Piezoelectric component fabrication using projection-based stereolithography of barium titanate ceramic suspensions

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Abstract
Purpose – Conventional machining methods for fabricating piezoelectric components such as ultrasound transducer arrays are time-consuming and limited to relatively simple geometries. The purpose of this paper is to develop an additive manufacturing process based on the projection-based stereolithography process for the fabrication of functional piezoelectric devices including ultrasound transducers.

Design/methodology/approach – To overcome the challenges in fabricating viscous and low-photosensitive piezocomposite slurry, the authors developed a projection-based stereolithography process by integrating slurry tape-casting and a sliding motion design. Both green-part fabrication and post-processing processes were studied. A prototype system based on the new manufacturing process was developed for the fabrication of green-parts with complex shapes and small features. The challenges in the sintering process to achieve desired functionality were also discussed.

Findings – The presented additive manufacturing process can achieve relatively dense piezoelectric components (approximately 95 per cent). The related property testing results, including X-ray diffraction, scanning electron microscope, dielectric and ferroelectric properties as well as pulse-echo testing, show that the fabricated piezo-components have good potentials to be used in ultrasound transducers and other sensors/actuators.

Originality/value – A novel bottom-up projection system integrated with tape casting is presented to address the challenges in the piezo-composite fabrication, including small curing depth and viscous ceramic slurry recoating. Compared with other additive manufacturing processes, this method can achieve a thin recoating layer (as small as 10 μm) of piezo-composite slurry and can fabricate green parts using slurries with significantly higher solid loadings. After post processing, the fabricated piezoelectric components become dense and functional.

Keywords Additive manufacturing, Piezoelectricity, Stereolithography, Barium titanate, Ceramic fabrication, Ultrasound transducer

Paper type Research paper

1. Introduction

Ultrasonic imaging is an important medical imaging technique. As ultrasound poses no known risks to patients, this technology has become one of the most widely used diagnostic tools in modern medicine (Shung, 2005). An ultrasonic imaging system requires an ultrasound probe as shown in Figure 1(a). One of the core components of the ultrasound probe is a transducer array, which can produce mechanical energy in response to electrical signals and produce electrical signals in response to mechanical stimulus conversely. Ultrasound transducer arrays have been used to detect and visualize muscles, tendons and many internal organs due to their advantages, such as high bandwidth, fast response and high sensitivity.

Piezoelectric components such as ultrasound transducer arrays are generally made of piezoelectric ceramic materials, e.g., Barium titanate (BTO) and Lead Zirconate Titanate (PZT). As these piezoelectric materials have relatively poor machinability, transducer arrays are typically fabricated into simple shapes, such as square or rectangle. Instead of simple
shapes, new ideas based on aperiodic and non-rectangular array shapes have been developed in the latest ultrasound transducer designs to achieve more efficient energy conversion (Akhnak et al., 2002; Thomenius et al., 2005). One of such design examples is shown in Figure 1(c), where a hexagonal pattern is used (Thomenius et al., 2005). The new design is found to have less lateral mode coupling, leading to a better acoustic efficiency. However, an ultrasound transducer array with complex array shapes and small dimensions poses significant challenges on its fabrication. Current manufacturing methods have great difficulty in fabricating such complex piezoelectric components. For example, the dice-and-fill process prepares piezo-components by cutting a piezo-ceramic plate into an orthogonal array and filling the kerfs with polymer material. Thus, such a fabrication process can only produce square arrays. To address such a challenge, we investigated the fabrication of piezoelectric ceramic components using additive manufacturing (AM) processes.

1.1 Related work

Current approaches to fabricate piezoelectric components are mainly based on machining. The main steps of the machining approach are shown in Figure 2(a). Functional ceramics are first built in bulk and then cut into shapes by machining tools such as a dicing saw used in dice-and-fill techniques (Smith and Auld, 1990; Liu et al., 2001). However, cutting bulk piezoelectric materials becomes increasingly difficult as current trends on piezoelectric component design require more complex geometries to enhance their performance (Smith, 1986). Moreover, machining processes usually have relatively big feature resolutions, which are limited by their machining tools. Some other machining processes such as laser dicing techniques (Lukacs et al., 1999; Farlow et al., 2001) have been developed to fabricate smaller features. However, the ablation side effects and conic shape of ceramic arrays fabricated by these techniques have also been observed, which will adversely affect the arrays’ piezoelectric performance.

Another approach to fabricate piezoelectric components is based on molding and AM [Figure 2(b)]. In these approaches, piezocomposite slurry is first made by mixing piezo-ceramic powders with polymers and solutions in certain mixture ratios. Various techniques have been developed to define the desired geometry in green-parts. An example is composite micro molding and lost silicon molding techniques (Hirata et al., 1997; Cochran et al., 2004), which consist of following steps. A silicon (or plastic) mold is first made using the lithography, galvano-forming and plastic molding (LIGA) process (Becker et al., 1986); then the piezocomposite slurry is cast into the mold; and finally, the mold is removed after applying a high temperature. The lost silicon molding or injection molding processes follow similar steps (Gentilman et al., 1994; Chu et al., 1999). However, these methods are indirect processes with multiple steps, and each step requires significant effort. Other examples include chemical vapor deposition (Aota et al., 2008) and tape casting methods (Chartier et al., 1997), which have been developed to directly deposit piezo-ceramic atoms or very thin tapes on a semiconductor substrate. However, the resulted geometry by these methods is usually simple, as it is difficult to control the processes for more complex shapes.

During the past 30 years, many novel AM processes such as stereolithography (SL), selective laser sintering and fused deposition modeling have been successfully developed and commercialized (Bourell et al., 2009). These AM processes have been investigated to fabricate piezo-ceramic parts before. For example, the fused deposition of ceramics (Lous et al., 2000; Safari et al., 2006) and robocasting processes (Cesarano et al., 1998) can directly fabricate piezo-ceramic parts by extruding piezocomposite slurry from a controlled nozzle. However, these processes generally have a limited resolution and building speed. It is difficult to use them to fabricate ultrasound transducer arrays. Several variations of SL (Brady and Halloran, 1997; Dufaud and Corbel, 2002; Sun and
Bertsch (2002; Bertsch et al., 2004) have also been developed by using a highly focused laser beam to scan over the ceramic slurry. But these processes are usually slow and require the viscosity of the materials to be small; hence, they can only fabricate materials with low solid loadings. Digital projection devices such as Digital Micromirror Devices provide powerful tools that can dynamically control the energy input of a projection image. By using these digital devices in the SL process, a whole layer can be fabricated simultaneously, and the building speed can thus become much faster. Several research and commercial projection-based SL systems have been developed (Farsari et al., 1999; Monneret et al., 1999; Bertsch et al., 2000; Sun et al., 2005; Lu et al., 2006; Pan et al., 2012; Song et al., 2015). However, most of the research are focused on the fabrication of photocurable resin or structural ceramics such as alumina. Some of the previous work that considered piezo ceramics (Dufaud and Corbel, 2002) only studied the green-part fabrication; the heat treatment procedure and related material property measurements were not discussed. In this paper, we presented our investigation on both green-part fabrication and post-processing steps. In addition to material property measurements, a functional device was built to demonstrate the capability of the projection-based SL process in piezocomposite fabrication.

1.2 Overview of piezocomposite fabrication based on additive manufacturing

As shown in Figure 2(b), the piezocomposite-based SL process usually involve two main steps to fabricate functional ceramic components:

1. Green-part fabrication to define part geometry and;
2. Debinding and sintering of green-parts to achieve densified components.

In this paper, we investigate using the projection-based SL process in fabricating piezoelectric BTO components. Compared with other AM processes (Lous et al., 2000; Safari et al., 2006; Brady and Halloran, 1997; Dufaud and Corbel, 2002; Sun and Zhang, 2002; Bertsch et al., 2004), the projection-based SL process is a low-cost and high-speed manufacturing process. However, there are challenges such as small curing depth and difficulty in spreading viscous slurry into uniform thin layers that need to be addressed for the piezocomposite fabrication. In our research, a set of techniques including a tape-casting-based layer recoating method and a layer separation method based on a sliding motion design have been developed to enable green-part fabrication from highly viscous and lowly photosensitive piezocomposite slurry. It is critical to use slurry with high solid loadings to achieve high density and piezoelectricity in the built components. The heat treatment of BTO green-parts that contain photocured polymers and delicate features is challenging, as piezo components have high requirements on material composition and density for them to have piezoelectric properties. In addition, both debinding and sintering of green parts need to avoid cracking and distortion.

The remainder of the paper is organized as follows. The green-part fabrication using the projection-based SL process is presented in Section 2. The debinding and sintering processes of BTO green-parts are discussed in Section 3. The measured material properties and related device fabrication are presented in Section 4. Finally, conclusions with future work are drawn in Section 5.

2. Green-part fabrication using the projection-based stereolithography process with piezoceramic slurry

The materials used in conventional SL processes are photocurable resin, from which only polymer components can be fabricated. The presented projection-based SL process needs to fabricate piezo-ceramic components by photocuring a mixture of photocurable resin and piezo-ceramic powders. However, adding solid particles into the liquid resin will significantly change the properties of the photocurable materials such as rheological behavior and photosensitivity, which will introduce a lot of challenges to the SL process. First, compared with liquid resins that are commonly used, the piezo-ceramic slurry made by mixing solid particles and liquid resin has an increased viscosity. Higher solid loading (e.g. above 60 Wt.%) in the composite suspension will lead to larger viscosity of the slurry, which can be substantially exceeding the maximum viscosity limit of 3,000 mPa s for the conventional SL processes (Griffith and Halloran, 1997). With such a high viscosity, it is difficulty to recoat a uniform thin layer within a reasonable time. The second challenge in the projection-based SL process for piezo-ceramic slurry is the reduced cure depth. That is, when light travels through the composite slurry, the solid particles will absorb and scatter the incoming light. The light energy that can access the photosensitive resin is decreased by an order of magnitude. Hence, the cure depth will be significantly reduced. To overcome these challenges, we developed a projection-based SL process by integrating tape-casting for slurry recoating and a sliding motion design for layer separation. Compared with other AM processes, our method can achieve a thin recoating layer (as small as 10 μm) of piezo-composite slurry and can fabricate green parts using slurries with significantly higher solid loadings.

2.1 Curing characteristics of barium titanate slurry

The curing of photocurable resin follows the Beer–Lambert law of absorption, which can be formulated as follows (Jacobs, 1992):

$$C_d = D_p \ln \left(\frac{E}{E_c}\right)$$

where $C_d$ is the cure depth, and $D_p$ and $E_c$ are resin parameters known as the penetration and critical exposure energy, respectively. Critical exposure is corresponding to the energy below which the polymerization does not happen. $E$ is the exposure dose on the resin surface.

Different from the curing characteristics of pure photocurable resin, when light travels through highly concentrated BTO slurry, it is scattered by the BTO particles and its propagation direction will be changed. Thus, in addition to the light absorption by photocurable resin, the light intensity is reduced by scattering as well. Equations have been studied in Tomeckova and Halloran (2010a, 2010b), Abouliatim et al. (2009), Griffith and Halloran (1997) and Gentry and Halloran (2003) to describe the effect of scattering on cure depth $D_p$ and cure width $\omega_{cur}$.
where \( d_{50} \) is the average particle size; \( \Delta n \) is the refractive index difference between the ceramic particle \( (n_p) \) and the liquid resin \( (n_\text{rl}) \), i.e. \( \Delta n^2 = (n_p - n_\text{rl})^2 \); \( Q \) is the scattering efficiency term on cure depth; cure width \( \omega_{\text{cure}} \) is obtained by adding the illumination width \( \omega_{\text{ill}} \) and excess width \( \omega_e \) due to light scattering in the horizontal direction; and excess width \( \omega_e \) is related to the width sensitivity \( S_w \) incident light energy \( E \) and the width critical energy dose \( E_w \).

The BTO slurry used in our study is prepared as follows. As-received BTO powders (Sigma-Aldrich, Saint Louis, MO) have an average particle size of 1 μm with obvious agglomerates. To obtain homogenous suspension, the powders were first deagglomerated in an azeotropic mixture of methylethylketone (66 vol%, MEK, Sigma-Aldrich, Saint Louis, MO) and ethanol (34 vol%, Sigma-Aldrich, Saint Louis, MO) with dispersant by ball milling for 12 h. The same ratio of azeotropic mixture was also used in Chartier et al. (1999) and Mikeska and Cannon (1988). The solid loading of the dispersion is 25 vol%. Phospholane PS-131 (AkzoNobel, Chicago, IL) and Triton x-100 (Dow Chemical Co., Midland, MI) were selected as dispersant due to their good dispersion properties (Mikeska and Cannon, 1988; Paik et al., 1998; Jang et al., 1998).

Dispersant with 0.5-0.8 Wt.% concentration was added into the mixture, on a dry weight basis of BTO powders. The dispersion is then dried at 50°C for 12 h. After the evaporation of the solvent in the dispersion, dry BTO powders with dispersant adsorbed onto their surface can be obtained. The deagglomerated BTO powders (containing 0.5-0.8 Wt.% dispersant) were dissolved in commercial photocurable resin (SI500, EnvisionTec Inc., Ferndale, MI). Additional 0.2 Wt.% dispersant was added into the suspension to ensure full dispersions of particles. The suspension was then milled for 1-2 h to break down the agglomerates formed during solvent evaporation. Afterwards, the suspension was degassed in a vacuum for 5 h.

Tests on the curing characteristics of BTO slurry have been performed. An image of a square with a length of 8.57 mm was projected using the prototype system. The thickness and width of the cured films with different weight ratios were measured with a length gauge (Heidenhain, Schaumburg, IL) and a caliper, respectively. The relations between cure depth/width and BTO weight ratio under different curing time (i.e. 1, 2, 8 and 16 s) based on our experimental setup are shown in Figure 3. For simplicity, slurry samples with weight ratio 30-50 per cent were prepared by ultrasonic mixing for 30 min. Slurry samples with weight ratios 60 to 80 per cent were prepared by directly mixing photocurable resin with BTO powders in a ball mill. The light intensity of our projection system is approximately 31.6 mW/cm² measured by an illumination level meter (Simpson Electric, WI). It can be seen from Figure 3 that the cure depth decreases as more BTO powders are added. The slight increase in cure depth from 70 to 80 per cent can be explained by non-homogenous mixing of 80 per cent slurry due to its high viscosity, and this further indicates the significance of the presented slurry preparation method. The cure depth curves suggest bigger cure depth can be obtained by increasing curing time, but a longer curing time will also yield bigger overcure in width. The experimental result shows the optimal weight ratio for BTO fabrication through our system is 60-80 Wt.% under a curing time of 2-8 s, such that a reasonable cure depth can be obtained with the minimum overcure width.

### 2.2 Bottom-up projection integrated with tape-casting for slurry fabrication

The fabrication process based on the prepared BTO slurry needs to overcome high viscosity and low photosensitivity of the mixtures caused by the addition of ceramic powders. We studied the existing ceramics manufacturing processes and integrated a tape casting process into the bottom-up projection-based SL process. The tape casting process is a widely used manufacturing approach to fabricate ceramic tapes. In the tape casting process, ceramic slurry is cast onto a flat surface by a doctor blade and then dried to form a solid ceramic tape. The integration of this process facilitates the layer recoating of viscous BTO slurry. Furthermore, as the bonding force between layers is small due to the small penetration depth of light, a sliding motion design with a smaller separation force (Zhou et al., 2013) is used to detach...
newly cured layer from the coated Teflon film. An illustration of our fabrication process is shown in Figure 4.

As shown in Figure 4, slurry recoating is conducted by a tape-casting subsystem comprising a slurry dispenser, a doctor blade and a film collector. As a new cycle starts, the slurry dispenser drops a line of slurry onto the film collector. The film collector is an aluminum plate with a clear glass sheet that is embedded inside. The clear glass sheet is coated with a Teflon film. When the film collector passes beneath the doctor blade, the slurry line is spread out and a thin slurry film is coated on the Teflon film. After the recoated slurry layer is transported to the position under the Z platform, the platform will move down to form a gap between the Teflon film and the previously built layers. This new slurry layer is then cured by a mask image that is projected from the bottom.

After a layer is cured, the film collector directly slides to the right side. Due to the lubricating effect of the Teflon film (Zhou et al., 2013), the shearing force during the sliding movement is relatively small. The vacuum between the cured layer and the film is broken after the film collector is slid for a certain distance. Thus, the new layer can be detached from the Teflon film. We call this layer separation procedure a sliding motion design. After that, the platform moves up and waits for a new slurry layer to be recoated. A fabrication cycle of the next layer begins after the film collector takes the recoated slurry layer back to the Z platform. More details about the sliding motion design and process parameter settings can be found in Song et al. (2015).

A prototype system as shown in Figure 5(a) was built to verify the developed tape-casting-integrated and projection-based SL process for BTO composite fabrication. BTO slurry (weight ratio 70 per cent) was prepared by following the procedures as described in Section 2.1. Piezoelectric ceramic powders have high refractive index with respect to the photosensitive resin in the slurry. This determines a small penetration depth as low as 40 μm. To ensure sufficient overcure between neighboring layers, the chosen layer thickness for the building process is 20 μm. The doctor blade height is set to be 100 μm. An annular transducer array that is fabricated with these parameter settings is shown in Figure 5(b). The transducer array is designed to have 64 elements that can be dynamically excited to achieve desired ultrasonic imaging shapes. Each element is in a fan shape, with two edges intersecting at the center of the array.

3. Debinding and sintering study of barium titanate green-parts

The BTO green-parts fabricated by the projection-based SL process are a mixture of polymers and BTO particles. In the mixture, BTO particles are separated by polymers. Hence, compression stress cannot be efficiently transmitted to the BTO particles when an external force is added. For the fabricated components to achieve piezoelectric properties, the polymers need to be removed and BTO particles need to be sintered together. The debinding process is conducted first to burn out the polymers in the samples. Following the debinding process, the sintering process with higher temperatures is performed to convert the debinded BTO green-parts into fully dense ceramic components that can have desired piezoelectric properties. In this section, the heat treatment procedures of both debinding and sintering processes are discussed. Based on them, the measured material properties of the sintered BTO components are presented in Section 4.

The temperature curves of both debinding and sintering processes of BTO green-parts are shown in Figure 6. First, in the debinding process (Figure 6(a)), an argon furnace is used...
to heat the fabricated green-parts. A batch of green-parts can be heated at the same time in the furnace. The temperature rises from the room temperature at a rate of 1°C/min and will be held at 200, 300, 400 and 500°C for 30 min, respectively. The polymer composition in the samples is fully burned out after they are held at 600°C for 3 h. During the debinding process, we use Argon atmosphere, low heating rate and 30 min hold at different temperatures to reduce the rate of polymer reaction and, consequently, to avoid part damage due to the vapors that are generated in the pyrolysis of polymers. Second, after green-parts are debinded in the argon furnace, the sintering process [Figure 6(b)] is carried out in a regular furnace under a higher temperature (1330°C) with a dwell time of 4 h. The ramp up rate in the sintering process is set to 3°C/min. We tested different sintering temperatures within 1200-1500°C, and finally choose 1330°C as the sintering temperature for BTO parts. The fabricated green part of segment annular transducer array (Figure 5) is debinded and sintered using the aforementioned heating procedures. The shrinkage during the debinding and sintering processes is about 26.7 per cent along the x- and y-axes and about 34.3 per cent along the z-axis. The density of the sintered component is 5.7 g/cm³ or approximately 95 per cent of bulk BTO material whose density is 6.02 g/cm³.

4. Testing results of sintered samples

4.1 Material property measurements

A series of samples in a cylindrical shape (diameter 10 mm, thickness 3 mm) were fabricated and post-processed to characterize the piezoelectric properties of the sintered parts. The debinded and sintered samples were first analyzed using scanning electron microscope. Figure 8(a) shows the sample surface after the debinding process, and Figure 8(b) characterizes the surface of a sample after 4 h sintering. It can be seen that polymers were burned out in the debinding process, which will leave a lot of voids inside the samples and make the sample become fragile. As shown in Figure 8(b), the sample becomes dense after the aforementioned sintering process.

The structure of the samples was also examined using a Rigaku X-Ray diffractometer (Rigaku Corporation, Tokyo, Japan). As shown in Figure 9, the fabricated material has a relatively well-crystallized perovskite phase and is suitable for multi-ferroic applications such as ultrasound transducers.

To understand the performance of the developed AM process on fabricating BTO components, the dielectric and ferroelectric properties of the sintered samples were measured. Circular Cr/Au electrodes with a diameter of 10 mm were first deposited by sputtering onto the sintered BTO samples as top electrodes. As shown in Figure 10, the dielectric properties were then measured using an Agilent 4294A impedance analyzer. The values of dielectric constant $\varepsilon$ and dielectric loss tangent $\tan \sigma$ of the samples at 1 KHz are 920 and 0.07, respectively. The measured piezoelectric constant ($d_{33}$) of the fabricated samples is around 87pC/N. The measured electromechanical coupling coefficient ($K_t$) is around 0.3. The measured properties compared with those of bulk BTO material are shown in Table I. As can be seen in the table, both curie temperature and electromechanical coupling factor of the 3D printed BTO components are close to the real values of BTO bulk material. The piezoelectric constant is smaller than the true value but is enough for the component to display good piezoelectricity. Both dielectric constant and dielectric loss tangent are influenced by the existing pores in the sintered parts and could be further improved by increasing the final density of the sintered components.

Polarization field (P–E) hysteresis properties were also evaluated using a radiant precision materials analyzer (Radiant Technologies, Albuquerque, NM). Figure 11 shows the ferroelectric hysteresis (P-E loop) of the sintered samples. It can be observed that the P-E loop exhibits good symmetry, which suggests satisfactory ferroelectricity of the fabricated...
samples. The remnant polarization ($P_r$) and the coercive field ($E_c$) are 12.6 μC/cm² and 8.15 kV/cm, respectively.

4.2 An ultrasound transducer fabrication and testing

To further demonstrate the developed AM process, a simple ultrasound transducer was designed and fabricated by using the sintered BTO components as the piezo layer. The structure of the fabricated ultrasound transducer is shown in Figure 12.

The sintered BTO sample has a 0.5 mm aperture with a 340 μm thickness. Poling of the BTO sample was conducted by applying a 2 V/μm polarization voltage field on the transducer at 120°C for 30 min. The acoustic performance of the transducer was measured through a pulse-echo test in a deionized water bath at room temperature. In the pulse-echo test [Figure 12(c)], the transducer is excited by broadband negative pulses emitted from a pulser/receiver unit (Panametrics PR5900, Olympus NDT Inc., Waltham, MA) and generates ultrasonic signal in the degassed water. This ultrasonic signal is transmitted in the water and finally reflected by a quartz. After the echo

<table>
<thead>
<tr>
<th>Piezoelectric and dielectric properties</th>
<th>Printed BTO</th>
<th>Bulk BTO (Lorena and Ricote, 2011; Kim et al., 1998; Bechmann, 1956)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curie Temperature $T$ (°C)</td>
<td>123</td>
<td>120</td>
</tr>
<tr>
<td>Electromechanical coupling factor $K_t$</td>
<td>0.3</td>
<td>0.35</td>
</tr>
<tr>
<td>Piezoelectric constant $d_{33}$ (PC N-1)</td>
<td>87</td>
<td>190</td>
</tr>
<tr>
<td>Dielectric constant $\varepsilon$ (1kHz)</td>
<td>920</td>
<td>1,700</td>
</tr>
<tr>
<td>Dielectric loss tangent $\tan \delta$</td>
<td>0.07</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Figure 11 Polarization – electric field hysteresis loop of sintered BTO samples
signal is received by the transducer, it will be converted into electrical signal, which will consequently be received by the same pulser/receiver unit.

The echo electrical signal is then digitized by a 500 MHz oscilloscope (LC534, LeCroy Corp., Chestnut Ridge, NY). Figure 13 shows the time-domain echo signal and its frequency spectrum. Echo response with an amplitude of 0.11 V (± 0.055 V) can be seen from 2.35 to 2.8 μs, which indicates the fabricated transducer can effectively achieve the conversion between ultrasonic signal and electrical signal. Center frequency \( F_c \) of the transducer can be calculated from frequency \( F_l \) and \( F_h \) at the magnitude of \(-6 \) dB in the frequency spectrum as: \( F_c = F_l + F_h / 2 = 7.2 \) MHz. The bandwidth (BW) of the transducer can be calculated as: \( BW = (F_h - F_l) / F_c \times 100\% = 35.85\% \). According to the center frequency 7.2 MHz and bandwidth 35.85 per cent, it can be suggested that the BTO piezo-based transducer fabricated by the AM process has good potentials to be used for clinic ultrasonic imaging.

5. Conclusions and future work

In the paper, a tape-casting-integrated and projection-based SL process has been presented for the fabrication of piezoelectric components. The developed AM process overcomes the problems of high viscosity and low photosensitivity associated with high solid loading slurry by using a slurry recoating method and a sliding motion design. The debinding and sintering processes have been developed for the fabricated BTO green-parts. Measured dielectric and piezoelectric properties of the sintered samples indicate that the developed AM process can fabricate piezoelectric components to be used in devices such as ultrasound transducers. The new fabrication process would enable novel piezoelectric device designs by using much more complex shapes in the fabricated BTO components.

Compared with the piezoelectric components that are fabricated by the traditional manufacturing processes, the BTO components fabricated the AM process still have inferior piezoelectric properties. At this stage, the final part density is

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**Figure 12** Application of a BTO sample in an ultrasound transducer

**Figure 13** Time-domain response and frequency spectrum of echo signal of the fabricated transducer
restricted by the maximum solid loading of BTO in photocurable resin. To further improve the piezoelectric properties, our future work includes:

- investigating different methods to increase the maximum solid loading of BTO slurry, such as using more powerful light energy, enhancing photosensitivity of BTO slurry, etc.;
- improving poling and electrode plating processes; and
- studying the benefits of using complex geometry in piezo component designs to enhance transducers’ ultrasonic performance.

References


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