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An electrode analysis for multilayer ceramic actuators

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Abstract

Electroelastic field concentrations ahead of electrodes in multilayer piezoelectric actuators are examined. By considering a representative unit in real multilayer actuators, the problem is formulated directly in terms of the electric potential between the electrode tips, results in a hyper-singular integral equation in which the unknown function is the electric potential. The analysis model is validated by comparison with a 2D finite-element analysis. The influence of the piezoelectric coupling coefficients on the field intensity factors is significant, suggesting that fully coupled electromechanical model established in this paper is worthwhile. The horizontal electric field component ahead of the electrode tips is highly singular. Since the stresses and electric displacements are singular behind the electrode tips, possible debonding between the electrodes and the piezoelectric medium needs to be considered when designing multilayer actuators.

Keywords: Actuators; Electrodes; Piezoelectric; Multilayer; Fracture mechanics

1. Introduction

Due to their high electromechanical coupling effect, piezoelectric materials are widely used in multilayer actuators, sensors, controlling devices, smart and intelligent structures. In order to address the issues concerning durability and reliability of these piezoelectric devices, fracture (failure under monotonic mechanical and electrical loads) behaviors of piezoelectric materials should be investigated and understood thoroughly. These multilayer structures are operated under increasing high electric and mechanical loads. The electric fields are applied to the piezoelectric materials through internal or external electrodes. The electroelastic interaction of piezoelectric ceramics with electrodes is of great importance. Accordingly, there is a need to investigate the effects produced by electrodes in order to understand the mechanical and electric failure phenomena and to improve the reliability of the devices.

In recent years, the study of interactions between the electrodes and piezoelectric ceramics has been the subject of increasing interest. Theoretical investigation and experimental analysis suggest that cracks may initiate and grow in piezoelectric ceramics under the application of mechanical and/or electrical loads [1–4]. Experimentally, observations show that interfacial cracking between electrode and piezoelectric ceramic is a common case of failure in multilayer piezoelectric devices [5]. Theoretically, investigations demonstrate that the edge of the electrode is a potential position of high stress and electric field concentrations [6,7]. For piezoelectric materials containing multilayered internal electrodes, electric field and elastic fields induced by quadratic electrostriction have been obtained via an analytic approach and the finite element method [8,9]. The in-plane electroelastic fields in a finite electrode layer embedded at the interface between two piezoelectric half planes were investigated by using the complex variable technique [10]. Electric-field induced interfacial cracking in multilayer electrostrictive actuators was studied in [11]. Later, an approximate solution to the in-plane electric field and stress concentration near electrode tip attached to the surface of the piezoelectric strip was provided [12] based on the iteration method. Recently, Chen and Chue studied a

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piezoelectric strip with a semi-infinite electrode [13]. Both anti-plane deformation with in-plane electrical field and in-plane electroelastic field were considered. Shindo et al. [14] investigated the fracture behavior of a piezoelectric ceramic under applied electric fields through experimental and theoretical characterizations. The modified small punch (MSP) tests were performed on a commercial piezoelectric ceramic. The fracture initiation loads under different electric fields were obtained from the experiment. A procedure is presented for determining the fracture and polarization switching properties due to electrical effects by experimental and theoretical means. Li and Lee [15] made a three-dimensional electroelastic analysis for a penny-shaped thin electrode coating on the surface of a hexagonal piezoelectric half-space. It was found that, in addition to electric displacement and electric field, elastic stresses exhibit singular behavior near the electrode edge. Narita et al. [16] investigated the static behavior of the elastic and electric variables in the vicinity of an internal electrode embedded at the interface of two dissimilar piezoelectric half-planes. Shindo et al. [17] performed a theoretical and experimental study to electrodes in multilayer piezoelectric actuators. Yang [18] presented a study on the electromechanical interaction between a compliant surface electrode and a semi-infinite piezoelectric material. It was shown that for surface electrode subjected to uniform displacement, the normal stress at the edges of the electrode displays a square root singularity, which may eventually induce the initiation of crack and introduce mechanical and electric instability. A circular surface electrode on a piezoelectric layer was considered and exact expressions for the electromechanical field near the electrode front are given [19].

The focus of this paper is the development of an analytical model to predict the electroelastic concentrations near the electrode tips in multilayer piezoelectric ceramic actuators. A representative element of a multi-electrode real multilayer piezoelectric actuator is considered. The resulting model is validated by comparison with a 2D finite-element analysis. The influences of piezoelectric coupling and electrode spacing are investigated. Possible crack initiation behavior near the electrode tips is discussed. Closed-form expressions for the electromechanical field near the electrode tips are given. Exact solution for dielectrics (in which there is no piezoelectric coupling) is obtained.

2. Description of the problem

Fig. 1 shows a typical unit in real piezoelectric ceramic multilayered actuators. Poling directions of the upper layer and the lower layer are opposite; h is the electrode spacing; the electrodes at $x = h$ are grounded, while the electrodes at $x = 0$ are maintained at a constant electric potential V_0 and are separated by a distance $2a$. The anti-plane problem for this configuration has been studied by He and Ye [20] and Li and Duan [21]. In this paper, we will concentrate on the in-plane electromechanical problem.

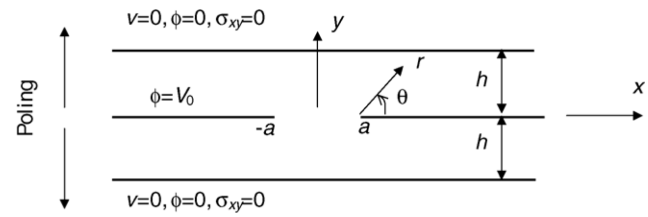

Fig. 1. A representative unit in real multilayer piezoelectric actuators. The poling directions of the upper layer and the lower layer are opposite so that the vertical displacements (y-direction) in adjacent layer can be accumulated; h is the electrode spacing; electrodes at $y = \pm h$ are grounded; electrodes at $y = 0$ are maintained at a constant electric potential V_0 and are separated by a distance $2a$. The anti-plane problem for this configuration has been studied by He and Ye [20] and Li and Duan [21].

Referring to Fig. 1 for the definition of the coordination system (x, y), the elastic stresses and electric displacements for piezoelectric ceramics, poled along the positive y-axis, are related to the strain and electric fields through:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \\ D_x \\ D_y \end{Bmatrix} = \begin{bmatrix} c_{11} & c_{13} & 0 & 0 & -e_{31} \\ c_{13} & c_{33} & 0 & 0 & -e_{33} \\ 0 & 0 & c_{44} & -e_{15} & 0 \\ 0 & 0 & e_{15} & \epsilon_{11} & 0 \\ e_{31} & e_{33} & 0 & 0 & \epsilon_{33} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ 2\varepsilon_{xy} \\ E_x \\ E_y \end{Bmatrix}, \quad (1)$$

where σ_{ij} and D_i (i, $j = x$, y) are stresses and electrical displacements; c_{ij}, e_{ij} and ϵ_{ii} are elastic constants, piezoelectric constants and dielectric permittivities, respectively; and ε_{ij} and E_i are, respectively, strains and electrical fields, which are related to the displacements and electric potential through:

$$\varepsilon_{ij} = \frac{u_{i,j} + u_{i,j}}{2}, \qquad E_i = -\phi_{,i}, \quad (2)$$

in which the summations over the indices i and j are assumed when appearing twice on left-hand side of an equation (i, $j = x$, y), u and v are the x-direction and y-direction components of the displacement vector; ϕ is the electric potential. In the absence of body forces and body charges, the equilibrium equations for the piezoelectric media are:

$$\sigma_{ij,j} = 0, \qquad D_{i,i} = 0. \quad (3)$$

Eq. (3) can be expressed in terms of displacements and electric potential with the substituting of Eqs. (1) and (2).

On the $y = 0$ plane, the normal displacement is constrained and the region betweens the electrode tips are electrically insulated. Because of the symmetry, the normal component of the electric displacement is zero. Further, the electric potential on the electrodes on $y = 0$ are prescribed as V_0. Then, the mixed boundary conditions on the $y = 0$ plane can be stated as follows:

$$v(x, 0) = 0, \quad |x| \geq 0, \quad (4)$$

$$D_y(x, 0) = 0, \quad |x| < a, \quad (5a)$$

$$\phi(x, 0) = V_0, \quad |x| > a. \quad (5b)$$