Fracture study of piezoelectric materials: a brief state of the art

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Abstract. Piezoelectric materials are intelligent materials which can realize the mutual conversion of mechanical and electrical energy and have been widely used in many fields. Due to their brittleness, these materials are prone to cracking under external loadings. In this work, a brief overview of the current states on the fracture of piezoelectric materials is presented from experimental, theoretical and computational aspects, and then some future work is suggested.

1. Introduction

In 1880, the brothers Curie found the piezoelectric effect which includes both the direct and inverse piezoelectric effect[1]. The former effect means that while some dielectrics are deformed by an external force, polarization will occur inside, and the voltage will appear on the two opposite surfaces. On the contrary, mechanical deformation will occur when dielectric body is subjected to applied electric field, known as the inverse piezoelectric effect. The common piezoelectric materials mainly contain piezoelectric crystals, ceramics and polymers. Profiting from the inherent coupled electro-mechanical effect, piezoelectrics have been broadly utilized in the components of various engineering structures, e.g., sensors (see figure 1) and actuators (see figure 2).

Figure 1. Piezoelectric sensor in smart cell phone.

Figure 2. Piezoelectric ceramic in motor actuator.

Although bearing excellent electro-mechanical performances, the piezoelectric materials are brittle and easy to crack (see figure 3 for the cracking of a piezoelectric film). Cracks may occur during the manufacture process or in service under mechanical, electric or thermal loadings, which will affect the performance and life of piezoelectric materials, and, more seriously, even cause them to fail prematurely. Therefore, the research on the fracture of such materials is of extreme significance.
Herein, the current states on related subject are concisely introduced from three aspects, i.e., experimental, theoretical and computational. Besides, the work that deserves to be further developed is also put forward.

![Crack initiation and growth in polyimide-supported indium tin oxide film](image.png)

**Figure 3.** Crack initiation and growth in polyimide-supported indium tin oxide film[2].

### 2. Typical work about the fracture of piezoelectric materials

#### 2.1. Experimental work
Some researchers focused on experimental methods to intuitively demonstrate the fracture phenomena of piezoelectric materials. Wang and Singh [3] adopted the Vickers indentation method to investigate the crack evolution of a piezoelectric lead-zirconium-titanate (PZT) subjected to mechanical loadings as well as electric fields. Focusing on electrically-insulated cracks, Zhang and Gao[4] carried out various fracture tests for piezoelectric solids. Bermejo et al.[5] examined the fracture resistance of a PZT under both thermal and mechanical loadings ranging from room temperature to 400 °C. Peng et al.[2] tested the electro-mechanical behaviors of the indium tin oxide thin films deposited on polymer substrates via a scanning electron microscope. Shindo et al.[6] executed three-point bending tests to study the static fatigue of piezoelectric ceramics with preset crack under cryogenic condition. Abuzaid et al.[7] experimentally conducted the piezoelectric active repair for edge-cracked plate under pure tension. Li et al.[8] inspected the temperature-dependent fracture of unpolarized and polarized piezo-ceramics using several test techniques.

#### 2.2. Theoretical work
Compared to experimental work, analytical methods are more widely adopted due to their lower cost and the ability to obtain closed-form solutions. Pak[9] generalized the linear elastic fracture theory to handle with cracks in piezoelectric domain through the the distributed dislocations approach together with the electric dipoles method. Wang[10] took the model of strip electric saturation to investigate the fracture problem of piezoelectric bodies. Gao et al.[11] checked the energy release rates (ERR) and the $J$-integral of a piezoelectric solid with an electrically insulated crack by the analytic solutions. Boldrini and Viola[12] obtained the closed-form results for cracks in an infinite piezoelectric domain under
electro-mechanical loading with the spectral approach. Wang and Han[13] revealed influences of internal cracks on the effective characteristics of piezoelectrics by the singular integral method. Bhargava and Jangid[14] combined the Stroh formula with the complex variable method to look into fracture of a piezoelectric body. Zhao et al.[15] applied the bi-layer beam model to analyze fracture of two-phase piezoelectric materials with interfacial cracks under mechanical/electrical loading. Yang and co-authors[16] utilized the Stroh formulism and conformal mapping method to analyze unsymmetrical cracks from an elliptical void in 1D hexagonal piezoelectric quasi-crystals. Using the singular integral approach, Zhou and Kim[17] discussed the stress intensity factors (SIFs) in piezoelectrics containing a thermal dielectric crack. Through the extended Lekhnitskii-Eshelby-Stroh equation, Hrstla et al.[18] investigated piezoelectric sharp notches of different geometry with interfacial cracks.

2.3. Computational work

The experimental methods require advanced test equipments and techniques, while the analytical ways are generally limited to some simple problems. In contrast, the numerical approaches are more suitable for extensive fracture problems resulting from their powerful adaptability and relatively low cost as well. Kumar and Singh[19] inspected the influences of external loadings on the SIFs and crack propagation in a piezoelectric ceramic via the finite element method (FEM). Abendroth and co-authors[20] computed 2D/3D electro-mechanical J-integral with a commercial FEM code. Narita et al.[21] used the nonlinear FEM to inspected the delayed cracking and localized poling around crack tips in piezo-ceramics. Through the FEM, Shindo et al.[22] considered the mode-I cryogenic crack in a piezoelectric rectangular body subjected to electro-mechanical loading. Fan et al.[23] obtained the SIFs of piezoelectric materials with cracks using the FEM. Sladek et al.[24] made use of the FEM to study planar cracking of piezoelectric media. Brusa and Sari[25] predicted the fracture behavior for piezoelectric materials with the FEM. Chen and Wang[26] proposed a micro-mechanical multi-physics FEM to investigate partly cracked interface in monodirectional piezoelectric composites. Pan[27] provided a 2D boundary element method (BEM) for the fracture simulation of cracked anisotropic piezoelectrics. Combining the BEM with the finite-part integral method, Qin et al.[28] probed the 3D fracture of a piezoelectric infinite medium. Pasternak[29] incorporated the integral equation approach into the BEM to gain the determination of 2D piezoelectric solids containing both cracks and inclusions. Lei et al.[30] detected the effects of the polarization direction and other factors on dynamic SIFs of piezoelectric interfacial crack through the BEM. Zhang et al.[31] used the BEM to deal with cracks of a finite piezoelectric plate. Lei and Zhang[32] implemented the BEM to evaluate the ERR and SIFs in piezoelectric materials including kinked cracks. Wunsche et al.[33] investigated micro cracks of 2D fiber-reinforced piezoelectric composite materials through a symmetric Galerkin time-domain BEM under transient dynamic conditions. Guo and Fang[34] investigated interfacial cracking of bi-piezoelectric materials by virtue of the element-free Galerkin method (EFG). Sladek et al.[35-37] adopted the meshless local Petrov-Galerkin approach in the cracking study of piezoelectric media. Meng[38] modeled the cracked functionally graded piezoelectric materials with an enriched EFG. Li and Zhou[39] carried out electro-mechanical coupled fracture analysis in piezoelectric materials with the EFG. Bechet et al.[40] applied new enriched functions to simulate the crack problem of piezoelectrics in the extended FEM (XFEM). Bui and Zhang[41] considered transient dynamic stationary cracks in piezoelectric materials by virtue of the XFEM. Liu et al.[42] took the XFEM to simulate transient fracture of functionally graded piezoelectric materials subjected to thermal shock. Zhang et al.[43] searched dynamic cracks in 2D piezoelectric materials by the XFEM. Also through the XFEM, Mishra and Burela[44] investigated fatigue crack propagation in piezoelectric materials under coupled thermo/electro/mechanical environment. Xu et al.[45] combined the XFEM with the extended layerwise approach to cope with fracture of laminated piezoelectric and composite plates.
3. Concluding remarks
Attributing to their outstanding electro-mechanical performances, piezoelectric materials occupy a significant place in engineering applications, and there is no shortage of them in the high-tech fields. As brittle materials, they are extremely sensitive to cracking. Consequently, the essentiality of the fracture research of these materials is naturally self-evident. In this article, we briefly summarized some published studies about the fracture of piezoelectric bodies using experimental, theoretical or computational methods. Although plenty of achievements have been reached in the past decades, many topics should still be further concerned in the near future, for example,

1. Development of advanced and versatile experimental tools and setups to capture the fracture characteristics (e.g., fracture toughness and crack trajectory) with higher convenience, wider applicability, higher precision and lower cost;
2. Development of more universal, more straightforward and more accurate fracture analysis theories (e.g., fracture parameters, fracture criteria and crack growth rules) for various types of piezoelectrics;
3. Development of new solution schemes in conjunction with artificial intelligent techniques (e.g., combination of the FEM, BEM, EFG, the XFEM and the phase-field fracture method with the artificial neural network);
4. Development of advanced numerical methods with higher efficiency, applicability and accuracy (e.g., multi-scale computational methods, coupled numerical tools among existing methods multi-field coupling modeling approaches);
5. Development of more advanced piezoelectric materials (e.g., better piezoelectric coupling effects, higher ductility and fracture toughness) based on the accumulated fracture database through the combination of experimental and machine learning approaches.

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