Comparison of Ultrasonic Phased Array Probes Based on PMN-PT and PZT 1-3 Composites

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Abstract. The using of PZT composite is very common in manufacturing ultrasonic probes for nondestructive evaluations (NDE). This paper describes the manufacturing of PMN-PT composites and the using as a new material for NDE ultrasonic probes.

The manufacturing process of phased array probes with the PMN-PT single crystal was investigated. PMN-PT based composites were directly used in the acoustic stack manufacturing process (matching layer, etc.) similar to conventional the PZT based composite. Therefore a PMN-PT single crystal wafer was diced mechanical to manufacture a 1-3 piezo composite, filled with epoxy and grinded to a thickness of about 210 micrometer. The polarization process was performed after the metallization of the final composite and then the electromechanical parameters were measured. The performance of the phased array probes was measured then by a so called PCUS® pro phased array electronic front end from Fraunhofer and compared with a PZT-based phased array probe. Therefore a 16 element linear array with an active aperture of 12mm x 12,75mm in a Fraunhofer IKTS standard housing was manufactured. The PMN-PT phased array probe shows a significant improvement of the sensitivity and a higher bandwidth.

Until now the advantages of PMN-PT are used in medical applications, but are not implemented in NDE applications. But because of its high sensitivity and broad frequency spectrum, PMN-PT transducers can be advantageous compared to conventional PZT transducers for special applications in NDE. A very high sensitivity is needed when the test object shows a very high damping and scattering of ultrasonic waves, for example investigations on fibre reinforces plastics. Additionally techniques like the sampling phased array require very small apertures and therefore need a very high sensitivity.

Introduction

PMN-PT is well known for its high sensitivity and broad frequency spectrum. Therefore PMN-PT transducers can be advantageous compared to conventional PZT transducers for special applications in NDE. A very high sensitivity is needed when the test object shows a high damping of ultrasonic waves, for example investigations on fiber reinforces plastics. Additionally techniques like the sampling phased array technique require very small apertures of single elements and therefore also need a very high sensitivity.
Until now the advantages of PMN-PT are used in medical applications, but are not implemented in NDE applications. The goal of this paper was to use this PMN-PT single

crystal material for the first time in the manufacturing process of NDE phased array probes and to compare its performance with a PZT based phased array probe. The manufacturing process of the piezocomposite is already explained in [3].

1. Probe Manufacturing

1.1 Piezoelectric 1-3 composites

Two types of piezoelectric 1-3 composites with similar properties were used.

The PMN-PT based composites were fabricated at IBULE Photonics© (Korea) and the PZT based composites at the Fraunhofer IKTS (Germany). Both types were manufactured with the dice-and-fill method and afterwards characterized with the resonance/antiresonance method as mentioned in the IEEE Standard on Piezoelectricity [4] using the impedance analyser Agilent 4294A. The characteristics of the absolute value and phase of the complex electrical impedance are shown in Fig. 1. For both composites the resonance frequency is slightly higher than 5 MHz and the first spurious modes occur at about 12 MHz.

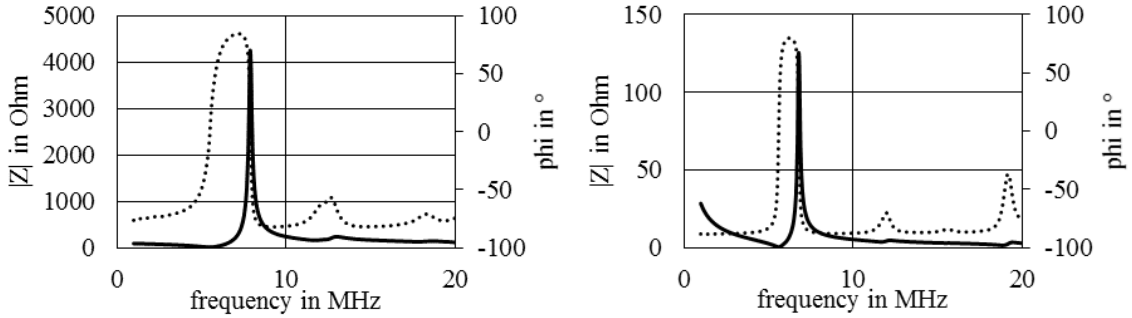

Fig. 1 Magnitude (full line) and phase (dashed line) of the electrical impedance of PMN-PT based (left) and PZT based (right) 1-3 composite.

The acoustic impedance and the electromechanical coupling coefficient were calculated after analysing the resonance and antiresonance frequencies and in consideration of the thickness and density of the composites. Table 1 summarizes the results. The most important parameter for the expected efficiency of the ultrasound probe is the electromechanical coupling coefficient. It is obvious, that the electromechanical coupling coefficient of the PMN-PT based composite material of 0.75 is much higher than the result of 0.61 for the PZT based composite.

Table 1. Properties of Used Piezoelectric 1-3 Composites

		PMN-PT based	**PZT based**
resonance frequency f_R	MHz	5.5	5.6
antiresonance frequency f_A	MHz	7.9	6.8
volume fraction	%	36	42
acoustic impedance Z_{eff}	MRayl	11	13.3
longitudinal sound velocity $c_{L,eff}$	m/s	3100	3024
electromechanical coupling coefficient $k_{t,eff}$		0.75	0.61

1.2 Transducer Design

The same design for a linear array was used for both transducers. Table 2 shows the relevant geometries. The dicing saw DISCO DAD 321 with a dicing blade for a cut width of 50 µm was used to cut the preferred shape from the composite raw materials and to structure the top electrode.

Table 2. Geometries for the Linear Array Structure

		PMN-PT based	**PZT based**
nr. of elements		16	16
interlement spacing	mm	0.8	0.8
active width	mm	12.75	12.75
active length	mm	12	12

1.3 Probe Assembly

The structured composites were first connected to a flexible printed circuit board with the help of an isotropic electrically conductive silver epoxy adhesive.

Conventional quarter wavelength matching layers were used to match both transducers to polystyrol as a load. Mixtures of a two component epoxy adhesive and fine grain alumina powders were used to achieve the necessary acoustic impedances of the matching layers. A high precision grinding machine for semiconductor materials was used to grind the matching layers to meet the required thickness.

A very soft and flexible epoxy based polymer was used for the backing. This backing has an acoustic impedance of 2.5 MRayl and a very high damping.

Microcoaxial cables connect the flexible printed circuit board to a Hypertronics H series connector. Both acoustic stacks were inserted in Fraunhofer IKTS standard housings made of stainless steel.

2. Probe Characterization

2.1 Measurement Setup

A measurement setup based on the commercially available phased array hardware PCUS® pro array developed at the Fraunhofer IKTS was used in combination with the Fraunhofer IKTS lab software. The elements were excited with a negative rectangular pulse with an amplitude of 150 V and a pulse lengths of 50 ns. Coupling gel was used to connect the transducers to the test body.

Three measurements were made to compare the performance of the PMN-PT phased array probe to a conventional PZT based probe.

First the performance of the single elements on a polystyrol test block with a flat back wall in a distance of 18 mm was evaluated. Therefore the elements are excited one after another. The excited longitudinal wave travels through the test body, is reflected at its back wall and travels back to the phased array probe. The received signals are analysed and a Fast Fourier Transformation (FFT) was used to evaluate the frequency spectra of the signals. A rectangular time window of 2 µs with the signal in its center was used for the FFT. The pulse length, peak-to-peak amplitude and sensitivity, middle frequency and -6 dB bandwidth were determined for each element and the variation of all elements calculated.

Afterwards sector scans between -45° and +45° were made on the same polystyrol test body. The used gain was varied until the amplitude at 0° reaches 80 % screen height. The same measurement was then repeated by using focal laws for the excitation to achieve a focussing at 18 mm in polystyrol.

Last, the defect detectability was evaluated with sector scan on a titanium test piece with three 0.5 mm holes in different depths (20 mm, 40 mm and 60 mm). The sector scan was realized by a variation of the incident angle between -45° and +45° with all 16 elements. For the excitation the same rectangular pulse (150 V, 50 ns) was used. The gain of the receiver was increased until the echo of the hole at 40 mm reached a screen height of 80 %.

2.2 Single Element Characterisation

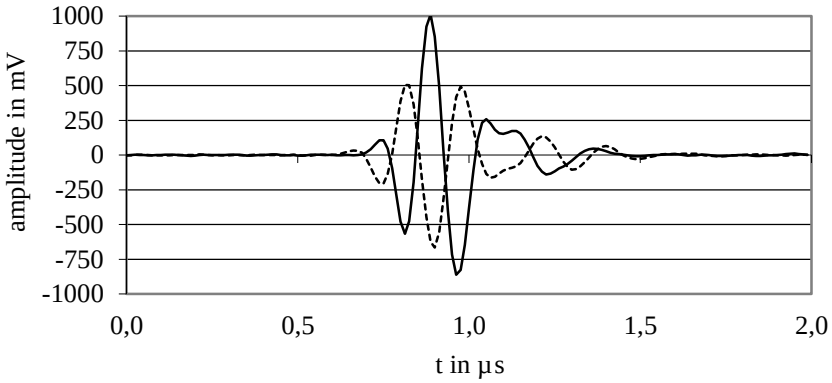

Fig. 2 Received time signals from element 1 of PMN-PT probe (full line) and PZT probe (dashed line).

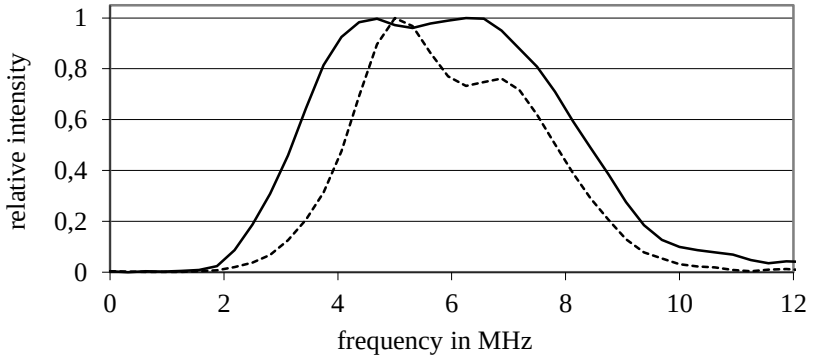

Fig. 3 Frequency spectra of the received time signals from element 1 of PMN-PT probe (full line) and PZT probe (dashed line).

Table 3. Single Element Performance

		PMN-PT based		**PZT based**	
		Mean Value	**Variation in %**	**Mean Value**	**Variation in %**
resonance frequency f_0	MHz	5.6	1l.6	5.7	4.7
-6 dB bandwidth B	%	100.5	1.6	60.4	5.8
-20 dB pulse length t	µs	0.58	10.3	0.56	12.4
Sensitivity S	dB	-39.9	2.3	-41.9	1.8

2.2 Sector Scan on Polystyrol Body

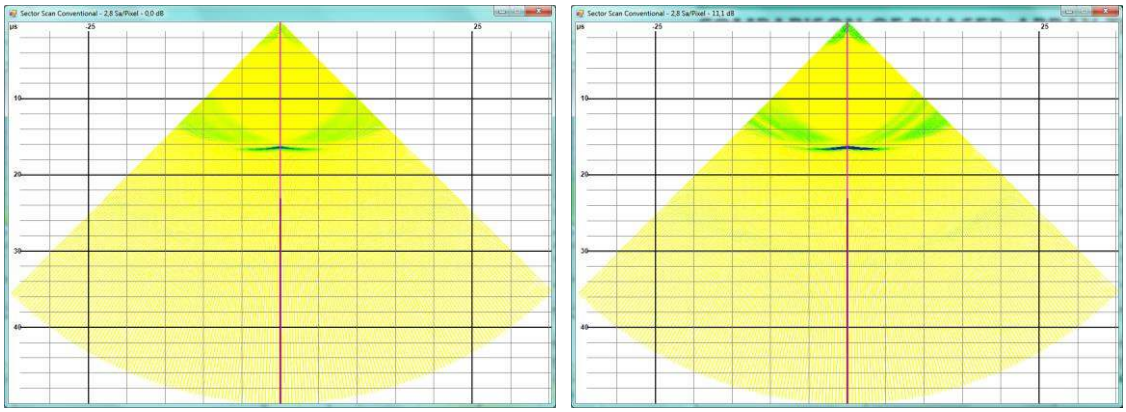

Fig. 4 Comparison of Sector scans (left: PMN-PT probe with 0dB, right: PZT probe with 11dB)

2.2 Sector Scan on Titanium Test Structure

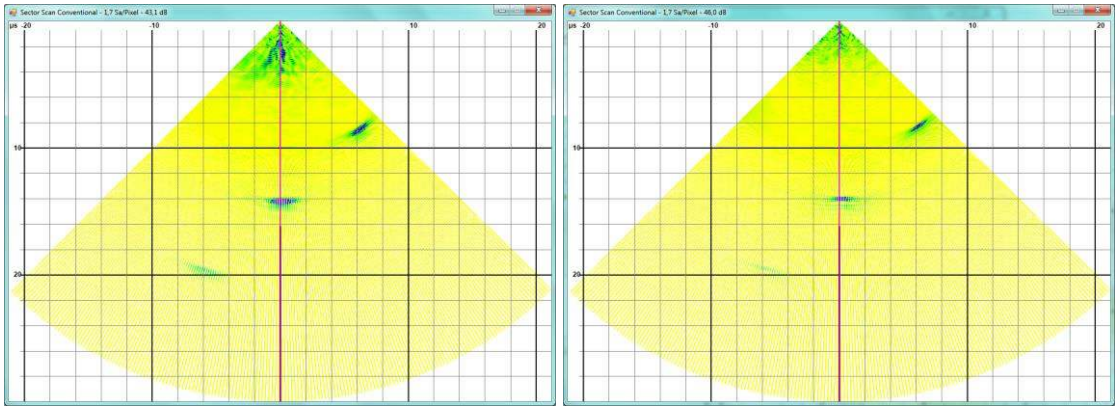

Fig. 5 Comparison of Sector scans (left: PMN-PT probe 41dB, right: PZT probe with 46dB)

3. Simulation

The one dimensional simulation model "WinWandler" developed by Dr. Köhler at the Fraunhofer IKTS [5] was used to calculate the expected difference of the sending-receiving behaviour of both phased array probes. The model is based on the Mason Model [6] and the full acoustic stack (consisting of backing, piezoelectric composite and matching layers) on a polystyrol body with a thickness of 18 mm was used for the layer model according to **Fig. 6**.

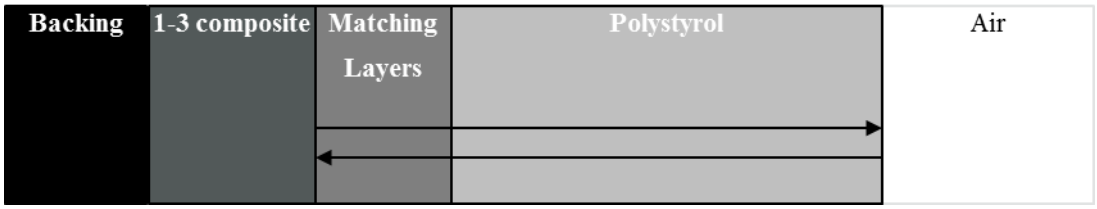

Fig. 6 Outline of 1D model for probe and measurement setup

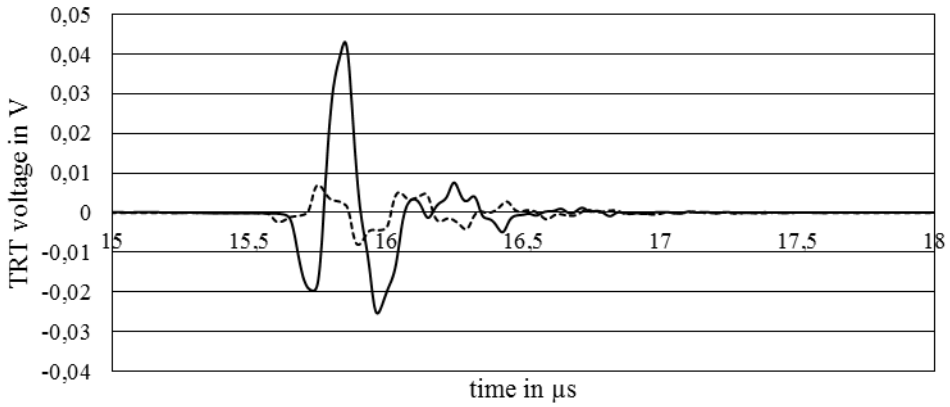

Fig. 7 Results of simulated signal (transmit receive transfer voltage) of PMN-PT probe (full line) and PZT probe (dashed line).

4. Conclusion

A probe for NDE based on a PMN-PT single crystal 1-3 composite material was successfully manufactured with the same design rules and technologies that are used for conventional PZT composite based probes. The single elements show a 12 dB higher sensitivity compared to conventional PZT based probes, a very high bandwidth of 100 % and a good uniformity. Also the necessary gain to detect a 0.5 mm hole in a depth of 40 mm in a titanium test body was nearly 5 dB lower. A further enhancement of the sensitivity and a decreasing of the pulse length can be possible by an optimization of the matching. The simulation model based on the materials parameter give similar results in the comparison of the probe performances. These results show that PMN-PT single crystal composites are a very promising material for the development of high sensitive and high bandwidth ultrasonic probes for NDE.

Acknowledgement

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