



Textured Ceramics for Multilayered Actuator Applications: Challenges, Trends, and Perspectives

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Abstract: Piezoelectric actuators, which utilize piezoelectric crystals or ceramics, are commonly used in precision positioning applications, offering high-speed response and precise control. However, the use of low-performance ceramics and expensive single crystals is limiting their versatile use in the actuator market, necessitating the development of both high-performance and cost-effective piezoelectric materials capable of delivering higher forces and displacements. The use of textured Pb (lead)-based piezoelectric ceramics formed by so-called templated grain growth method has been identified as a promising strategy to address the performance and cost issue. This review article provides insights into recent advances in texturing Pb-based piezoelectric ceramics for improved performance in actuation applications. We discussed the relevant issues in detail focusing on current challenges and emerging trends in the textured piezoelectric ceramics for their reliability and performance in actuator applications. We discussed in detail focusing on current challenges and emerging trends of textured piezoelectric ceramics for their reliability and performance in actuator applications. In conclusion, the article provides an outlook on the future direction of textured piezoelectric ceramics in actuator applications, highlighting the potential for further success in this field.

Keywords: Piezoelectric actuators, Pb-based piezoelectric ceramics, Templated grain growth, Surface grinding, Hysteresis, Thermal stability, Fatigue

1. INTRODUCTION

Piezoelectricity refers to the ability of certain materials, typically ceramics to generate an electric charge in response to an applied mechanical stress or to deform in response to an applied electric field. This property has made piezoelectric ceramics highly desirable for a wide range of applications in

fields such as energy harvesting, sensing, and actuation [1-4]. One of the most common applications of piezoelectric ceramics is available in the form of multilayered ceramic actuators (MLCA), which are used in various fields, including robotics, medical devices, and automotive systems [1,2,5-9]. They are a type of device that excels at converting electric energy into mechanical energy via the piezoelectric effect, resulting in strain output [10-13]. The MLCA has several advantages when compared to electromagnetic actuators for a wide range of applications, especially those that require fast responsiveness, mobility, or noise reduction. Additionally, the absence of electromagnetic interference makes it suitable for

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use in close proximity to sensitive electronic equipment [9,14,15]. Due to these features, piezoelectric actuators are highly attractive for a miniature microactuator, especially in precision applications like lens driving in optical assemblies, micro/nanopositioning in semiconductor and micro-electromechanical system (MEMS) manufacturing, and nano-scanning probes in scanning electron microscopy [8,9,16-19].

In high-precision positioning mechanisms for industrial equipment, piezoelectric multilayered actuators utilizing piezoelectric crystals or ceramics are frequently employed, delivering rapid responses and precise controls [12,18,20,21]. However, their applicability is hampered by the high cost of single crystals, posing a challenge to the actuator market [10-12,22]. To address this issue, the development of cost-effective and improved piezoelectric materials capable of producing higher strain/displacements is in demand.

The electromechanical response of piezoelectric materials depends on a range of factors, including crystal structure, microstructure, composition, and processing conditions [1,23]. Single-crystal piezoelectric materials exhibit higher performance compared to polycrystalline ceramics due to their unique crystal structure and orientation [13,24]. In a single crystal, the orientation of the crystal lattice is uniform throughout the entire material leading to a high degree of anisotropy. As a result, single-crystal piezoelectric materials can achieve higher conversion of electrical energy into mechanical energy and vice versa. On the other hand, polycrystalline ceramics are made up of many small crystals

with different orientations, resulting in a non-uniform distribution of the piezoelectric properties. This leads to lower piezoelectric responses [1]. Overall, the high degree of uniformity of the crystal lattice in single-crystal piezoelectric materials leads to their superior performance compared to polycrystalline ceramics. However, single-crystal piezoelectric materials are more difficult and expensive to manufacture, which limits their use in practical applications. Therefore, attention has been paid to enhancing the properties of polycrystalline ceramics, typically by engineering to obtain uniformity of the crystal orientation between grains of the ceramics, which was possible by various methods to induce a preferred orientation of the grains through crystallographic texturing. Among the traditional methods such as hot-forging and hot-pressing, templated grain growth has emerged as the most promising method for achieving textured ceramics with the highest crystallographic orientation [25,26]. As shown in the schematic Fig. 1(a), templated grain growth involves using templates to direct the growth of ceramic grains along a specific orientation. This method has the advantage of obtaining a high degree of texture, being relatively simple, scalable, and applicable to a variety of ceramic materials [25]. In the case of Pb-based piezoelectric ceramics, usually texturing along the (001) direction has been found to significantly improve their electromechanical properties narrowing the performance gap between polycrystals and single crystals of the same composition [25].

The electromechanical response, specifically the electric

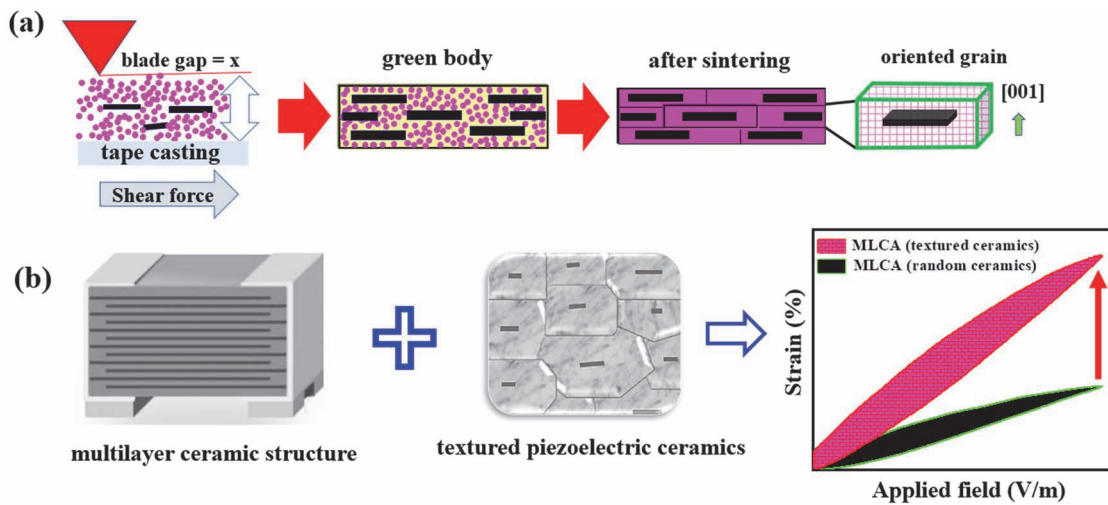


Fig. 1. (a) Conceptual schematic showing how TGG process is realized and (b) a schematic illustrating the impact of the introduced texture on the strain enhancement for MLCA.

field-induced strain, is a critical need in the performance of piezoelectric ceramics for actuator applications [12]. Usually, a high electromechanical response is achieved from a highly textured ceramic structure. Achieving a high degree of texture by TGG methods can be determined by several factors. Generally, in the TGG methods, a small population of anisotropic template particles is dispersed in a fine matrix particle. The templates are aligned during tape-casting, and an epitaxial grain growth from the templates results in a microstructures composed of aligned grains as shown in Fig. 1. The texture quality of the final material is a function of the template crystallographic match with the target material, template alignment along a preferred direction during tape casting, and the sintering conditions, provided that the amount of templates is appropriate and the templates are chemically stable with the target material during sintering [25,27-31]. Tape casting is a commonly used technique for aligning the anisotropic-shaped templates in fine matrix powder. The aspect ratio of the template and the particle size difference between the matrix and the template for optimized tape casting conditions are critical factors that can affect the desired preferred alignment of the template in the fine matrix [25]. Usually, the higher the degree of texture, the more efficient the conversion of electrical energy to mechanical motion, making the material more suitable for actuator applications than randomly-oriented ceramic counterparts as shown schematically in Fig. 1(b). However, texturing Pb-based systems also have potential drawbacks, such as a high sintering temperature of around 1,200°C limiting the use of cheap metal electrodes for making co-fired MLCAs [10], decreased Curie temperature (T_c) due to the remaining templates after sintering limiting their use in high-temperature applications [32], increased hysteresis due to domain wall pinning by the introduced residual template which lowers the electromechanical performance [25]. Therefore, understanding and addressing the effect of these factors are crucial for optimizing their properties and improving their reliability and availability for MLCA applications. In this review paper, we will discuss various textured Pb-based piezoelectric ceramics for MLCA applications and address processing issues on the performance of textured ceramics. We will explore current challenges and emerging trends focusing on the hysteresis, thermal stability, and fatigue resistance of textured piezoelectric ceramics and strategies for

mitigating them. Finally, the article concludes with prospects giving future directions for the continued success of textured piezoelectric ceramics in MLCA applications.

2. TEXTURED CERAMICS IN MULTILAYERED CERAMIC ACTUATORS

Actuators are designed for practical applications in multilayered structures to maximize their electromechanical performance at lower voltage levels [9,10]. Multilayered actuators can be created using either stacking or co-firing process [9,10]. The stacking process involves piezoelectric disks being glued together to form a multilayer, with the stacking axis serving as the linear motion axis when voltage is applied. On the other hand, the co-firing process, which utilizes tape casting methods, uses a single sintering process for a duplex structure composed of a layered stack of tape-cast sheets, with electrodes printed in-between. In this section, we will discuss the MLCAs through co-firing first and then through the stacking process.

2.1 Multilayered textured ceramics actuators through a co-firing process

Typically, Pb-based piezoelectric ceramics are conventionally sintered at temperatures around 1,200°C [10]. To co-fire the ceramic and electrode multilayered stack at the sintering temperature of the ceramics, expensive metal electrodes such as platinum (Pt, melting point 1,768°C) or palladium (Pd, melting point 1,552°C) are required as the electrodes should be stable at the sintering temperature [10]. Using relatively cheaper metal electrodes such as silver (Ag, melting point 961°C) and Ag-Pd alloys (90Ag/10Pd, melting point around 1,000°C) is possible if the ceramic sintering temperature can be lowered [10]. Other much cheaper base metal electrodes such as nickel (Ni, melting point around 1,453°C) and copper (Cu, melting point around 1,084°C) are also available, but the co-firing requires a reducing atmosphere. To make textured piezoelectric ceramics available for use in MLCA with a cheaper metal electrode, the sintering temperature of several textured Pb-based piezoelectric ceramics has been lowered by using various sintering additives [30,33-39]. One such additive is CuO,

which has been shown to accelerate the textured grain growth process by creating a eutectic liquid-phase with PbO at temperatures below 900°C [30,33,34,40]. Yunfei *et al.* [33] reported that the addition of 0.25 wt% CuO to 0.16Pb($\text{Yb}_{1/2}\text{Nb}_{1/2}$) O_3 -0.52Pb($\text{Mg}_{1/3}\text{Nb}_{2/3}$) O_3 -0.32PbTiO₃ (0.16PYN-0.52PMN-0.32PT) ceramics resulted in a high degree of texture (99%) at a low sintering temperature of 975°C, compared to textured samples without CuO sintered at 1,200°C, which only exhibited a degree of the texture of 96%. Similarly, Chang *et al.* [34] also reported the addition of 0.5 wt% CuO to 0.28Pb($\text{In}_{1/2}\text{Nb}_{1/2}$) O_3 -0.40Pb($\text{Mg}_{1/3}\text{Nb}_{2/3}$) O_3 -0.32PbTiO₃ (0.28PIN-0.40PMN-0.32PT) ceramics led to a higher degree of texture (up to 94%) at a sintering temperature of only 960°C for 5 min. Other sintering additives have also been used to assist templated grain growth at lower temperatures. For example, Li₂CO₃ has been successfully used as a sintering aid to obtain sintered random and textured 0.36PIN-0.30PMN-0.34PT piezoelectric ceramics at a sintering temperature as low as 950°C [35]. In addition, fine powder (100 to 200 nm) of a piezoceramic material of 0.4Pb($\text{Mg}_{1/3}\text{Nb}_{2/3}$) O_3 -0.25PbZrO₃-0.35PbTiO₃ (0.40PMN-0.25PZ-0.35PT) and 1 wt% PbO as a sintering additive has been used to fabricate textured ceramics and multilayered actuator using Ag electrode with a high degree of grain orientation at a relatively low sintering temperature of 950°C [36]. In a study conducted by Kim *et al.* [41] multilayered ceramics consisting of five layers of 0.69Pb($\text{Zr}_{0.47}\text{Ti}_{0.53}$)-0.31Pb[($\text{Zn}_{0.4}\text{Ni}_{0.6}$) $_{1/3}\text{Nb}_{2/3}$] O_3 (0.69PZT-0.31PZNN) thick films and 80Ag/20Pd internal electrodes were sintered at 950°C. As reported [41], the use of 80Ag/20Pd electrodes coated on the PZT-PZNN thick films considerably assisted the texturing process and an actuator fabricated using textured ceramics exhibited 28% higher displacement due to the high strain response at the same applied field level. These works suggest the promising results of using textured ceramics for high-performance actuator applications. Therefore, developing a wide range of low-temperature sintered textured ceramics could be beneficial to enable the use of inexpensive metal electrodes during co-firing process.

2.2 Multilayered textured ceramic actuators formed by stacking process

A stacking process is another typical approach for making

multilayered ceramic actuators [10], which involves grinding or surface polishing sintered ceramic discs and then electrodes and gluing them together in alternating directions. This process offers the advantage of not requiring high-temperature heat treatment after electrode pasting, allowing a wider range of electrode materials to be used. However, the grinding or surface polishing can introduce a mechanical strain to the near-surface of the ceramic samples, which is detrimental to their piezoelectric properties [42-45]. Previous research on polycrystalline ceramics has shown that thermal annealing can remove the induced mechanical strain [44,45]. Therefore, before using the ground ceramic discs, it is important to investigate the optimum annealing temperature at which all stored strains during grinding are removed.

Textured Pb-based multilayered ceramics actuators formed by the stacking process have not been reported to the best of our knowledge and there is currently no research on how surface grinding affects the piezoelectric properties of textured ceramics. Here, we investigated the effect of surface grinding on the electrical properties of textured 0.4PMN-0.22PZ-0.38PT ceramics and compared them with those of random ceramic counterparts. Detailed information on textured 0.4PMN-0.22PZ-0.38PT ceramics can be found in the reference [46]. The textured 0.4PMN-0.22PZ-0.38PT exhibited a field-induced unipolar strain of 0.26% at 2 kV/mm. The surface grinding on both sides of the flat surface of the disc pellet samples was performed using 800 grits SiC papers [44] at 100 rpm using a grinding and polishing machine, where the as-sintered samples with a thickness of 1 mm were ground to 0.25 mm. Then, the samples were subjected to various thermal treatments from 600°C to 1,200°C. X-ray diffraction was used to determine the level of induced strain. In addition, the field-induced strain of the samples was determined using a laser displacement sensor (aixACCT Systems GmbH 2013, Germany).

The X-ray diffraction patterns for random and textured 0.4PMN-0.22PZ-0.38PT ceramics annealed at different temperatures, 600°C to 1,200°C for 1 h are shown in Fig. 2. The main peak around 2θ of 31° for the random ceramic and 44.5° for the textured ceramic were selected shown in magnified insert [see Fig. 2(a) and (b)] to analyze the mechanical strain induced by grinding. As shown, the degree of peak broadening decreases as the annealing temperature increases. The observed peak broadening could be due to the

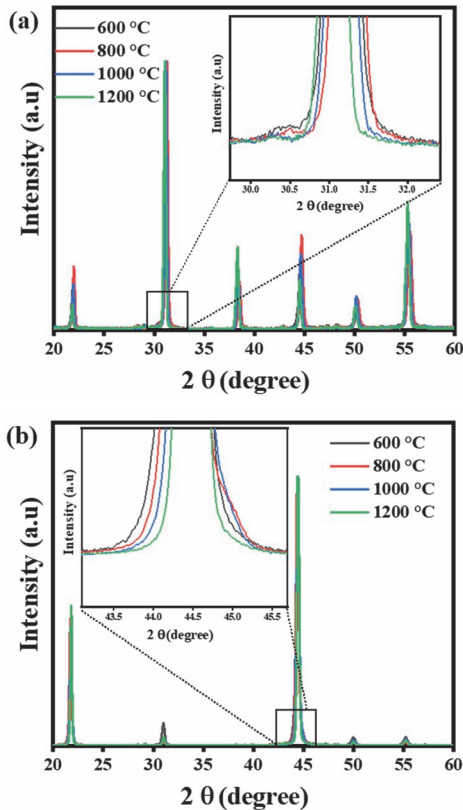


Fig. 2. X-ray diffraction patterns for (a) random and (b) textured 0.4PMN-0.22PZ-0.38PT ceramics annealed at different temperatures (600 to 1,200°C). The main peak around 2θ of 31° for the random ceramic and 44.5° for the textured ceramic are shown in magnified inserts.

induced microstrain in the sample [47,48]. To further confirm the difference in the peak broadening for both random and textured samples, the full-width at half maximum (FWHM) analysis was performed using Gaussian fitting [47,48]. The FWHM is a measure of the width of the peak at half of its maximum intensity and can be used to determine the degree of peak broadening [47,48]. As shown in Fig. 3, the FWHM analysis indicates that the textured samples exhibit a relatively higher drop in the peak broadening compared to the random sample as the annealing temperature increases. This observed difference could be attributed to the difference in the crystal orientation of the textured and random samples. The textured sample has a preferred crystallographic orientation along the (001) direction, which results in a higher degree of crystallographic anisotropy in the material. The grinding process introduces mechanical strain into the material, which affects the crystal structure and may result in peak broadening.

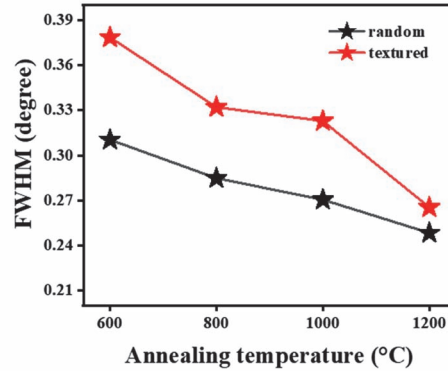


Fig. 3. The full-width at half maximum (FWHM) of X-ray diffraction peaks obtained by Gaussian fitting of the magnified peak around 2θ of 31° for random and textured around 2θ of 44.5° of 0.4PMN-0.22PZ-0.38PT ceramics, which were annealed at various temperatures ranging from 600 to 1,200°C.

Therefore, the textured sample, which has a more anisotropic crystal structure, could be more susceptible to the effects of mechanical strain and exhibits a higher degree of peak broadening compared to the random sample.

In Fig. 4(a), the changes in the degree of microstrain with respect to the annealing temperature of random and textured 0.4PMN-0.22PZ-0.38PT ceramics annealed from 600°C to 1,200°C for 1 h are shown. The microstrain in this case is the strain caused by the mechanical grinding or surface polishing of the samples. It is calculated using the Debye-Scherrer equation: $\epsilon = B/4 (\tan\theta)$, where ϵ is the microstrain, B is the full width at half maximum of the diffraction peak, and θ is the Bragg angle. As mentioned earlier, the FWHM analysis in Fig. 3. indicates that the textured sample exhibits a higher degree of peak broadening compared to the random sample. This observation is in agreement with the drop in the microstrain as the annealing temperature increases, which is more significant in the textured sample compared to the random sample. The decrease in microstrain is attributed to the removal of induced mechanical strain during grinding by the thermal annealing process. In Fig. 4(b), the variations in the field-induced unipolar strain of random and textured 0.4PMN-0.22PZ-0.38PT ceramics upon annealing from 600°C to 1,200°C for 1 h are shown. In both samples, the field-induced unipolar strain increases with increasing annealing temperature. A larger variation is observed in the textured sample, and typically annealing above 1,000°C results in a significant increase in the unipolar strain, which is consistent with the decreased

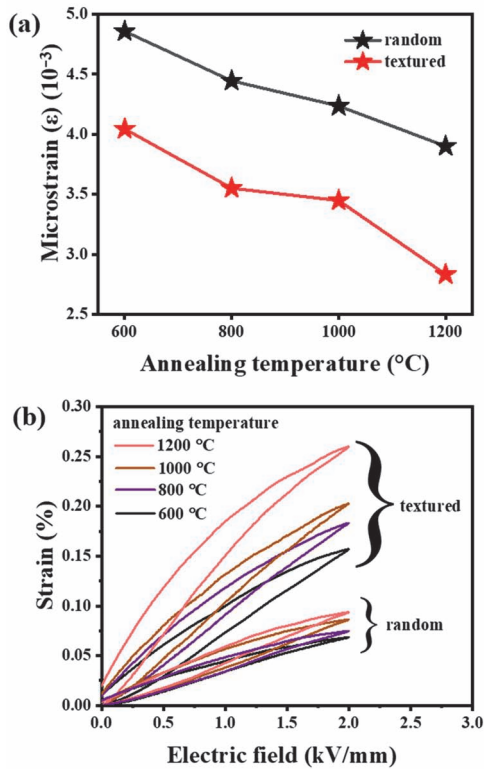


Fig. 4. (a) The changes in microstrain with respect to the annealing temperature of random and textured 0.4PMN-0.22PZ-0.38PT ceramics annealed from 600°C to 1,200°C for 1 h and (b) the variations in the field-induced unipolar strain of random and textured 0.4PMN-0.22PZ-0.38PT ceramics upon annealed from 600°C to 1,200°C for 1 h.

microstrain as the annealing temperature increases.

In summary, we investigated the effect of surface grinding on the electrical properties of textured and random 0.4PMN-0.22PZ-0.38PT ceramics and compared them with those of random ceramic counterparts. The results indicate that the grinding process introduces mechanical strain into the material as confirmed by X-ray diffraction peak broadening. The textured sample, which has a more anisotropic crystal structure, is more susceptible to the effects of mechanical strain and therefore exhibits a higher degree of peak broadening compared to the random sample as confirmed by the larger decrease in FWHM, i.e., microstrain. Thanks to the thermal annealing process, which was found to remove the induced mechanical strain during grinding, mechanically-induced microstrain can be practically removed, leading to an increase in field-induced unipolar strain. Future research may focus on optimizing the grinding and thermal annealing

process to achieve even better results to minimize the negative effects of mechanically-induced strain on the piezoelectric properties of textured ceramics.

3. CURRENT CHALLENGES AND EMERGING TRENDS

3.1 Hysteresis in textured ceramics

Piezoelectric materials exhibit a hysteresis behavior, which means that their strain response depends not only on the current electric field but also on their history of electric-field exposure [49]. The hysteresis in this case describes the relationship between the electric field and strain response during both the loading and unloading phases. Polycrystalline piezoelectric ceramics typically have a broader and less well-defined hysteresis loop than single-crystal due to variations in the polarization and strain response caused by multiple randomly oriented grains [50]. In contrast, single-crystal ceramics exhibit a narrower and more well-defined hysteresis strain due to the absence of grain boundaries and crystallographic variations [50]. Hysteresis can have positive or negative effects on the performance of piezoelectric actuators depending on the type of application. In vibration control or noise reduction applications, hysteresis can help to dampen mechanical vibrations and provide a smoother response [51,52]. In contrast, hysteresis can lead to inaccuracies and errors in applications requiring precise control or positioning [53-55].

The use of templated grain growth methods to produce crystallographically textured ceramics with preferred orientations has advantages in enhancing performance. However, the presence of embedded template grains can increase hysteresis by acting as barriers to the movement of domain walls [56,57]. While techniques exist to mitigate the effects of hysteresis, such as the use of feedback control systems to correct hysteretic errors [58], one approach to reducing hysteresis in textured ceramics would be to optimize the template amount as minimum as possible for texturing while maintaining a high degree of texture [56,57].

Here, we investigated the effect of thermal annealing of surface ground samples on the hysteresis of both textured and random polycrystalline piezoelectric ceramics, as discussed in

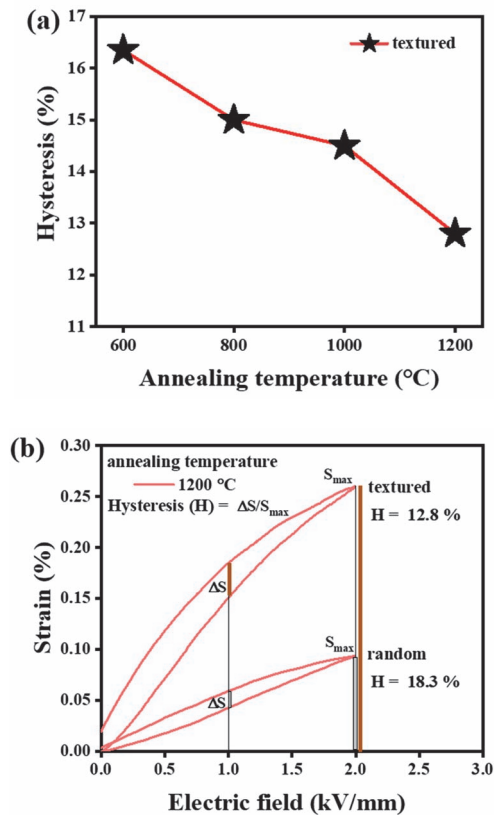


Fig. 5. (a) Comparison of the hysteresis level between random and textured 0.4PMN-0.22PZ-0.38PT ceramics after annealing at annealing 1,200°C for 1 h and (b) the variations of hysteresis in textured 0.4PMN-0.22PZ-0.38PT ceramics upon annealing from 600°C to 1,200°C for 1 h.

the previous section 2.2. The hysteresis was measured during unipolar strain cycles, defined as the strain difference at half the maximum applied electric field divided by the maximum strain as shown in Fig. 5(b). The result showed that for the textured sample, the hysteresis decreased from 16.35% to 12.8% as the annealing temperature increased from 600°C to 1,200°C as shown in Fig. 5(a). This suggests that surface grinding not only degrades the strain level but also increases hysteresis. In Fig. 5(b), we compared the hysteresis strain of both random and textured 0.4PMN-0.22PZ-0.38PT ceramics annealed at 1,200°C for 1 h. Despite the presence of embedded templates in the textured sample [as shown in Fig. 6(a)], the hysteresis of the random sample was much higher at 18.3%, compared to the textured sample at 12.8%. We speculate that this could be due to the large grain size difference between the two samples as shown in Fig. 6(a) and (b). The random ceramics have much smaller grains which may lead to domain

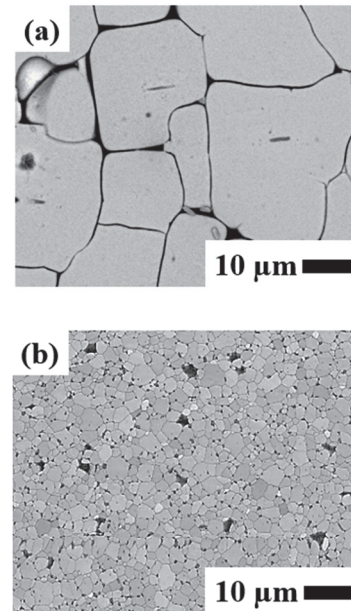


Fig. 6. Cross-section microstructure of (a) polished and etched textured and (b) random 0.4PMN-0.22PZ-0.38PT ceramics.

wall pinning by the grain boundary effects that may have overcome the effects in the textured ceramics [59-61].

3.2 Curie temperature/thermal stability of textured ceramics

The T_C is a critical temperature above which piezoelectric materials lose their piezoelectricity. In the case of Pb-based ceramics, which have typically a higher T_C than widely used BaTiO₃ (BT) templates, when textured by TGG methods, the T_C of the resulting textured ceramics tends to decrease as the BT content increases [46]. Therefore, it is important to optimize the minimum possible amount of templates added for texturing to minimize the decrease in T_C [60]. Usually, between 3 to 5 vol% of BT templates are used for texturing Pb-based material systems. Recently, Yang *et al.* [60] reported textured PMN-0.28PT ceramics with a degree of texture at 99% by using only 1 vol% BT templates with 0.25 wt% CuO/B₂O₃ sintering aids. Yan *et al.* [61] reported textured 0.675PMN-0.325PT ceramics with a high degree of texture at 98% using only 1 vol% BT template. Additionally, Yang *et al.* [62] reported textured Pb(In_{1/2}Nb_{1/2})O₃-Pb(Sc_{1/2}Nb_{1/2})O₃-PbTiO₃ (PIN-PSN-PT) ceramics containing a rare-earth component Sc₂O₃, which was found to increase the

rhombohedral-tetragonal phase transition temperatures (T_{rt}) of the system leading to enhanced thermal stability. Several studies have investigated the thermal stability of textured ceramics, particularly in relation to their application as actuators [63-66]. For example, Liu *et al.* [65] reported enhanced thermal stability in Cu-modified textured 0.42PMN-0.25PZ-0.33PT ceramics. Yan *et al.* [63] also reported that a rather inferior thermal stability of MnO₂-doped textured 0.40PMN-0.25PZ-0.35PZT could be improved by poling the ceramic at a higher temperature of 140°C which helped to reduce the interface region volume formed in the vicinity of BT templates.

Given that comparing the temperature-dependent electro-mechanical properties of both textured and random ceramics of the same composition would give clarity on the impact of texturing on the thermal stability of the material, we compared the field-induced strain of randomly oriented and textured 0.4PMN-0.22PZ-0.38PT ceramics [46] at different temperatures. We measured the strain of both ceramics at temperatures of 50°C, 150°C and 200°C as shown in Fig. 7. The amplitude of the electric field was fixed at 2 kV/mm for all measurements. The strain in the textured ceramic decreased from 0.25% at 50°C to 0.236% at 150°C and 0.225% at 200°C, while the strain in the randomly oriented ceramic increased from 0.099% at 50°C to 0.137% at 150°C and 0.146% at 200°C. This can be explained by the fact that the textured ceramic had a lower T_c compared to the randomly oriented ceramic (T_c of 230°C and 260°C, respectively), which means that the textured ceramic may have shown the decreased strain due to a partial depolarization of domains because of the testing temperatures being close to its T_c [46]. In contrast, the randomly oriented ceramic was still far from its T_c and therefore exhibited an increase in a strain which could be due to the contribution at higher temperature associated with the thermally activated domain motion which may have been pinned at room temperature [67]. Moreover, it is worth noting that the variation in the maximum strain with temperature in the case of randomly oriented ceramics (at 4.7%) is significantly higher compared to the textured sample (at 2.35%) as can be seen from Fig. 7(a) and (b). This indicates that the thermal stability of the textured ceramics is higher, as the strain variation with temperature was relatively small. This can be attributed to the ease of domain rotation in textured ceramics because the oriented grains are in the direction of the

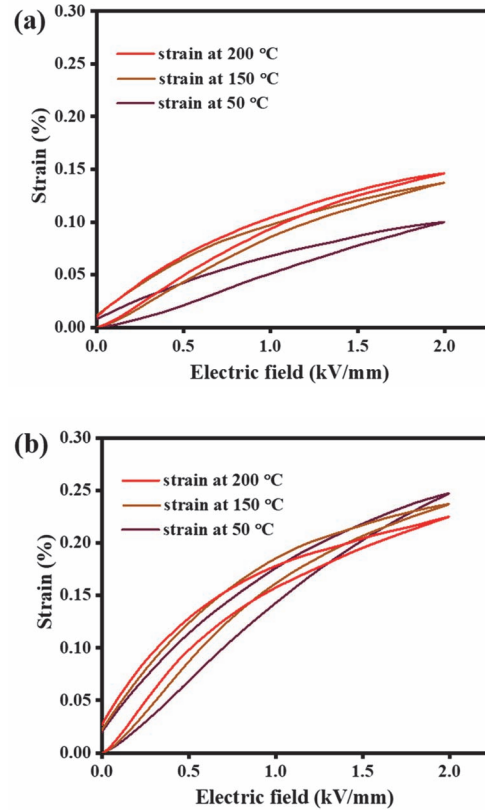


Fig. 7. Strain cycle of (a) random and (b) textured 0.4PMN-0.22PZ-0.38PT ceramics measured at different temperatures of 50°C, 150°C and at 200°C.

applied external electric field [25,46,68,69] leading to smaller susceptibility to thermal fluctuations compared to the randomly oriented ceramic. Overall, the thermal stability of textured ceramics is promising for developing high-performance actuators for high-temperature applications.

3.3 Fatigue resistance of textured ceramics

Fatigue resistance refers to the ability of a material to withstand repeated stress or strain cycles without failure. In the ceramic's actuator applications, fatigue resistance is crucial as the material is subjected to a large number of electric field-induced strain cycles during its lifetime [70-73]. The repeated cycles of stress and strain can cause microcracks to form in the material, which can eventually lead to failure [74]. Therefore, it is important to study the fatigue resistance of textured ceramics to ensure their long-term performance in actuator applications. Studies on the fatigue resistance of

textured ceramics have shown that the textured materials exhibit superior performance compared to their untextured counterparts. For example, Liu *et al.* [73] reported that the field-induced unipolar strain of textured 0.42PMN-0.25PZ-0.33PT ceramics was maintained up to 10^6 cycles, while the untextured counterpart exhibited 14% degradation. As reported [73] the unipolar fatigue resistance of the textured ceramics is of the inherent fatigue anisotropy, weakened local bias fields, and increased intrinsic contribution due to more tetragonal content coming from the added tetragonal BT templates. The temperature dependence of the fatigue behavior of textured ceramics could also impose a significant concern for actuator applications. Here, the temperature-dependent fatigue behavior of a textured 0.4PMN-0.22PZ-0.38PT ceramics was measured using the samples obtained from reference [46]. The strain response was measured after 10 cycles and after 500,000 cycles at both 25°C and 150°C. The rate of cycling, the amplitude of the electric field, and the loading frequency were all kept constant. Results showed that

the strain response of the material decreased by approximately 11% at 25°C and 7% at 150°C after 500,000 cycles as shown in Fig. 8. which could be due to ease of domain wall motion at higher temperatures associated with the thermal activation [67,75].

4. CONCLUSION AND PROSPECTS

The development of textured ceramics has shown promising results for high-performance actuator applications. To make a wide range of textured materials available for multilayer ceramic actuator (MLCA) applications, reducing their sintering temperature would be potential advancement for using cheap metal electrodes during the co-firing process. The process of producing multilayered ceramic actuators through stacking requires grinding or surface polishing which may introduce mechanical strain to the ceramic samples, which affects their piezoelectric properties. To overcome this, thermal annealing can be used to remove the induced mechanical strain before using the ground ceramic discs. Templated grain growth methods can produce textured ceramics with a preferred orientation, which can enhance performance but also increase hysteresis by acting as barriers to the movement of domain walls. To reduce hysteresis in textured ceramics, optimizing the minimum possible amount of templates added for texturing while maintaining a high degree of texture could be an effective approach. Understanding and mitigating hysteresis in piezoelectric materials is crucial for improving their performance in high-precision positioning applications. Moreover, optimizing the minimum possible amount of templates added for texturing or advances in the development of templates that will not decrease the T_C of textured ceramics is needed for maintaining the performance at high-temperature application areas of actuators. Additionally, the thermal stability of textured ceramics has been investigated, and textured ceramics have been found to exhibit higher thermal stability compared to randomly oriented ceramics, which is promising for developing high-performance actuators for high-temperature applications. Fatigue resistance is a critical factor for the long-term performance of piezoelectric ceramics in actuator applications. Textured ceramics have been found to exhibit superior fatigue resistance compared to untextured

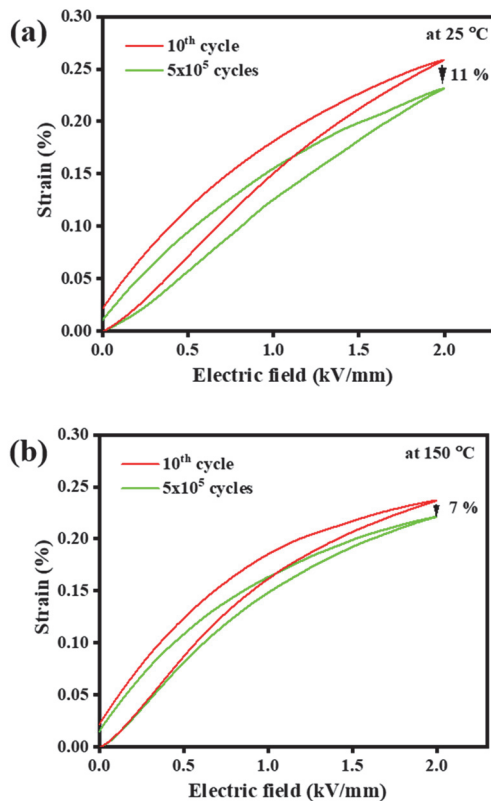


Fig. 8. Strain cycle of textured 0.4PMN-0.22PZ-0.38PT ceramics measured at (a) 25°C and (b) 150°C (10th cycle).

counterparts. However, the temperature dependence of fatigue behavior could pose a significant concern for actuator applications. Overall, future advancement in exploring and understanding low-temperature sintering approaches, surface grinding, hysteresis, thermal stability, and fatigue for better performance of textured piezoelectric ceramics is crucial for improving their reliability in actuator applications.

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