CERAMIC/POLYMER 2-2 COMPOSITES FOR HIGH FREQUENCY TRANSDUCERS BY TAPE CASTING

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Abstract – The aim of this research is to produce 2-2 PZT/polymer composite using tape casting technology. PZT tapes were printed with a fugitive phase (carbon) to define voids which were then backfilled with epoxy after the carbon was removed by thermal treatment at 1250 °C. Final dimensions of the 2-2 composite were in the range of 25 μm for the ceramic bar and 5 μm for the epoxy-filled kerf. Specific emphasis was placed on achieving uniformity and straightness of the ceramic beam and kerf thicknesses. The composites were fabricated into 20 MHz single element pachymeters and benchmarked against commercial devices fabricated by dice-and-fill. The tape cast material compared favorablely with high sensitivity and a little lower bandwidth. Fabrication of a 35 MHz linear array transducer is in progress. Electrode patterning to define individual array elements has been successfully completed.

I. FABRICATION OF HIGH FREQUENCY ULTRASOUND TRANSDUCERS

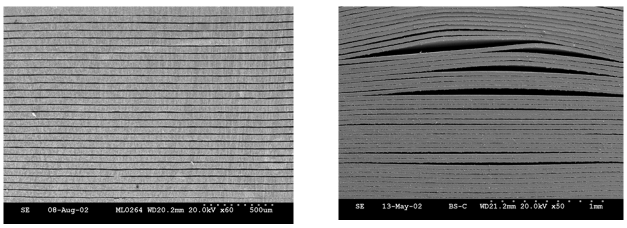
Piezoceramic/polymer composite for ultrasound transducers has many advantages compared to monolithic ceramic such as low density resulting in a good acoustic impedance to the human body, low dielectric constant resulting in a high piezoelectric voltage constant, high coupling in the thickness mode for broad bandwidth, and high conformablility for ease of fabricating focused transducers. Ultrasonic array and single element transducers made with PZT/polymer composites have been limited to frequencies < 20 MHz because of the difficulties in machining PZT ceramics to fine feature sizes (post spacing < λ/2) [1-3]. Patterned ZnO [4] and polymer films [5] have been used to as high as 100 MHz; however, these materials do not possess the very high piezoelectric and/or favorable acoustic properties of PZT/polymer composites.

Ritter, *et al*., [6, 7] have described a technique for making 30 MHz linear arrays where ceramic plates are polished to 33.5 μm thick, coated with epoxy containing polystyrene microspheres (6.2±0.9 μm), and laminated to form a 2-2 composite. This represents a significant improvement over what can be achieved with dicing saw technology.

However, the fabrication of higher frequency composites and phased arrays is still limited in the laminated plate technique by the difficulty in handling very thin ceramic. An alternative method, the subject of this paper, is to use tape casting technology to fabricate finely featured PZT composite preforms. The technique makes use of multilayer ceramic processing developed for the capacitor industry. The state of the art for this technology is ceramic layer thicknesses < 5 μm with separating electrode layers on the order of 1 μm. These features are much finer than any other PZT composite fabrication technique and suggests the possibility for linear and even phased arrays in the 30 to 50 MHz range.

II. COMPOSITE FABRICATION

Carbon ink was screen printed onto fine grain PZT Type II (TRS 200FG) green tape (thin sheets 25 ~ 50 μm in thickness consisting of PZT ceramic powder dispersed in a polymer matrix) to obtain the desired fugitive structure in composite. Polymer binders used in this research were polyvinyl butyral and polyethylene glycol. The stacks of tapes were then isostatically laminated and cut. The polymers used as binder phases for tape casting were removed by slow heating. This also volatilized the carbon and defined the kerf spaces. The samples were then sintered (densified by heating). Epoxy (Epotek 301) was back filled under vacuum into the space formed by decomposition of the fugitive phase. Figure 1 shows the cross-section of PZT/polymer composite fabricated by the tape casting approach. It is shown that approximately 38 µm thick, relatively straight PZT beams, which are made of a single layer of PZT tape, are separated by epoxy-filled kerfs. The average thickness of kerfs is approximately 7 µm, and it is calculated that the ceramic volume fraction in the composite is approximately 84%.



(a) (b)

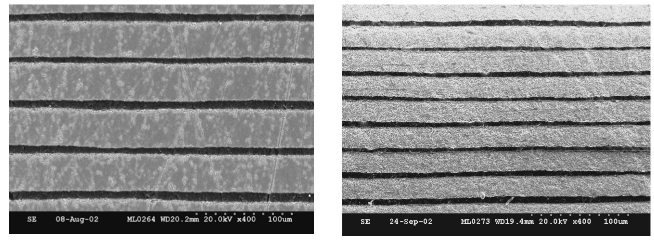
Figure 1: Scanning electron microscope (SEM) picture of PZT/polymer 2-2 composite fabricated by tape casting approach: a) composite fabricated with 3 sides supported by ceramic (no fugitive phase) and b) composite with only 2 sides supported.

Further details of the composite fabrication process have been previously reported. [7]. The emphasis of that work was to improve the uniformity of kerf spacing and beam width so that the composites could be used for linear array transducers, and to reduce beam and kerf widths to achieve higher resonance frequencies. Uniformity of the layers were improved by increasing ceramic content in the tape formulation [8].

III. Increasing Frequency and Properties

To avoid lateral coupling in both single element an array transducers, ceramic beam spacing must be kept below λ/2 (or λ/4 for phased array transducers). Several methods were investigated for reducing the thickness of the ceramic beam width and kerf spacing so that composites could be fabricated for 20 to 50 MHz transducers.

When making ceramic tape the thickness of the ceramic layer is decided by the gap height of the doctor blade during casting. The thickness of dried tape is also key factor for tape strength and workability. In this research, 25 µm thick tape was prepared. The microstructure of PZT/polymer composite using 25 µm thick tape is compared composite using 40 µm thick tapes in Figure 2. The resulting ceramic layer thickness after sintering is ~22 µm with the kerf size ~5 µm. This composite can be used to frequencies >30 MHz.



(a) (b)

Figure 2: Scanning Electron microscope (SEM) picture of PZT/polymer 2-2 composite using (a) 40 µm thick tapes and (b) 25 µm thick tapes.

Impedance spectra of three composites with 22 µm beam thickness and a kerf space of 4.5 µm for a volume fraction of 83% are shown in figure 3. The composites were precision lapped to a thickness of 110, 75 and 36 µm. Each resonance is very clean with few spurious modes and no evidence of interfering lateral stop band modes. The composites had resonance frequencies of 18, 25 and 60 MHz, respectively. Thickness coupling was very reasonable for a Type II (PZT-5A) 2-2 composite. The highest frequency composite had the lowest coupling probably because the aspect ratio of the PZT beams was no longer optimum. These higher frequency composites should be made with thinner tape. However, even with a degraded coupling these composites exhibit much better properties at >50 MHz than the alternative technologies ($LiNbO_3$, PVDF, ZnO, etc.).

IV. Single Element Transducer Performance

Single element pachymeters were constructed from 25 MHz composites and tested for pulse echo characteristics. The active aperture was selected to achieve an electrical impedance close to 50 ohms at a frequency of 25 MHz. A 20 MHz transducer was constructed to compare the technology to commercial pachymeters made by dice-and-fill (Blatek, Inc., State College, PA). Based on the spatial scale of the constituents and the measured frequencies of stop-band edge resonances, transducers with center frequencies up to at least 35 MHz can be fabricated by simply thinning the composite by precision lapping or polishing.

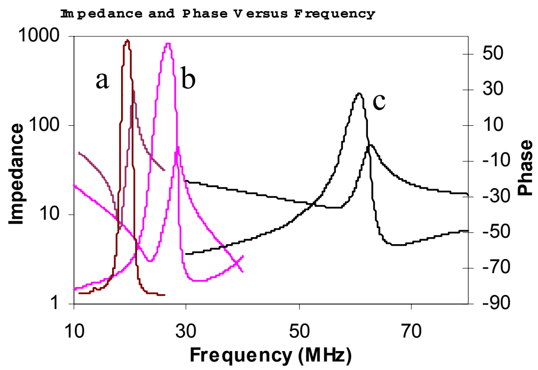


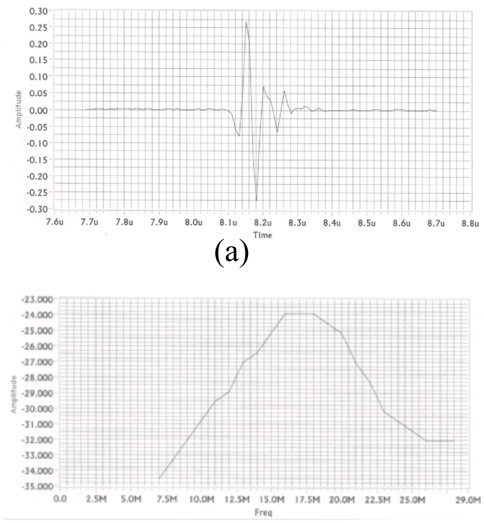
Figure 3: Impedance spectra of 2-2 composites with 22 µm thick beams with composite thickness (a) 110 µm K_t= 0.52 (b) 75 µm K_t= 0.62 (c) 36 µm K_t= 0.45.

The transducer was fabricated from a square composite. The composite was electroded with sputtered gold, and a 6 MRayl quarter-wave matching layer was bonded to the transducer face. The aperture size was 1.5mm x 3mm. The transducer was conformed around a mold to give it a spherical curvature to define a 12mm focal length. Leads were attached with silver epoxy and an 8 MRayl backing was cast onto the back of the composite.

Pulse echo data was collected by placing the transducer in a water tank, pulsing it, and looking at the receive signal reflected from a stainless steel target. To conform with normal pachymeter testing the steel target was not placed at the transducer focal point but rather at front of the delay surface. The impulse response and frequency spectrum are shown in figure 4. Measured transducer parameters compared to a typical pachymeter made by dice-and-fill are shown in Table I. The commercial pachymeter was constructed in the same way as the tape cast composite transducer except that it had a round aperture.

Table I: Comparison of Transducer Parameters for a Tape Cast Composite and a Commercial Pachymeter

Transducer	-6 dB BW	Sensitivity	-20 dB pulse length	Center Frequency
Tape Cast	93	0.6V	0.092	18
Commercial	100	0.3V	0.086	20



(a)

(b)

Figure 4: The measured (a) impulse response and (b) frequency spectrum for the 25 MHz transducer.

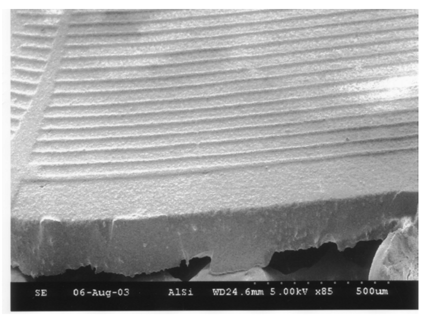
In general the tape cast composite transducer compared very favorably to the commercial device. The band width was a little smaller and the sensitivity was higher, but these differences are probably due to the differences in aperture size and shape. Although pachymeters are a fairly low volume application, adequately served by dice-and-fill technology, the results of this test show that the tape cast material is at least as good with the advantage that tape cast technology can be used for much higher frequencies.

V. Array Transducer

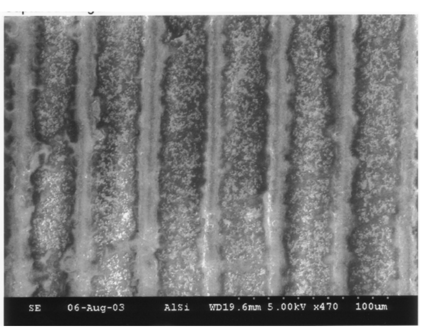
A 30 to 35 MHz linear array transducer is currently being constructed from tape cast composite material. There are multiple challenges to constructing such a high frequency array. First, the array performance is expected to be much more sensitive to non-uniformity and curvature of the array elements. Second, the top electrode must be patterned to define the array elements. Third, electrical connections must be made to each of the very fine elements. A 30 MHz linear array has been previously reported by researchers at Penn State [6]. This transducer was fabricated using the stacked plate approach. The patterning and interconnect schemes used in that work are being employed to construct an array transducer from tape cast composite.

The effect of element curvature was estimated by modeling using PZFlex and Field II. The main difference between strain and curved elements was the effect on acceptance angle. The simulation showed a -6 dB radiation pattern of 6-7º for a composite with slightly curved elements and less than 2.5º for straight composite elements. Given the improvement in element uniformity that resulted from previously reported process improvements, it is expected that transducer performance will not be adversely affected by used of tape cast composites.

The array design will consist of individual PZT elements with each beam in the composite corresponding to a single element. To do this, electrodes must be applied to the PZT beams but not the kerf. A negative resist method was developed to sputter each separate ceramic beam with its individual electrode. The transparency of Epotek 301 polymer used in this research made it possible to utilize negative photo resist. The resist was fixed by shining light through the epoxy. Resist on the PZT was then removed and the ceramic was sputtered with Cr/Au. The remaining resist was then pealed off the epoxy. The resulting electrode pattern is shown in Figure 5. The ceramic layers were successfully masked.



(a)



(b)

Figure 5: SEM micrograph of the patterned tape cast composite being fabricated into an array transducer. Negative photoresist was used to apply Cr/Au to the PZT beams in the composite but not the epoxy kerf-fill.

VI. Conclusions

PZT/epoxy 2-2 composites were fabricated using tape casting technology to achieve the features and sizes needed for high frequency ultrasound transducers. Composites with resonant frequencies in the 20 to 55 MHz range were constructed by laminating PZT tape printed with carbon ink followed by firing to densify the PZT and volatilize the carbon. The resulting kerf space was then filled with epoxy. Single element pachymeters constructed from the composite compared very favorably with commercial devices made by dice-and-fill. A 35 MHz linear array is currently being fabricated from tape cast composite. The array has been successfully patterned.

VII. Acknowledgements

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VIII. References

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