RECENT ADVANCES IN PIEZOCOMPOSITE MATERIALS FOR ULTRASONIC TRANSDUCERS

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Abstract: Piezocomposite materials have been used, with increasing frequency, in ultrasonic NDT transducers for at least ten years. While these materials have enabled many applications that had previously been impossible, some specific shortcomings have precluded their use in other applications. Since their introduction, a number of improvements have been realized that have broadened their applicability and improved test results.

This presentation provides an overview of piezocomposite technology and materials, and reviews their benefits and shortcomings. Developments that have improved their performance, reliability, and applicability will be described. In particular, benefits relative to ultrasonic phased array probes will be discussed.

Introduction: For more than thirty years, the design of ultrasonic transducers for nondestructive testing (NDT) has incorporated commercially available monolithic piezoelectric materials, such as lead zirconate titanate (PZT). These materials typically have high acoustic impedances and a limited range of electrical properties. More recently, piezocomposite technology has overcome these deficiencies and offered the transducer designer a greater range of acoustic and piezoelectric properties for optimum transducer performance.[i]

There have been, however, some difficulties, as well, with piezocomposites, largely related to raw materials and manufacturing processes. These difficulties have limited, to a degree, their applicability and have increased the cost of manufacturing piezocomposite probes. During the ten years since GE Inspection Technologies first introduced piezocomposite transducers for NDT, improvements in processes and materials have broadened the applicability and enhanced the reliability of this material.

Piezocomposite is simply a combination of piezoelectric ceramic and other materials, usually polymers, which yields new piezoelectric properties.[i] The most common fabrication method for piezocomposite material, often referred to as "dice and fill", is illustrated in Figure 1. This method produces a matrix of ceramic posts surrounded by a polymer filler (Figures 2 and 3). These ceramic posts can be smaller than 0.05 mm in width, with kerfs separating them by less than 0.025 mm.

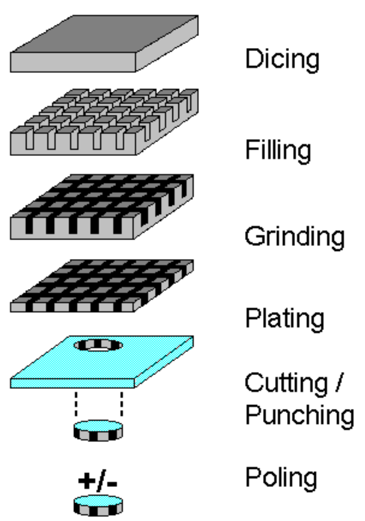

Figure 1: Dice and Fill Method of Piezocomposite Fabrication

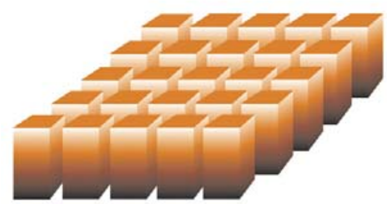

Figure 2: 1-3 Piezocomposite Matrix

Figure 3: Ceramic Matrix Material as Diced

With the introduction of phased array probes for NDT more than five years ago, piezocomposite manufacturing processes have become more critical because of the large number of small piezoelectric elements in a typical array probe, and the need of a high degree of uniformity among the elements of the array.[ii] Individual phased array elements are most often created by dicing a larger, single piece of piezocomposite material, as shown in Figure 4. In some cases, array elements can be less than 0.25 mm in width. We present herein a few of the benefits of process improvements in dice and fill piezocomposite fabrication relative to probe performance.

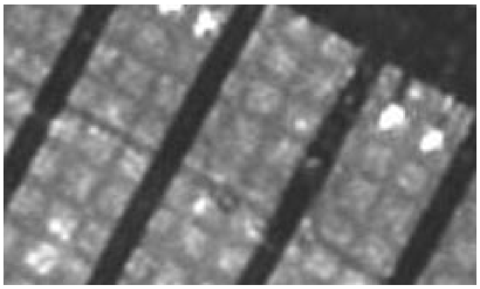
Figure 4: Phased Array Elements Diced Into 1-3 Piezocomposite Block

Results: Most fundamental to the quality of piezocomposite is the raw material from which it is machined. These monolithic piezoceramics, usually PZT, have a grain structure and, sometimes, internal flaws such that they fracture easily during the dicing operation. The exclusive use of fine-grained, flawless raw materials is desirable but not always possible. Ceramics are often selected for their electrical characteristics over their structural integrity. The Scanning Electron Microscope (SEM) image in Figure 5 shows a highly magnified cross section of a piece of PZT. With virtually all piezoceramics, inadequate equipment or process will produce fractured rows, such as those shown in Figure 6. If undetected, fractured rows will lead to missing posts in the finished piezocomposite component, as seen in Figure 7.

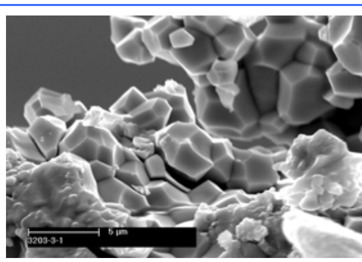

Figure 5: SEM Image of PZT Cross Section

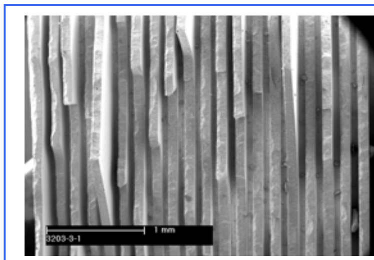

Figure 6: SEM Image of Fractured Rows After Dicing

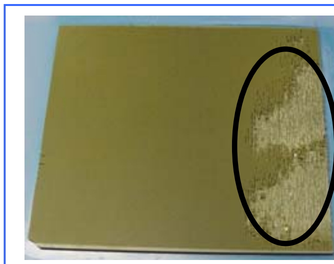
Figure 7: Missing Posts in Piezocomposite Material

Because the ceramic posts make up the active, piezoelectric part of the piezocomposite piece, areas devoid of posts are inactive. Use of this defective material in the production of phased array probes has resulted in non-uniform sensitivity among the individual elements. Figures 8 and 9 show actual element-to-element sensitivity plots of acceptable and unacceptable phased array probes.

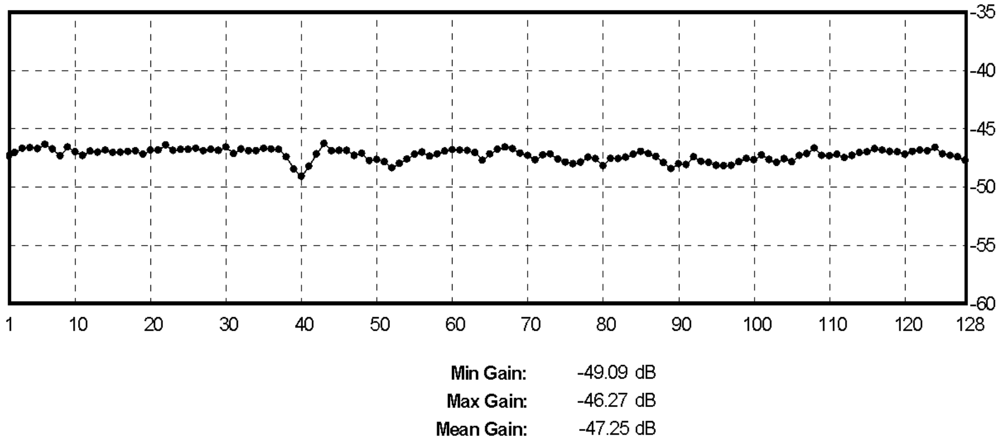

Figure 8: Acceptable Phased Array Sensitivity Plot – 128 Elements, <3 dB spread.

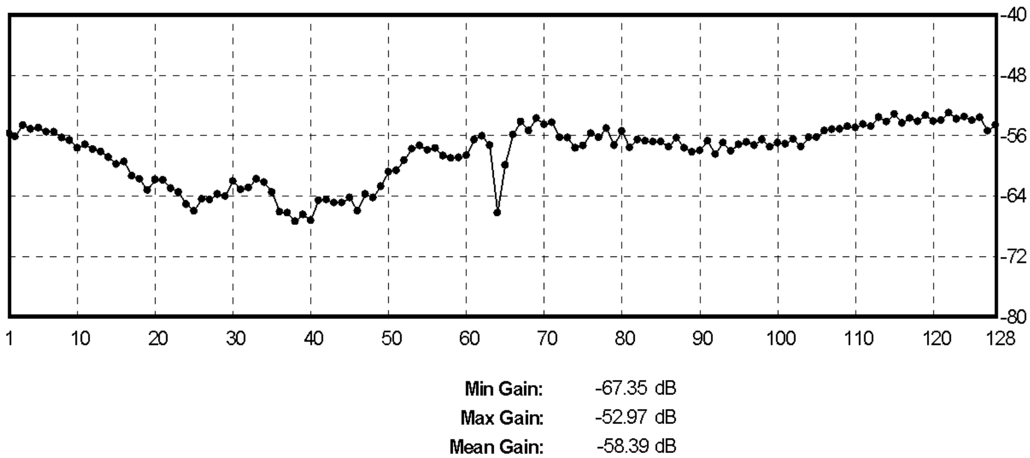

Figure 9: Unacceptable Phased Array Sensitivity Plot – 128 Elements, >14 dB spread.

Improvements in the ceramic dicing process have resulted in improved performance of both single-element and phased array probes. In the case of phased arrays, the ability to dice extremely fine and consistent patterns has enabled the production of probes with very small, highly uniform elements, the importance of which is described below.

Additionally, the ability to produce fine dicing patterns has enabled the fabrication of piezocomposite materials with lower volume fractions. Volume fraction is defined as the ratio of ceramic to polymer. A material with high volume fraction is mostly ceramic (Figure 10), while a low volume fraction material is mostly polymer (Figure 11). Most piezocomposite materials for NDT applications have volume fractions between 30% and 70%.

Figure 10: High Volume Fraction

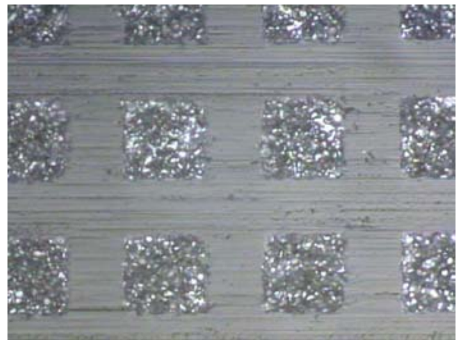

Figure 11: Low Volume Fraction

One advantage of low volume fraction piezocomposite materials is its low acoustic impedance, which is desirable when coupling the probe to plastics and liquids. Improved acoustic matching yields greater inspection sensitivity as acoustic energy is more efficiently transmitted from probe to test object. Lower acoustic impedance also results in greater bandwidth as it becomes easier to match damping materials to probe elements.[iii] The benefits of bandwidth to phased array performance are described below.

Discussion: Phased array probe performance is dependent upon the ability to produce small, highly uniform elements. The extent to which a phased array sound beam can be steered or focused is directly related to the divergence of the sound beam from each individual element. If the elements are too large (Figure 12), most of the energy will be concentrated directly in front of the element, with very little divergence. The result is low amplitude when trying to steer or focus the phased array probe. Elements must be sufficiently narrow such that energy will be distributed along broad, semi-circular wavefronts (Figure 13). This allows the array beam to be steered over a greater range of angles.

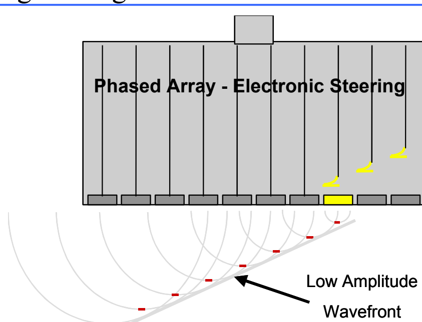

Figure 12: Insufficient divergence results in low amplitude when trying to steer phased array beam.

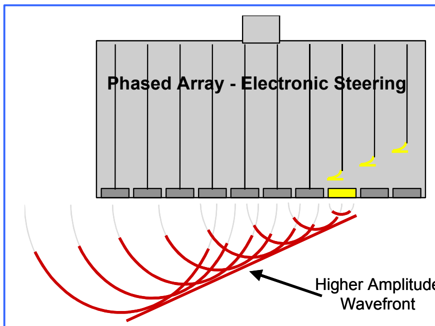

Figure 13: Smaller, more divergent elements yield higher amplitude wavefront.

Bandwidth is also important to phased array performance. In general, broadband probes have superior ability to penetrate coarse-grained and attenuative materials.[iii] Figure 14 shows the screen presentation, using a standard flaw detection instrument, of a 6 mm diameter side drilled hole in a sample block of gray cast iron, using a conventional, monolithic PZT probe. Signal to noise ratio is less than 8 dB. The same presentation in Figure 15 was produced by a broadband, piezocomposite probe of the same frequency and size. Note that, in addition to significantly improved signal to noise ratio, instrument gain has been reduced by 37 dB.

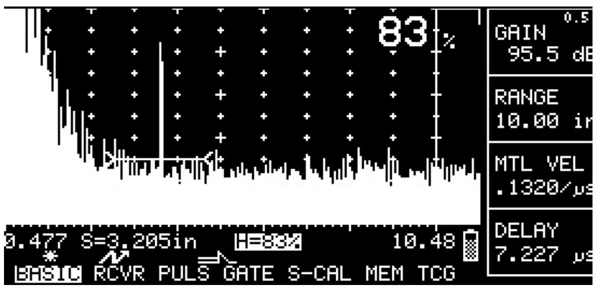

Figure 14: 6 mm side drilled hole in cast iron block using monolithic 5 MHz PZT probe.

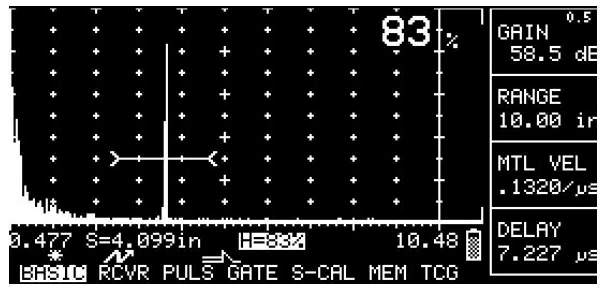

Figure 15: 6 mm side drilled hole in cast iron block using piezocomposite 5 MHz probe.

Bandwidth is particularly important in the case of phased array probes for the reduction of grating lobes, caused by the regular, periodic spacing of array elements. These unwanted secondary sound beams produce spurious signals that can result in image artifacts. The location of grating lobes is given by formula

$$\theta = \sin^{-1}\left(m \frac{\lambda}{\Delta x} \right)$$

In the above formula, m is the order of the lobe, λ is bandwidth, and Δx is the pitch (element spacing) of the array probe.

Figures 16 and 17 were produced using Field II modeling software.[iv] Figure 16 shows the modeled sound field of an undamped, narrowband 16-element phased array probe steered at 15 degrees. The first order grating lobe, located at near 0 degrees, is higher in amplitude than the main beam at 15 degrees. In an actual application, this array probe would be virtually unusable. Figure 17 shows that, by damping the probe and shortening the pulse, sound field characteristics improve significantly.

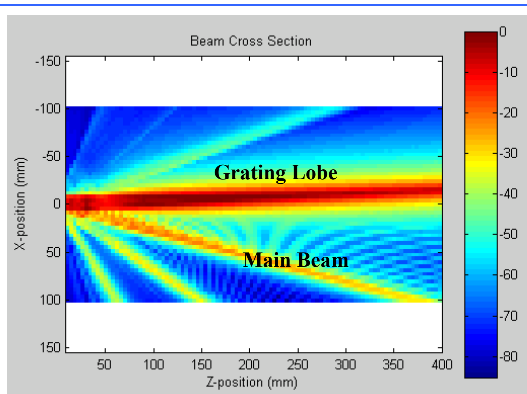

Figure 16: Narrowband phased array. Grating lobe amplitude exceeds main beam.

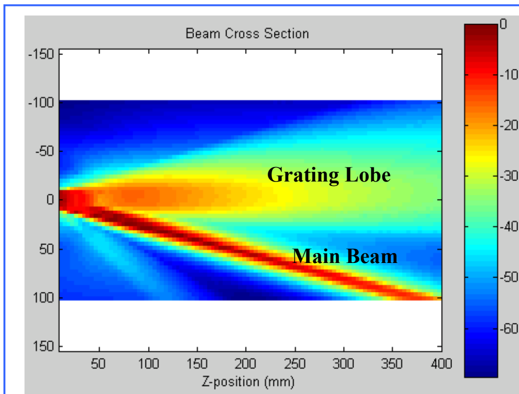

Figure 17: Broadband phased array. Main beam amplitude exceeds grating lobe.

Conclusions: Piezocomposite materials have been in use in medical ultrasonic transducers for approximately twenty years. The introduction ten years ago of piezocomposite probes for NDT presented new challenges as performance requirements became more stringent. Over the past five years, the bar has been raised yet again with the even more rigorous requirements of phased array technology.

Much has been learned about the raw materials from which, and the processes by which piezocomposite materials are made. While we continue to work and expect further improvements, great progress has been made. Better, more sophisticated machining equipment, deeper understanding of raw material characteristics, and processes that have been refined through two decades of experience have produced ultrasonic transducers that are substantially superior to conventional, monolithic probes in both sensitivity and penetration of difficult materials. Piezocomposite phased array probes offer these same advantages, plus unprecedented versatility as one probe replaces many probes. This translates to significant reductions in inspection costs for users of this relatively new technology.

References:

[i] Meyer, Paul A., "The Evolution of a Piezocomposite Transducer Design", presented at Canadian Society for Nondestructive Testing, Niagara Falls, Ontario, Canada, May 15 – 18, 1995.

[ii] Meyer, Paul A., "Design Considerations for the Use of Ultrasonic Phased Array Probes in Weld Inspection", presented at the 3rd International Pipeline Conference, Calgary, Alberta, Canada, October 1-5, 2000.

[iii] Meyer, Paul A., "Performance Advantages of Piezocomposite Transducers", presented at American Society for Nondestructive Testing Conference, Dallas Texas, USA, October 4 – 8, 1995.

[iv] Jensen, J.A., "Field: A Program for Simulating Ultrasound Systems", Med. Biol. Eng. Comp., 10th Nordic-Baltic Conference on Biomedical Imaging, Vol. 4, Supplement 1, Part 1:351-353, 1996b.