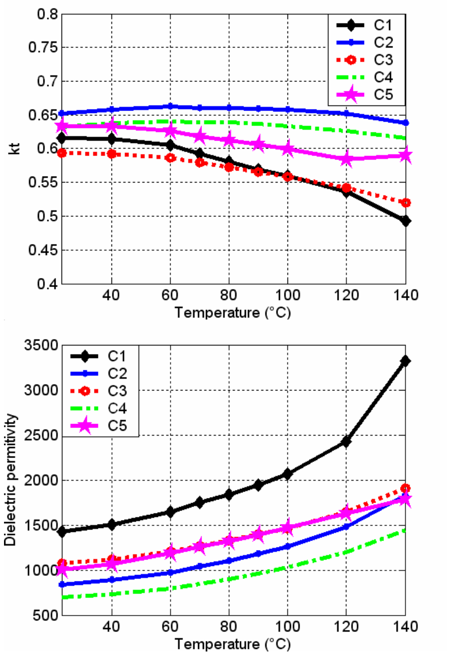


Figure 1 : Real and imaginary part of the C5 piezocomposite sample electrical impedance at 20°C and 100°C.

Electroacoustic parameters (kt, Vl, permittivity and losses) were extracted by fitting the experimental impedance data with a modified KLM model including losses. Results as a function of temperature are shown on figure 2.



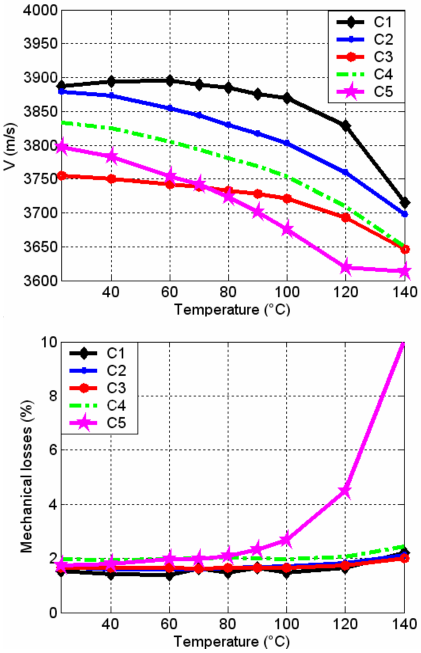


Figure 2 : Coupling coefficient, Dielectric permittivity, Celerity and Mechanical losses for C1, C2, C3, C4 and C5 piezocomposite samples as a function of temperature.

From these results we can observe the influence of filler material by comparing parameters of samples C3 (filler resin F1) and C5 (filler resin F2). From figure 2 we can note that; below 60°C the behaviour of both references is very similar, over this temperature (60°C) the glass transition phenomenon of F2 resin (sample C5) occurs and directly impacts the electromechanical performances of the composite. On the other hand, the mechanical losses of composite soar up with temperature increase, so directly affect the sensitivity of the array. With respects to the above observations, sample C3 with resin F1 remains the best candidate for high temperature transducer.

The stability of piezoelectric ceramic performance on a wide temperature range is observed to be dependent of the ceramic type. For all configurations, we noted that coupling coefficient (kt) and longitudinal velocity decrease with the temperature rise and their permittivity increases accordingly. In all cases, mechanical losses remain constant. Finally, best electro acoustic properties stability has been observed on lowest permittivity ceramic types and better thermal behaviour is obtained for the 5H based composites type.
The electroacoustic characteristics of composites are mostly governed by the ceramic composition through the temperature range. The filler resin has to exhibit glass transition temperature higher than the maximum operating temperature. Finally, composite samples C1, C2, C3 and C4 fit the requirements for high temperature transducer design, more specific choice can be done based on the examination of particular transducer configuration.

IV. ARRAY PERFORMANCES AS A FUNCTION OF TEMPERATURE

In order to assess the performances of the described piezocomposites and acoustic stack materials, two array transducers based on respectively C3 and C5 compositions were carried out. Specifications of the array are disclosed as follows:

- Applications : NDT
- Nb elements : 32
- Center frequency : 5MHz
- Pitch : 1mm
- Elevation aperture : 10mm
- Focus : Na
- Acoustic matching : Plexiglass / Rexolite
- Temperature range : [-20°C,100°C]

To manufacture these arrays specific packaging and process for high temperature and harsh environment were developed. The acoustic stack assembly was obtained by bonding using a high T° glue. Electrical interconnections were performed with flexible circuits and a 32 elements high temperature micro-coaxs shielded cable, with external jacket was 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.

Figure 3 : Photo of the final array packaged and interconnected for harsh environment.

Both arrays were measured in a thermally regulated silicon oil bath within the 20°C-100°C range. Transducers are connected to the 5072PR pulser-receiver via a 192 channel multiplexer. The array is positioned in contact with a plexiglass plate. The measurements start with the recording of individual impulse response of the 32 elements of the array. The figure 4 shows a typical impulse response obtained on both arrays for 20°C and 80°C.

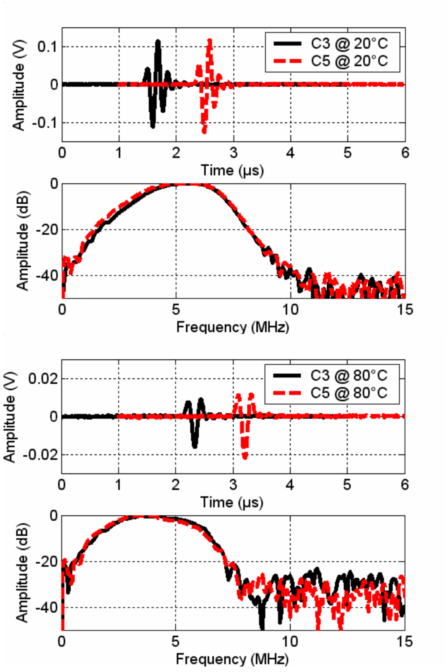


Figure 4 : Time response, frequency response of the central element of C3 and C5 based arrays at 20°C and 80°C.

Electroacoustic performances extracted from average values for C3 and C5 arrays for 20°C to 80°C and after a full cycle are summarized in the table below.

		20°C	40°C	60°C	80°C	20°C
Sensitivity	C5	248	159	75	33	236
(mV)	C3	225	149	58.9	26	220
Homogeneity	C5	0.63	0.91	2.08	4.38	8
(dB)	C3	1.17	1.17	1.47	1.41	1.35
Pulse duration @-20dB	C5	459	443	411	417	481
(ns)	C3	487	482	463	467	489
BW @ -6dB	C5	75.23	84.34	95.5	108	74
(%)	C3	68	74.4	89	103	67
Fc @ -6dB	C5	5.17	4.87	4.37	3.87	5.21
(MHz)	C3	5.29	5.06	4.56	4.10	5.3

Table 2 : Synthesis of electroacoustic performances of C3 and C5 based arrays for 20, 40, 60, 60, 80 and 20°C.

The electroacoustic measurements of the two array samples demonstrate that performances are comparable in term of sensitivity and bandwidth for both configurations. Sensitivity loss during temperature increase is mainly due to modification of reflection coefficient between plexiglass plate and silicone oil. However, the array based on C5 configuration exhibits stronger variations in homogeneity due to lack of stiffness and deformation occurred in the composite plate.

V. CONCLUSION

All the acoustic stack components (matching layers and backing) are available with properties and thermal conductivity compatible with high performance arrays and high temperature environment. Demonstration was done on that design and manufacture of piezocomposite materials for high temperature applications are achievable, without any trade-off on performances of transducer. With regard to the piezocomposite design, filler resin is the key material; and piezoceramic and volume fraction have to be carefully selected in accordance with the application. Finally, this study has demonstrated that high temperature NDT transducers can reach electroacoustic performances of their medical counterparts when properly designed.

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