

1-3 Piezoelectric Composites for High Power Ultrasonic Transducer Applications

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Abstract — In this paper, we demonstrated that 1-3 PZT/polymer composites, fabricated using PZT-4 ceramic and a polymer possessing a high glass transition temperature and low loss, can be used as high power ultrasonic transducer materials for high intensity focused ultrasound (HIFU) applications. The mechanical quality factor of the 1-3 composite with 64% ceramic volume fraction is over 200. The dielectric loss tangent is the same as that of the ceramic used in the 1-3 composite at 1 kHz. The electromechanical coupling coefficients were 0.64 for pure epoxy filler and 0.68 for epoxy incorporating microspheres. The 1-3 composite transducers demonstrated a large operating bandwidth and elevated power capacity.

specially for HIFU applications. Microsphere filled and unfilled epoxies, possessing a high glass transition temperature and low loss, were used as the passive phase. The ceramic volume fraction in the 1-3 composite was 64%. The experimental results demonstrated that these 1-3 composite samples have a mechanical quality factor Q_m over 200. The dielectric loss tangents at 1 kHz were the same as that of the ceramics used in the 1-3 composites. The coupling coefficients were 0.64 and 0.68 for the pure epoxy and microsphere filled epoxy respectively. The 1-3 composite transducers can be operated at elevated power and over a broad bandwidth.

INTRODUCTION

Ultrasonic transducers for high intensity focused ultrasound (HIFU) applications require that piezoelectric materials have high electromechanical coupling coefficients, and low dielectric and mechanical losses. PZT-4 and PZT-8 piezoelectric ceramics are widely used as HIFU transducer materials due to their low dielectric and mechanical losses [1, 2]. These materials, however, also have low coupling and are difficult to focus. Annular arrays incorporating these materials have high cross talk between array elements.

1-3 piezo-ceramic/polymer composites designed for medical imaging and NDE applications [3, 4] have high coupling coefficients and can be conformed to complex shapes. Most of these materials are not suitable for HIFU transducer applications due to their high dielectric and mechanical losses.

In this study, PZT-4 ceramics were used as the piezo-active phase in 1-3 composites designed

LOSSES IN THE 1-3 PIEZOCOMPOSITES

There are three loss sources in a 1-3 piezocomposite. The losses come from the piezoelectric ceramic phase, the losses from the polymer phase, and the losses from the non-uniform structure.

There are three kinds of losses in the ceramic phase [5], i.e, the mechanical loss, the dielectric loss and the piezoelectric loss. The mechanical quality factors of the piezoelectric ceramics are related to the resonant modes. For example, the mechanical quality factor Q_m of a transversal resonance mode is measured by $1/\tan(s_{11}^E/s_{11}^E)$, the Q_m of a longitudinal resonance mode is defined by $1/\tan(s_{33}^D/s_{33}^D)$, and the Q_m of a thickness resonance mode is given by $1/\tan(c_{33}^D/c_{33}^D)$. Where the s_{11}^E and s_{33}^D are elastic compliance constants under constant electric field and constant electric flux conditions. The s_{11}^E and s_{33}^D are the imaginary parts of the relevant constants. The c_{33}^D and c_{33}^D are the real and imaginary elastic stiffness under constant electric

flux condition. Hence, different resonant modes will have different mechanical quality factors and different dielectric loss tangents.

The losses in 1-3 composites are mainly determined by the ceramic phase and the volume fraction of the ceramic if the polymer phase is not very lossy. The reason is that the stiffness and the dielectric constant of the ceramic phase are much higher than those of the polymer phase. According to the theoretical analysis and experimental results [6], the mechanical quality factor of a 1-3 piezo-composite sample is less than those of both the ceramic phase and polymer phase if the low loss polymer phase is filled in the 1-3 composite. Another factor to affect the mechanical quality factor of a 1-3 composite is the stiffness of the polymer phase. The polymer matrix in a 1-3 composite is driven by the piezoelectric ceramic rods. A stiffer polymer matrix means a greater mechanical load on the ceramic rods, therefore, a lower mechanical quality factor. For example, the mechanical quality factor of a 1-3 composite will be the same as that of the longitudinal resonance mode of the ceramic rod if the kerf of the 1-3 composite is filled by air.

FABRICATION OF THE 1-3 COMPOSITE

The 1-3 composite samples were fabricated by a dice and fill method [7]. In the process of preparing the samples, the PZT-4 ceramic plates were periodically cut in two perpendicular directions by an automatic dicing saw. The ceramic volume fraction was 64%. The kerfs were filled by both unfilled and filled high glass transition temperature epoxy with microspheres. The samples were degassed and cured at 120 °C. The samples then were lapped to the required thickness and gold electrodes were sputtered. The electrical poling conditions were 15 minutes in oil at 130 °C under 3kV/mm.

The electrical impedance of the test samples was measured using an HP 4194 impedance analyzer. The electromechanical properties of the 1-3 composites are listed below.

	Microsphere Filled Epoxy Composite	Unfilled Epoxy Composite
Velocity (km/s)	3.90	4.16
Coupling Factor	68%	64%
Qm	225	203
Tanδ	0.004	0.004

This table shows that the 1-3 composite sample with filled epoxy has a higher coupling factor, a higher

mechanical quality factor and a lower velocity compared with the sample incorporating unfilled epoxy.

In order to operate the 1-3 composite transducer at elevated power, it is necessary to make the electrodes thicker than typically used for low power 1-3 composites. Silver electrodes could be better than gold electrodes because silver has a lower electrical resistance than gold.

TRANSDUCER DESIGN AND CHARACTERIZATION

A high power transducer requires a piezoelectric material with low mechanical and dielectric losses. It also requires that the acoustic impedance of the piezoelectric material match that of the load medium and its electrical impedance match that of the driving source.

The 1-3 composite with higher ceramic volume fraction has higher acoustic impedance. Acoustic impedance matching layers must be used to overcome the large acoustic impedance mismatch between the 1-3 composite and the load medium. Generally speaking, a single quarter wavelength matching layer system is easier to design and can achieve a smooth frequency spectrum, but the bandwidth is limited and the insertion loss is still higher. Double quarter wavelength matching layers are difficult to implement, but may give broader bandwidth and lower insertion loss.

In this study, a double quarter wavelength matching layer system was designed using Piezo CAD software. In order to achieve low insertion loss no backing was used in this design. The designed center frequency was 2 MHz and the design parameters of the matching layers are listed below.

	First Layer	Second Layer
Acoustic Impedance	6.6 MRayls	2.8 MRayls
Thickness	0.256λ	0.256λ

A high power transducer requires that the matching layer materials must have a high glass transition temperature and low loss if the matching layer materials are made using loaded epoxy.

The transducers were pulsed by a Panametrics 5052UA ultrasonic analyzer. The ultrasonic analyzer was set at energy 1 and 50 Ω damping. The echo signals from a stainless steel flat plate were sent to a LeCroy 9410 dual 150 MHz oscilloscope to perform the frequency analysis. The measured pulse echo performance is listed below, with transducer #1 and #2 incorporating filled and unfilled epoxy respectively.

Transducer	#1	#2
Center Frequency	2.21MHz	1.95MHz
6 dB Bandwidth	83%	65%
Echo Voltage	8.0V	5.3V

This table shows that broad bandwidth results in large echo voltages for pulse echo applications.

The transmitting and receiving performances of these two transducers were tested using the same equipment as the pulse echo measurement. In addition, a large PZT-5H ceramic plate with a thickness of 12.7 mm and a diameter of 76.2 mm was used to receive and transmit a short pulse. Only the signal from the front surface of this PZT-5H plate was used to characterize the transmitting and receiving performances.

In order to measure the transmitting performance of the high power transducer, the transducer was pulsed using a Panametrics 5052 UA ultrasonic analyzer. The transmitting pulse was received by the PZT-5H plate, and only the first pulse (front surface transduction) was sent to the oscilloscope to perform the frequency analysis. The results are listed below,

Transducer	#1	#2
Center Frequency	1.78 MHz	1.65 MHz
Peak Frequency	1.38 MHz	1.60 MHz
3 dB Bandwidth	101%	78%

For the receiving performance characterization the PZT-5H plate was used as the transmitting transducer and only the first transmitted pulse was received by the investigated transducer. The test data are shown below,

Transducer	#1	#2
Center Frequency	2.01 MHz	1.75 MHz
Peak Frequency	1.40 MHz	2.00 MHz
3 dB Bandwidth	104%	86%

These results show that the 1-3 composite transducers can operate in a very large acoustic bandwidth.

POWER HANDLING OF THE TRANSDUCERS

In order to test the power handling of these transducers, simple electrical matching networks were designed to match the electrical impedance of the driving source. The electrical impedance matching network is composed of a series inductor and a parallel

capacitor. The parameters for both transducers are listed below,

Transducer	#1	#2
Matching Frequency	1.40 MHz	1.60 MHz
Inductance	5.9 μ H	6.9 μ H
Capacitance	3.9 nF	1.5 nF

At the matched frequencies a continuous sine wave (100% duty cycle) was applied to these transducers. Both transducers were driving for over 30 minutes at 15 watts per square center meter. No damage was observed.

CONCLUSION

In this study, 1-3 composites were fabricated for high power ultrasonic applications. The 1-3 composite can be operated at elevated power if the ceramic, polymer and ceramic volume fraction are properly chosen.

The 1-3 composite with microsphere filled epoxy shows enhanced coupling and a high mechanical quality factor over the unfilled epoxy 1-3 composite. This is a result of the light mechanical load applied to the ceramic rods by the epoxy matrix.

The 1-3 composite transducer can be designed to operate in a broad acoustic bandwidth. It is also possible to design a broadband electrical network to operate the transducer over a large bandwidth, since the electrical impedance is flat near the peak transmitting frequency.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the help of Mr. Craig Miller and Donna Schwartz at Blatek, Inc. This work is supported by ONR under contract N00014-98-c-0264.

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