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DEPP functionally graded piezoceramics via micro-fabrication by co-extrusion

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Abstract This paper introduces the Dual Electro/Piezo Property (DEPP) gradient technique via Micro-Fabrication through Co-eXtrusion (MFCX) which pairs a high displacement lead zirconate titanate (PZT) piezoceramic with a high permittivity barium titanate (BT) dielectric. By grading with this material combination spatially across an actuator, the electric field is concentrated in the more active region for improved efficiency, higher displacements, and complex motions. To aid in synthesis and analysis of any gradient profile, compositional maps are provided for key material properties (density, stiffness, permittivity, and piezoelectric coefficients). The DEPP technique was validated, independent of the MFCX process, by powder pressing a conventional bimodal gradient beam which demonstrated through experiments high displacement capabilities at lower driving potentials than comparable functionally graded piezoceramic actuators. For more complex gradients, the MFCX process was adapted to the DEPP gradient technique and illustrated by the fabrication of a linearly graded prototype whose monolithic nature and gradual material variation significantly reduces internal stresses, improves reliability, and extends service lifetime.

Introduction

Functionally graded materials have been widely utilized in passive materials to eliminate thermal stresses and fracture [1–4], enhance fracture toughness [5], as well as to improve wear resistance [6, 7]. Only recently has this concept been extended to active materials such as piezoceramics to increase reliability and generate higher-order motions in actuators [8, 9]. By grading the material properties across the piezoceramic structure to create a Functionally Graded Piezoceramic (FGP), complex motions such as bending, twisting or warping can be realized as opposed to the strictly axial strains exhibited by homogeneous piezoceramics. These higher-order motions are created by stress/strain gradients within the structure, with more severe gradients leading to increased motion. Unfortunately, drastic gradients also result in higher stress levels and discontinuities that significantly increase the failure rates of these devices. Conventional layered bonding fabrication processes tend to further exacerbate the problem with peak stresses and discontinuities located at material interfaces, typically resulting in delamination. All these problems limit the lifetime of piezoceramic actuators to 10^5–10^6 cycles [10, 11], which is not acceptable for many industrial applications. FGP are monolithic ceramics that automatically overcome delamination problems because they eliminate the bonding layers; however, to achieve the material property variations necessary for higher-order motions, sophisticated grading techniques and fabrication processes are required. This paper outlines a synergistic gradient technique coupled with an advanced fabrication process that results in extended-life, high-performance FGP actuators suitable for industrial use.

Key to the success of FGP is the gradient technique. One of the earliest FGP was the RAINBOW (Reduced And

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INternally Biased Oxide Wafer) actuator [8, 12–14], which varies the piezoelectric response of the material through selective reduction of one surface of the actuator to a metallic composition. This gradient technique is difficult to precisely control and typically results in bowed actuator shapes. Others have adapted composite techniques to grade piezoceramics [15, 16], but these actuators suffer from the original problems of delamination at material interfaces and the electric field losses inherent to powering active composites. Recent research has concentrated on producing monolithic FGP through doping the base piezoceramic materials to affect property variations in the resistivity [9], conductivity [17, 18], piezoelectric coefficient [19–23], permittivity [24], porosity [25], or a combination of these properties [26, 27]. The monolithic nature of many of these FGP require that the driving potentials be applied across the entire specimen thickness where power may be squandered in less active material, thereby reducing actuator performance and efficiency. The Dual Electro/Piezo Property (DEPP) grading technique, introduced in this paper, varies both the piezoelectric coefficients and the electrical permittivity, concentrating the applied electric field in the material with a larger piezoelectric effect. This increases the actuator deflection and lowers the required driving electric potentials. To accurately account for the material property variations and resulting complex electric fields during actuator synthesis and analysis, the constituent materials selected for this technique and maps detailing the compositional effects on relevant material properties are provided. As validation of the DEPP technique independent of fabrication process, a conventional bimodal actuator was fabricated using a traditional powder pressing method and was evaluated for its deflection response and material quality.

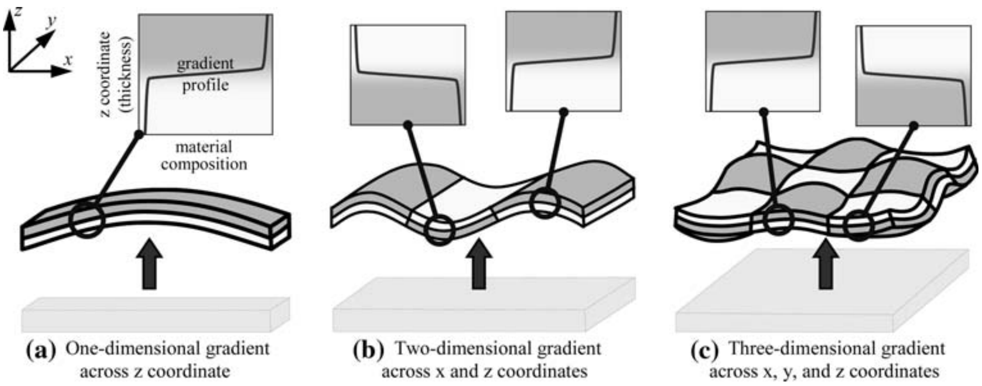
The DEPP technique uses material doping because of its versatility, which allows for fabrication through several processes: powder pressing [17–20, 24, 28], tape casting [9, 29], centrifugal casting [30], and electrophoretic deposition [26]. These processes can be adapted to grade most material properties, but typically are restricted to simple, discretely layered gradients in one dimension which may still form internal stress discontinuities. Micro-Fabrication by Co-eXtrusion (MFCX), developed by Crumm and Halloran [31], promises to overcome these limitations and allow for precise spatial control of material variations to produce more complex gradient profiles in one, two, and three dimensions. This process uses a thermoplastic media composed of ceramic powder and polymeric binders that can be easily formed into complex gradients and shapes then reduced in scale via extrusion. While MFCX naturally limits the material gradient to the two dimensions perpendicular to the extrusion direction, three dimensionally graded actuators can be realized through assembling and hot pressing co-extruded building blocks together prior to sintering. Co-extrusion has proved successful for high-yield, low-cost fabrication of piezoceramic artifacts such as hydrophones [32] and hollow piezofibers [33, 34]. For DEPP FGP, the general MFCX process had to be adapted to accommodate the variety of material compositions necessary for generic profiles and to eliminate warping of the FGP during firing. To demonstrate the gradient control and precision of the DEPP modified MFCX process, a more complex, linearly graded FGP was fabricated and evaluated for its deflection response and material quality in the same manner as the bimodal FGP actuator. Gradients, such as this linear profile, can lead to significant improvements in the lifetime of piezoceramics; yet, even this simple linear profile can be difficult to produce with most other fabrication techniques given their lack of precise gradient control. This synergistic coupling of the DEPP gradient technique and the MFCX process provides a powerful FGP methodology for the production of efficient, high displacement actuators with improved reliability, and paves the road for innovative multi-dimensionally graded piezoceramics.

Dual Electro/Piezo Property (DEPP) gradient technique

To generate motions beyond simple axial strains as in monolithic piezoceramics, select material properties must vary spatially. For example, a bimodal gradient in material composition across one dimension produces bending (Fig. 1a), alternating the gradient in two dimensions creates rippling (Fig. 1b), and further alternating it across the entire plane of the actuator generates dimples (Fig. 1c). While most methods vary only one material property [9, 17–25], the DEPP gradient technique targets both the piezoelectric coefficients and electrical permittivity. This exploits the synergism between the two to increase the electric field in the region where the piezoelectric coefficients are higher, resulting in larger displacements, lower electric fields, and enabling multi-dimensional grading without potential shorting issues as with other techniques [9, 17, 18].

Many different dopant materials could be used to generate these material gradients, but most combinations are not compatible with required steps in piezoceramic fabrication. The combination of APC's 856 composition (PZT)—large piezoelectric effect $d_{33} = 620$ pm/V [35], and Ferro's Z9500 barium titanate based dielectric composition (BT)—with a high relative permittivity or dielectric constant $\varepsilon_r = 10{,}000$ [36], produces the dual property variation while maintaining a high level of compatibility. This is evident in the high tolerance of both the PZT and BT constituents of the lead positive atmosphere

Fig. 1 Functionally Graded Piezoceramic (FGP) gradient types and their corresponding deformations



(a) One-dimensional gradient across z coordinate

(b) Two-dimensional gradient across x and z coordinates

(c) Three-dimensional gradient across x, y, and z coordinates

required during firing process as well as in the identical sintering temperatures (Table 1) that enable fully dense specimens regardless of composition. While the sintering rates and the degree of shrinkage do differ for the individual gradient constituents, mixtures of the percentages used in this study produced nominally flat specimens with the refined burnout and sintering schedules. This section describes the effects of PZT/BT composition on relevant material properties and verifies the capabilities of the DEPP gradient through the fabrication and experimental testing of a bimodally graded FGP using traditional powder pressing techniques.

DEPP compositional property maps

To properly synthesize or analyze an FGP actuator, details of the composition's effect on material properties are required. This database of material property gradients was assembled by testing 1/2'' diameter powder pressed pellets of PZT/BT. Specimens ranged in composition from pure PZT to approximately 77/23 vol% PZT/BT. Four different pellets at each material composition were tested for their density, stiffness, relative permittivity, and piezoelectric coefficients to generate maps of the variations with respect to the volume percentage of BT (Fig. 2). These maps can be utilized either for: (a) the selection of proper material composition in the gradient profile necessary to generate a given actuator performance (synthesis) or (b) the identification of the relevant material property gradient across a fabricated sample for substitution into theoretical models that predict performance and internal stresses/reliability (analysis).

Density (ρ)

While the density variation of the material has an insignificant impact on the quasi-static performance of an actuator, it is necessary to accurately mix the powders into the desired material compositions used to fabricate a specific gradient profile within an FGP. The sample densities (ρ) were measured using a Mettler AE1000 digital balance and density determination kit. The material density decreases fairly linearly from 7.58 g/cm^3 to 7.12 g/cm^3 as the amount of BT rises (Fig. 2a).

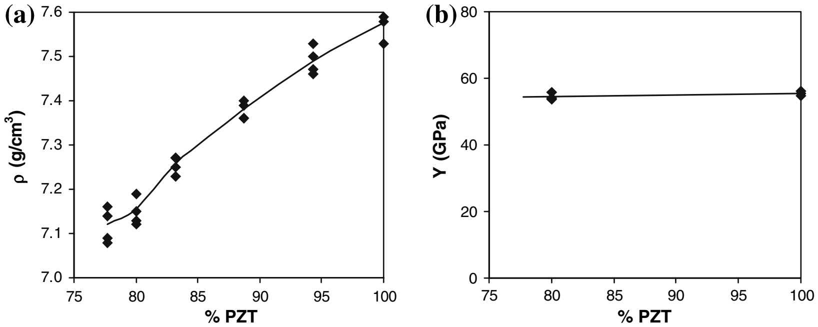
Young's modulus (Y)

The variation in the stiffness of the graded material was measured using a J.W. Lemmens, Inc. Grindo-Sonic nondestructive material testing system that uses a specimen's vibratory response to calculate the stiffness properties (Y) using their EMOD software. The specimen geometry is extremely important for these tests and is limited to beams and discs, requiring the fabrication of 3 mm square beams of the 100 vol% PZT and 80/20 vol% PZT/BT materials. There was only a slight variation in the material Young's Modulus (55.5–54.5 GPa, <2%) across the DEPP composition range (Fig. 2b). Though controlled stiffness variation can slightly increase actuation performance, large discrepancies can lead to greater stress discontinuities within the FGP, limiting actuator lifetimes. Because of this, FGP

Table 1 Manufacturer supplied data for DEPP gradient technique constituent materials

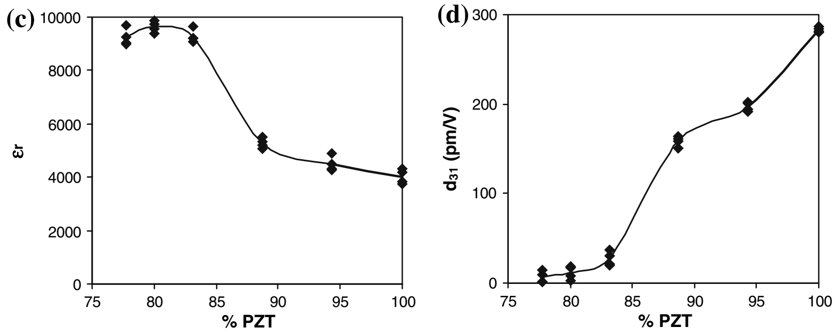
Supplier	Material	Modulus Young's (GPa)	Density (kg/m^3)	d^{33} (pm/V)	d^{31} (pm/V)	Dielectric constant
APC	PZT-856	58.0	7,500	620	–260	4,100
Ferro	Z9500	n/a	5,600	–	–	10,000

Fig. 2 Dual Electro/Piezo Property (DEPP) gradient material property variations with composition



Density

Stiffness



Relative permittivity

Piezoelectric coefficient

constituent materials should be chosen so that stiffness variation is minimal.

Permittivity (ε_r)

The material permittivity is crucial to the performance of DEPP FGP and was a target property for variation during material selection because material with a higher permittivity will experience lower activating electric fields while adjacent material with a lower permittivity will see higher fields. This improves electrical efficiency during activation. The relative permittivity (ε_r) of the samples was calculated by measuring the capacitance (C) with a Fluke 79 III multimeter and basic capacitor equations:

$$C = \varepsilon \frac{A}{t} \tag{1}$$

and

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{2}$$

where A is the sample area, t its thickness, ε_0 the permittivity of free space and ε its permittivity. The dramatic, nonlinear rise in permittivity from 4,022 for pure PZT to a plateau of approximately 9,642 at 20 vol% BT (Fig. 2c) is exactly the trend desired. The 20 vol% change in material composition accounts for a 140% increase in the dielectric properties. Because of this large permittivity range over such a small composition change, 80/20 vol% PZT/BT is an effective lower bound for the materials used in the DEPP gradient technique.

Piezoelectric strain coefficient (d)

Variation of the piezoelectric strain coefficients (d) across the specimen thickness results in strain gradient(s) that produce higher-order deformations rather than the simple axial strains exhibited by homogeneous piezoceramics. The piezoelectric coefficients of the various material samples were measured using an APC 8000 Pennebaker d_{33} tester. For this material, the d_{33} and d_{31} values are related according to the relation [35]:

$$d_{31} = \frac{d_{33}}{2.2}. \tag{3}$$

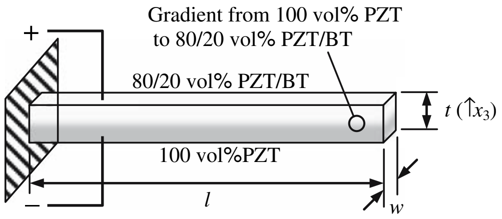
The tests show a dramatic reduction of 96% in piezoelectric activity across the tested composition range (Fig. 2d), with the d_{31} coefficient dropping from 283 pm/V to 6 pm/V. The variation plateaus at approximately 80 vol% PZT, similar to the permittivity, which further justifies the recommended composition range. When the resulting piezoelectric strain gradient is coupled with the variation in permittivity, the two gradients work synergistically to increase the deformations and electric efficiency of the FGP actuator.

Bimodal gradient prototype

To compare the capabilities of the DEPP gradient technique to other established FGP doping methods, a simple bimodally graded FGP specimen was powder pressed using two material compositions: pure PZT and 80/20 vol% PZT/BT. The two powder compositions used for the bimodal gradient were each mixed according to the density map (Fig. 2a). A lubricated steel die with a 50.8 × 25.4 mm cavity was filled approximately 1 mm deep with the first powder composition (100 vol% PZT) and an equal volume of the second powder (80/20 vol% PZT/BT) was evenly distributed on top of the first and then pressed at 10 MPa. The green specimens were sealed in an alumina crucible with a PZT powder bed that ensures a positive lead atmosphere. The samples were sintered at 180 °C/h in a high temperature furnace to a soaking temperature of 1320 °C for 2 h. Cooled specimens were lightly sanded before plating opposite faces with a sputtered AuPd electrode and poling at a 2,000 V. The final test specimen was 32.66 mm long, 2.29 mm wide, and 2.31 mm thick after mounting in a cantilevered beam configuration (Fig. 3).

While only two distinct material compositions were used, due to a slight amount of layer mixing during pressing and diffusion during sintering, a continuous material gradient is produced. The material variation of a slightly thinner sample taken from the same pressing as the prototype was measured using a Cameca SX100 electron microprobe analyzer that registers the barium concentration in the material across the thickness of the sample (Fig. 4). The measured smooth, continuous gradient that occurs over approximately 0.46 mm of the specimen thickness is preferred to discrete, stepwise gradients because it eliminates stress discontinuities within the actuator that can lead to cracking and device failure [37]. As depicted in the scanning electron micrograph (Fig. 5a), the porosity is good at 96% theoretical density and there are no visible features marking the interface between the material compositions; thereby, indicating a high quality DEPP gradient.

(a) Photograph



(b) Schematic

Fig. 3 Powder pressed bimodal FGP actuator prototype (l = 32.66 mm, w = 2.29 mm, t = 2.31 mm)

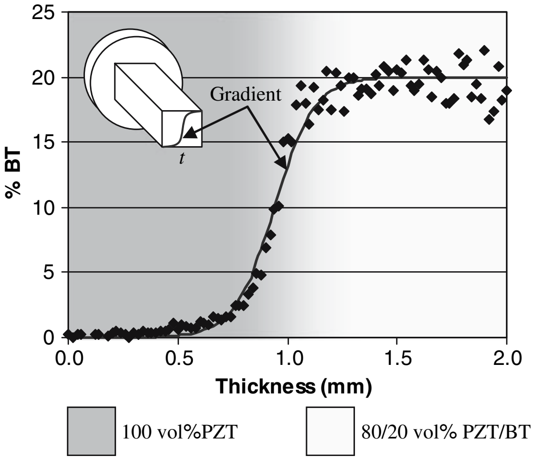


Fig. 4 Barium titanate (BT) percentage through the thickness (t) of the powder pressed bimodal functionally graded piezoceramic (FGP)

Powder pressed FGP deflection response

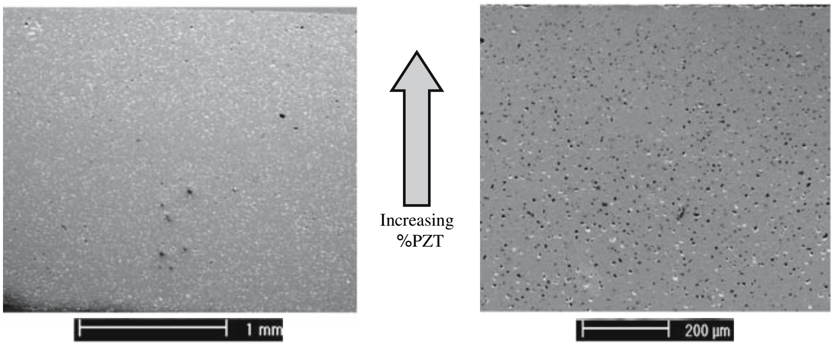
The deflection behavior of the powder pressed specimen was evaluated using the experimental apparatus in Fig. 6 and compared to FGP theory. Voltage was incrementally applied from zero to a maximum of 700 V via a Kepco APH 2000 DC power supply and then stepped back down to zero. The process was repeated for negative driving potentials. At each electric potential the resulting displacement was measured by a Philtec A88NE1 fiber optic probe and compared to the predictions of a published analytic free deflection (Δ) model [38]:

$$\Delta = \frac{l_1^2}{2}\left[\frac{C_1C_5 - C_2C_4}{C_2^2 - C_1C_3}\right] \tag{4}$$

where l_1 is the specimen length and the values C_i are defined as:

$$C_i = \int_0^{l_3} \left\{[x_3 - a]^{i-1} Y_{11}(x_3)\right\} dx_3 \quad \text{for } i = 1 \text{ to } 3, \tag{5}$$

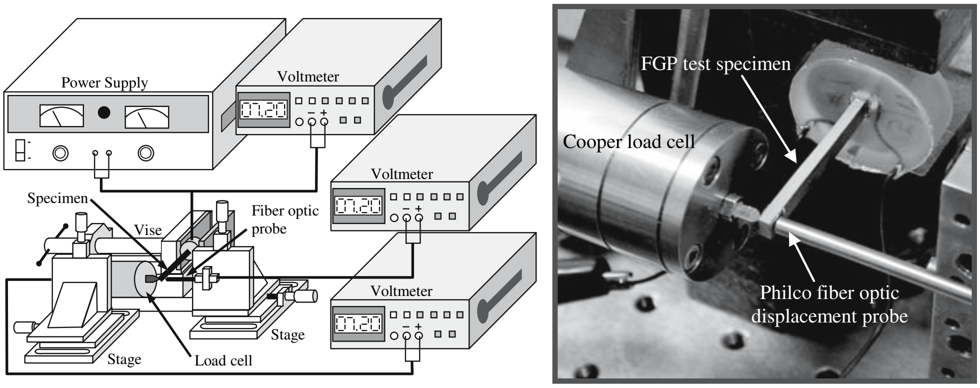
Fig. 5 Polished surface of the functionally graded piezoceramic (FGP) specimens



(a) Powder pressed specimen (bimodal gradient)

(b) MFCX specimen (linear gradient)

Fig. 6 Functionally graded piezoceramic (FGP) experimental test apparatus



$$C_i = \int_0^{l_3} \left\{ [x_3 - a]^{i-4} d_{31}(x_3) E_3(x_3) Y_{11}(x_3) \right\} dx_3 \quad \text{for } i = 4 \text{ and } 5, \tag{6}$$

with x_3 denoting the thickness coordinate, l_3 the specimen thickness, and a the location of the actuator neutral axis. The varying electric field (E) is defined as:

$$E_3(x_3) = \frac{-\Delta V}{\varepsilon_{33}(x_3) \int_0^{l_3} \left\{ \frac{1}{\varepsilon_{33}(x_3)} \right\} dx_3}, \tag{7}$$

where ΔV is the applied electric potential. This model differs from conventional models by accounting for variations, either continuous or discrete, in the material stiffness, permittivity, piezoelectric coefficients, and activating electric field strength. These parameters are constants inhomogeneous piezoceramics and can traditionally be factored out of the integrals in Eqs. 5 and 6. But for FGP, these parameters vary through the material in complex ways (as seen in the material property maps), especially the nonlinear electric field (Eq. 7) that depends of the reciprocal of the permittivity profile. By measuring the BT concentration across a specimen (Fig. 4), all of the material property variations within an FGP can be determined using the maps of Fig. 2 and substituted into Eq. 4 to predict the FGP's deflection.

The analytic prediction and experimental performance of the powder pressed FGP are given in Fig. 7. The specimen generated ±43.5 μm of motion when subjected to ±700 V. The specimen outperformed by 5.6% the model which predicts ±41.2 μm of motion for these conditions. Though the linear model does not capture the hysteresis of

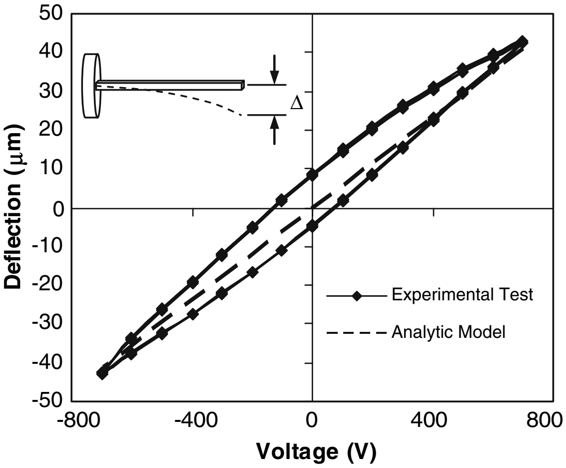


Fig. 7 Deflection–voltage performance of the powder pressed bimodal functionally graded piezoceramic (FGP)

the actuator which reaches a maximum of 13.4 μm, this is very good correlation considering slight variations in the specimen thickness along its length and some minimal curvature within the FGP. The performance is on par with comparable FGP that are driven at electric potentials in excess of double those applied here [9, 19, 20, 26, 28]. These results validate the DEPP gradient technique and demonstrate that it can be used in conjunction with powder pressing to produce simple, one-dimensionally graded FGP.

Co-extrusion of DEPP gradient piezoceramics

Production of more complex higher-order gradients than those easily achieved through powder pressing requires the precision and resolution of Micro-Fabrication by Co-eXtrusion (MFCX). While this process has proven effective in fabricating complex piezoceramics [31–34], it had to be tailored to deal with the demands of the DEPP gradient technique that requires the use of many different material compositions.

MFCX fabrication process

The basic procedure for MFCX of FGP (Fig. 8) consists of five steps: media preparation, feedrod formation, extrusion, burnout and sintering, and post processing.

- *Step 1: Media preparation*: Once the desired material compositions needed to form a specific gradient are selected, the constituent powders (mixed according to the data in Fig. 2a) are ball milled in water for 24 h using zirconia media. The powders are incorporated into a thermoplastic media with ethylene ethyle acrylate (EEA), isobutyl methacrylate (B67), polyethylene glycol (PEG 1000), stearic acid, and heavy mineral oil [39] in a 120 °C C.W. Brabender Instruments, Inc. PL2100 shear mixer. Mixing continues until all ingredients are thoroughly incorporated and a stable input torque is reached, which directly correlates to the media viscosity. It is crucial that the viscosities match—ensuring no cross-sectional distortion during co-extrusion. The viscosity of the mixture can be adjusted either by adding ceramic powder (increasing viscosity) or mineral oil (lowering viscosity). The ceramic/polymer media hardens when cooled, and in this state can either be machined or reheated and plastically formed into any desired shape.
- *Step 2: Feedrod formation*: A desired material gradient is produced by making a larger scale feedrod with a low-resolution gradient analogous to the target profile. Individual feedrods of each material composition that is to be used are first compacted in a 25 mm square die at 120 °C under 770 kg load with a Bradford University Research Ltd. Extruder. A single batch of extrusion media produces a solid feedrod approximately three inches long which can be cut and reassembled with other media compositions to create the scaled-up gradient in the final feedrod. Voids can be achieved in the structure with the MFCX process by including a fugitive carbon-based media that is eliminated during the firing procedure. The final feedrod is again heated and compacted to eliminate gaps between its assembled components.
- *Step 3: Extrusion*: Once the desired layout of the gradient profile is assembled, the final size of the FGP is achieved by extruding the heated feedrod at 120 °C, reducing the cross-section in both dimensions to a smaller, square configuration or in one dimension to produce a flattened tape. A single extrusion run (from

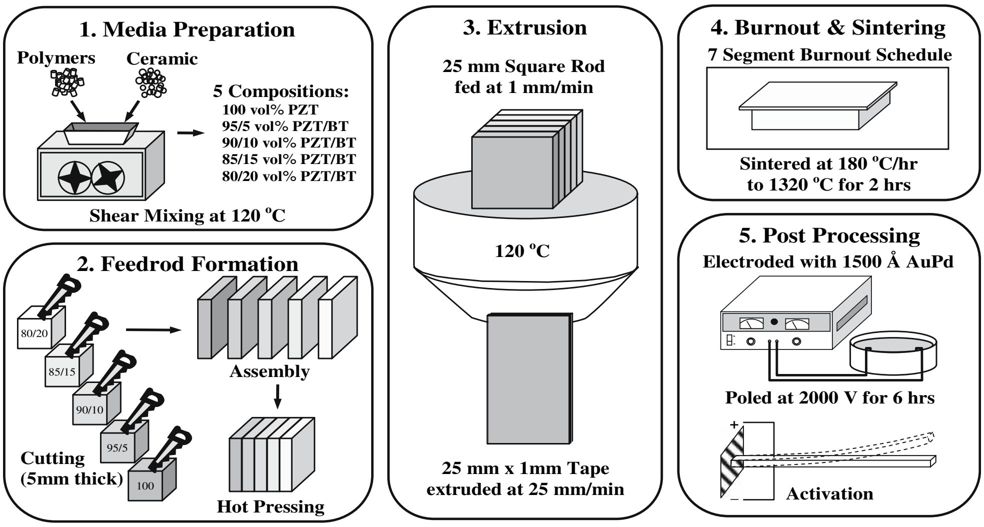


Fig. 8 Overview of the Micro-Fabrication through Co-eXtrusion (MFCX) process for DEPP FGP

one media batch or 75 mm feedrod) produces a large quantity of FGP tape (approximately 1.2 m depending on the size reduction). The extruded material can subsequently be machined into the final actuator shape (e.g. beam or patches) or reheated and rebundled into another feedrod with repeated extrusions yielding FGP on a variety of scales, down to the micron level [31, 33].

- *Step 4: Burnout and sintering*: Once the final FGP form is achieved, the polymers and other ingredients in the media are removed from the green ceramic in a two step firing process. First, the polymers are burned-out in a Thermolyne F48015 bench-top muffle furnace using a carefully controlled, slow heating schedule reaching 520 °C over 14 h [39]. Prior to the second sintering phase, the specimens are placed on an alumina plate with a fine coating of the loose ceramic powder between them. A second dusting of powder was placed on top of the specimens followed by a thin ceramic plate that eliminates warping of the specimen. In the second step, the specimens are sintered in a Micropyretics Heaters International (MHI) HIPAN-Series high temperature furnace to the manufacturer specified temperature of 1320 °C by heating at a rate of 180 °C per hour and allowing the material to soak for 2 h, then ramping the temperature back down at the same rate before post processing.
- *Post processing*: The post processing of the FGP specimens consists of two separate steps: electroding and poling. Two opposing sides of the FGP actuators are electroded with 1,500 Å of AuPd using a Technics Hummer 6 sputtering system. The specimens are then poled at room temperature in a peanut oil bath, slowly ramping the applied electric potential (via the Kepko DC power supply) to 2,000 V over 2 h, maintaining this voltage for 6 h before it is reduced back down to zero. Since the applied electric field is no longer simply the voltage divided by the specimen thickness, the electric field strength experienced by the lower permittivity material can be dramatically higher than what would be expected for normal, homogenous piezoceramics, and should be closely monitored.

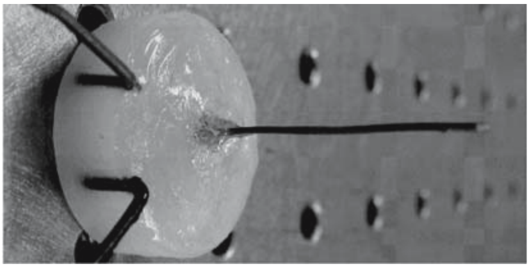
Linear gradient prototype

While the modified MFCX process can be applied to any gradient profile, the general process was demonstrated by fabrication and experimental characterization of a linearly graded FGP using the DEPP technique. This more gentle profile, compared to abrupt bimodal gradients or layered actuators, reduces the internal stress levels [37], extending the actuator lifetime. In this case, to generate a linear gradient, five different material compositions were used—pure PZT, 95/5, 90/10, 85/15, and 80/20 vol% PZT/BT. Each individual composition was compressed into a 6 mm feedrod and machined down to a thickness of 5 mm using a Roland Modela MDX-15 3-D plotter. The five individual layers were assembled in the die in order of increasing BT, heated, and compressed into a final feedrod. The feedrod was reduced in the layered dimension from a 25 mm square rod to a 1 × 25 mm tape by extrusion at a ram speed of 1 mm/min. Green ceramic beams were cut from the co-extruded tape and sintered and polished into a 24.68 mm long and 2.87 mm wide linearly graded FGP beam (Fig. 9) which is dramatically thinner ($t = 0.84$ mm) than the powder pressed specimen.

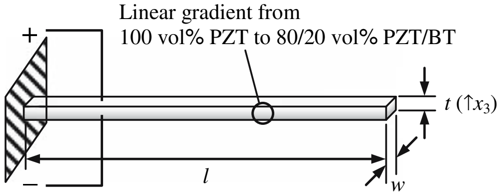
The co-extruded FGP specimen's material composition was analyzed for barium content using the electron microprobe analyzer. The same smoothing of the compositional variation observed in the powder pressed specimen was once again present (Fig. 10), with the original layered gradient giving way to a continuous linear gradient because of the finer resolution of the co-extrusion process and diffusion during sintering. Material samples from the same fabrication run were used for these tests and the polished surface (Fig. 5b) once again shows acceptable porosity (95% density) and no discernable material interfaces. Because of the thickness reduction from extrusion and the compatibility of the DEPP constituent materials, the MFCX process requires only five different material compositions to obtain a linear material gradient.

MFCX FGP deflection response

The experimental deflection–voltage testing was implemented in the same manner as for the powder pressed FGP,



(a) Photograph



(b) Schematic

Fig. 9 Co-extruded linear functionally graded piezoceramic (FGP) actuator prototype ($l = 24.68$ mm, $w = 2.87$ mm, $t = 0.84$ mm)

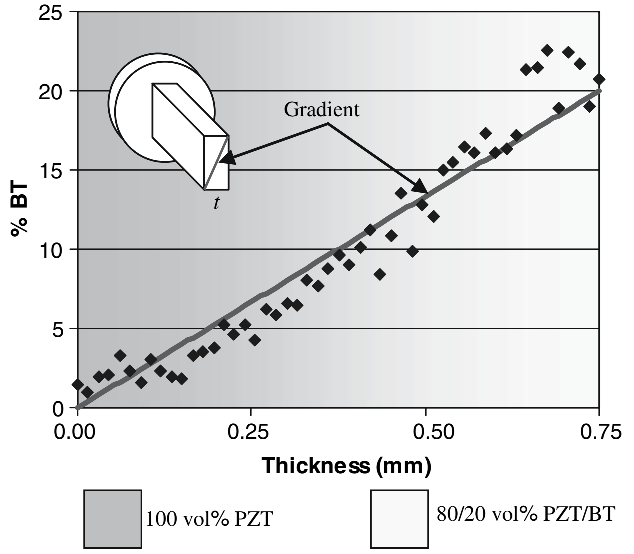


Fig. 10 Barium titanate (BT) percentage through the thickness (t) of the co-extruded linear functionally graded piezoceramic (FGP)

only the maximum driving potential was limited to ±200 V because of the reduced sample thickness. The material property variations for these specific FGP were determined using the material property maps (Fig. 2) and the measured linear composition gradient (Fig. 10). Each of the variations, along with the specimen dimensions, were substituted into Eqs. 4–7 to predict the activating electric field profile and the resulting actuator deflection capabilities.

The linear DEPP FGP deflected a range of ±32.7 μm, compared to the theoretical prediction of ±34.8 μm, a 6.5% deviation (Fig. 11). The characteristic hysteresis of piezoceramics was again visible in the co-extruded FGP, reaching a maximum of 12.4 μm during the experimental test. As with the powder pressed results, there is good correlation given the linear nature of the model and the slight amount of waviness seen in the co-extruded FGP specimen due to different material shrinkage rates, which can be mitigated through further refinement of the manufacturing process. While the linear gradient does slightly reduce the displacement in comparison to a bimodal gradient, the lifetime is significantly improved [37], making it suitable for more industrial applications.

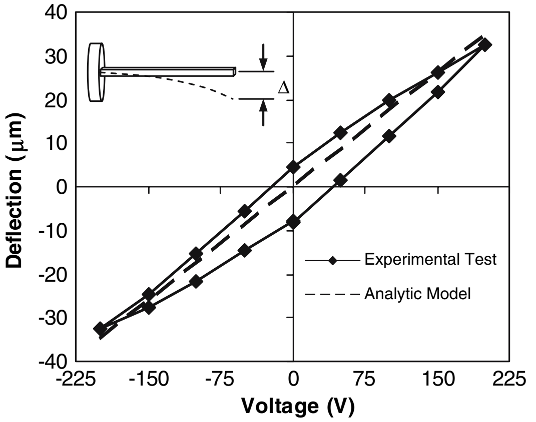


Fig. 11 Deflection–voltage performance of the co-extruded linear functionally graded piezoceramic (FGP)

Conclusion

This paper introduces the Dual Electro/Piezo Property (DEPP) gradient technique via Micro-Fabrication through Co-eXtrusion (MFCX). The DEPP gradient technique was developed around a lead zirconate titanate (PZT) piezoceramic and barium titanate (BT) dielectric that synergistically produce dramatic material property variations (a 140% increase in permittivity coupled with a 96% reduction in the piezoelectric effect), concentrating the bulk of the applied electrical energy in the most active material resulting in actuators with high electrical efficiencies and large displacement capabilities. Characterization of the gradient constituents produced detailed property-composition maps that aid in designing complex gradients and revealed a high-performance composition range of 100 vol% PZT to 80/20 vol% PZT/BT that preserves the necessary level of material compatibility to allow for easy fabrication. The DEPP technique was independently validated using a powder pressing fabrication process known to successfully produce FGP actuators. This process yielded a high quality bimodal FGP bender with low porosity (96% density) and seamless interfaces between material compositions. The deflection capabilities of ±43.5 μm at ±700 V agreed to within 5.6% of theory and matched or exceeded the displacement performance of similar FGP, even though some of these actuators were driven by almost double the electric potential used to activate the DEPP FGP. The powder pressing technique is limited in its gradient control and resolution and can only easily produce one-dimensionally graded piezoceramics. To fully realize the potential of FGP actuation the MFCX process was tailored to the DEPP gradient technique and used to fabricate a linearly graded actuator. The resulting material had acceptable porosity (95% density) with a smooth uninterrupted variation in material composition that leads to lower internal stresses and increased reliability, opening the door to more use in industrial applications. The measured deflection of ±32.7 μm at ±200 V correlates to within 6.5% of the more complex theory that includes the nonlinear electric field profile and material property variations within the activated specimen. This work sets the foundation for the DEPP FGP methodology which produces synergistic, reliable, and efficient FGP actuators while the MFCX process allows for precisely controlled material gradients, potentially positioning FGP technology to exploit the untapped capabilities of multi-dimensionally graded piezoceramics.

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