Textured Ceramics: The Next Generation of High Performance Transducer Materials

Abstract — Efforts to improve the performance of underwater sensing materials are focussed on the piezoelectric materials used in transducer designs. Although a mainstay for decades, PZT ceramics have inherent performance limitations. These limitations have been surpassed by the higher performance of single crystal materials. However, single crystals have drawbacks associated with them that prevent their widespread adoption. Textured ceramics, on the other hand, are able to circumvent the drawbacks of single crystals and still outperform PZT ceramics. While still in the commercial developmental phase, textured ceramics show promise for widespread adoption rather than single crystals from a cost/benefit point of view, provided certain hurdles are overcome.

1 Introduction

Lead zirconate titanate (PZT) ceramics are the most widely used piezo-materials in use today due to their well established and time tested performance in transducer designs. PZT ceramics are available in a range of sizes and properties tailored to different applications, among them ; sensing, actuation, resonant sound generation, commercial ignition systems, and medical ultrasound. For the maritime and defence industry, PZT ceramics are broadly organized according to their material and performance properties as defined by the US standard MIL1376B or the European standard CELENEC EN-50324. Ceramic manufacturers typically develop ceramics to these standards, and many also manufacture ceramics that lie outside these standards. The broad range of available PZT materials might suggest a wide range of expected piezoelectric performance, however, PZT performance at the material level across different PZT types is fairly consistent.

2 PZT performance limits

PZT suppliers provide ceramic property data such as density, mechanical compliances, dielectric constants and piezo properties. Among the piezo properties are the "*d*" and "*g*" constants for materials. The *g* constant represents the ratio between the electric field developed and the applied stress (Vm/N); the *d* constant is the ratio between the electric charge per area developed and the applied stress (C/N). The product $d{\bullet}g$ is an important quantity, as it appears in important measures of performance:

The electromechanical coupling factor k is the ratio of the stored electrical energy to the input mechanical energy (E_y is the Young's modulus):

$$k^2 = g \cdot d \cdot E_y \tag{1}$$

High coupling factor materials convert a greater amount of the input energy. In the case of a sensor products (such as a hydrophone) it is necessary to maximize the conversion of the incoming acoustic signal into an electrical signal for detection by interfacing electronics. The hydrophone figure of merit (FOM_h) is determined using the $d{\bullet}g$ product [1]

$$FOM_h = g \cdot d \cdot V_o \tag{2}$$

For better performance within a given ceramic volume V_o, the $d{\bullet}g$ quantity should be enhanced, as this would maximize the ceramic energy density, the coupling coefficient and the FOM_h.

A survey of the $d{\bullet}g$ values from commercially available sources was conducted by gathering g_{33} and d_{33} values from PZT datasheets. The values were taken for Navy type ceramics outlined in standards MILSTD 1376B and CELENEC EN-50324 as well as from ceramics that lie outside these standards. The g_{33} and the d_{33} constants are shown in figure 1.

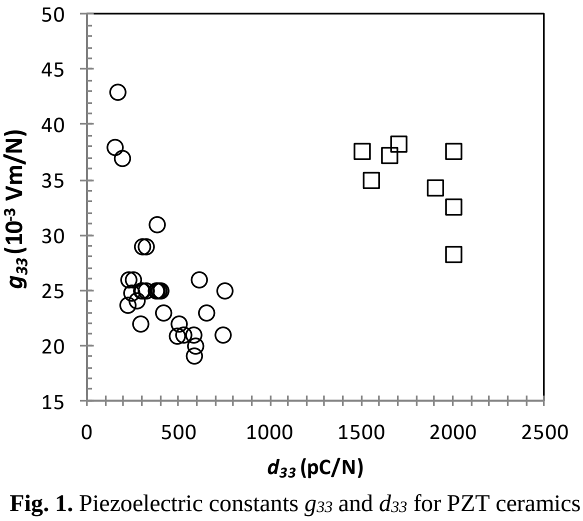

Fig. 1. Piezoelectric constants g_{33} and d_{33} for PZT ceramics (circles) and single crystals (squares).

The data suggests that while it is possible to source ceramics with a high g_{33} or a high d_{33}, it is not possible to source PZT ceramic where both values are simultaneously high, which is necessary to increase overall piezoelectric performance. The maximum value of the $d_{33}{\bullet}g_{33}$ product for the PZT family of materials is approximately 8,000 to 14,000 x10^{-15} m^2/N and is reasonably constant through a range of g_{33} and d_{33} values for different PZT ceramics, which suggests a performance limitation at the material level.

3 High performance single crystals

Efforts aimed at increasing performance have focussed on the development of high performance single crystal materials, especially compositions of the following types: lead magnesium niobate – lead titanate (PMN-PT), lead magnesium niobate – lead zirconate titanate (PMN-PZT) and related variants.[2] The performance levels among commercial sources of single crystals show very high *g* and *d* values simultaneously (figure 1), thus giving $d_{33}•g_{33}$ values five to six times that of PZT (figure 2).

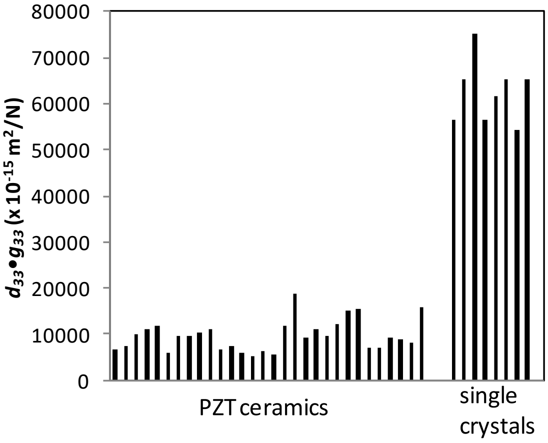

Fig. 2. $d_{33}•g_{33}$ values for commercially available PZT ceramics and high performance single crystals.

3.1. Drawbacks of single crystals

Based on published performance data, single crystals promise large increases in performance over PZT ceramic. They have been available commercially for over a decade, however, several drawbacks have limited widespread and rapid adoption.[3] These drawbacks include both highly variable properties from part to part as well as within the part itself due to compositional inhomogeneities that can develop during the crystal growth process. In addition, there can be a large dielectric property variance with temperature as well as partial depoling at relatively low temperatures (70 C to 90 C), although more recent single crystal compositions have improved upon this.[2] Single crystals have also shown low material toughness resulting in poor chip resistance and easy crack propagation which reduces yields during transducer fabrication and assembly.[3] Finally, crystal sizes relevant to underwater acoustics are difficult to produce and are costly, and much of the current crystal supply is dedicated to high frequency ultrasound applications in the MHz range.

In summary, consistent quality crystals in sizes of interest to underwater acoustics are difficult to reliably procure at reasonable cost. In addition, transducer assembly processes developed for PZT ceramics do not necessarily transfer over easily or cleanly when using single crystals in transducer assemblies.

4 Textured ceramics

Textured ceramics show promise in circumventing the drawbacks of single crystals while retaining performance properties that are much higher than PZT. Textured ceramics mimic the structure of single crystals through the introduction of a limited number of oriented crystalline templates into the ceramic powder matrix. The ceramic matrix takes on the crystallographic orientation of the aligned crystalline templates during the sintering process, where crystal growth within the ceramic body occurs over a short distance around the templates. It is this crystal growth in the powder matrix that allows textured ceramics to approximate single crystal behavior.

Commercial sources of textured ceramic are being developed and proof-of-concept examples of textured ceramics fabricated under laboratory conditions have been manufactured using compositions similar to, or the same as, those used in single crystals. Results show simultaneously high *d* and *g* values; $d•g$ values have been shown to be favorable with reported values among those reported so far in the range of 30,000 to 50,000 x10^{-15} m^2/N [2,4,5].

There are potential key advantages to textured ceramics over single crystals. Textured ceramics are fabricated using ceramic processes (unlike single crystals), which generally result in highly homogeneous parts, within a single part and part to part. Also, ceramic manufacturing processes are highly cost efficient compared to single crystal growth processes. Finally, the mechanical properties of conventional ceramics are largely retained, thus making them easier to machine and assemble during fabrication of transducers.

4.1. Current challenges

Although textured ceramics show promise, one of the key challenges that must be overcome is part size and geometry. Textured ceramics are fabricated using a tape casting technique, which puts down a layer of long flat ceramic tape approximately 250 microns thick. These layers are then stacked and sintered. Reports of usable thicknesses of relevance to underwater applications have been minimal, and this is due to the large number of layers than must be stacked and sintered to produce ceramics with enough volume to yield a usable FOM_h. In this regard, textured ceramic thickness is still too thin for broad adoption. Additionally, the majority of the work to date has focussed performance properties for sensor applications. More in depth developmental work is required on these materials for resonator applications where a high mechanical quality factor Q_m is important.

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