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Interaction of a conductive crack and of an electrode at a piezoelectric bimaterial interface

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ABSTRACT

The interaction of a conductive crack and an electrode at a piezoelectric bi-material interface is studied. The bimaterial is subjected to an in-plane electrical field parallel to the interface and an anti-plane mechanical loading. The problem is formulated and reduced, via the application of sectionally analytic vector functions, to a combined Dirichlet–Riemann boundary value problem. Simple analytical expressions for the stress, the electric field, and their intensity factors as well as for the crack faces' displacement jump are derived. Our numerical results illustrate the proposed approach and permit to draw some conclusions on the crack–electrode interaction.

1. Introduction

Interface cracks in multi-layered piezoelectric systems have attracted substantial interest from researchers since they can significantly reduce device functionality. A comprehensive review of crack problems arising in piezoelectric bimaterials is presented, e.g., in Govorukha et al. [1] including in-plane, anti-plane cracks and other problems. Without pretending to be exhaustive, we may note some important works related to the anti-plane interface crack problem in piezoelectric bimaterials.

Based on the integral equation approach, the anti-plane problems of a crack situated at the interface between piezoelectric layers or between a piezoelectric layer and an elastic layer were considered in works by Narita and Shindo [2], Soh et al. [3], Kwon and Lee [4], Li and Tang [5], Wang and Sun [6], Feng et al. [7] for both electrically permeable and electrically impermeable assumptions on the crack faces. The papers by Fil'shtinskii and Fil'shtinskii [8], Hou and Mei [9], Gao and Wang [10] are devoted to the consideration of anti-plane interface crack problems for a piezoelectric compound subjected to piecewise uniform out-of-plane mechanical loading combined with in-plane electric loading at infinity, and also line loading at an arbitrary point.

The anti-plane problem of three collinear interface cracks between dissimilar transversely isotropic piezoelectric materials subjected to electromechanical loading was analyzed by Choi and Shin [11] and Choi and Chung [12]. The problem of a three-layer structure constructed of a piezoelectric and two elastic strips cracked at the interface was analyzed by Narita and Shindo [13], Kwon and Lee [14].

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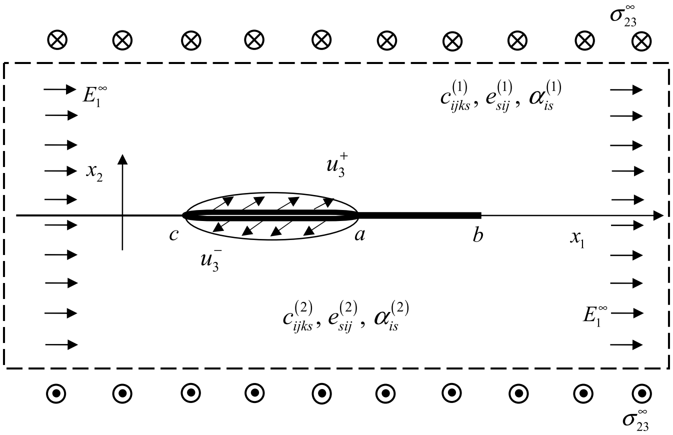

Fig. 1. Electrically conductive crack $c \le x_1 \le a$ approaching an electrode $a < x_1 < b$ at the interface $x_2 = 0$ between two piezoelectric materials. $u_3^{\pm}$ are unknown values of the crack faces' displacement.

The electroelastic interaction between a screw dislocation and a semi-infinite interface crack embedded in a two-phase piezoelectric medium has been investigated in the paper by Soh et al. [15]. Solutions for a screw dislocation interacting with a semi-infinite crack, finite crack, and edge crack between two bonded dissimilar piezoelectric materials were obtained in closed form by Wu et al. [16]. Many investigations were devoted to the anti-plane case of cracks moving along the interface of piezoelectric materials. The comprehensive review of such investigations is given in the recent paper by Nourazar and Ayatollahi [17].

In many cases, conducting interface cracks arise (Ru [18]). Such cracks were analyzed, e.g., by Beom and Atluri [19] and Loboda et al. [20] for "open" and contact zone crack models, respectively. Wang and Zhong [21] and also Wang et al. [22] studied a moving conducting crack at the interface of two dissimilar piezoelectric materials for an out-of-plane mechanical loading case. Lapusta et al. [23] analyzed a crack with mixed conditions at the crack faces. Although these cracks can interact with electrodes, to the best of our knowledge, this interaction has not been studied before. The present paper addresses this interesting and practically important case.

2. Problem formulation

Consider an electrically conductive crack $c \le x_1 \le a$ approaching an electrode $a < x_1 < b$ at the interface $x_2 = 0$ of a piezoelectric bimaterial (Fig. 1). The upper and lower components of the bimaterial are piezoceramics with poling direction x_3 and properties c_{ijks}, e_{sij}, α_{is}, where the mentioned values are stiffness, piezoelectric, and dielectric components, respectively.

We assume that a vector $\boldsymbol{P}^{\infty} = [\sigma_{23}^{\infty}, E_1^{\infty}]^{\mathsf{T}}$ is prescribed at infinity. We also assume the absence of stresses and electric field in the crack, the absence of the electric field as well as of stress and displacement jumps in the electrode zone and continuity conditions on the remaining part of the bimaterial interface. Thus, the boundary conditions at different parts of the interface have the form

$$\sigma_{23}^{(1)} = \sigma_{23}^{(2)} = 0, \qquad E_1^{(1)} = E_1^{(2)} = 0 \quad \text{for } c < x_1 < a \tag{1}$$

$$E_1^{(1)} = E_1^{(2)} = 0, \qquad \langle \varepsilon_{31} \rangle = 0, \qquad \langle \sigma_{23} \rangle = 0 \quad \text{for } a < x_1 < b \tag{2}$$

$$\langle \sigma_{23} \rangle = 0, \qquad \langle D_2 \rangle = 0, \qquad \langle \varepsilon_{31} \rangle = 0, \qquad \langle E_1 \rangle = 0 \quad \text{for } x_1 \notin (c, b) \tag{3}$$

Here and in the following, σ_{ij}, ε_{ij}, D_i, E_i denote stresses, strains, electric induction, and electric field, respectively. Recall that some basic piezoelectricity relations have the following form:

$$\sigma_{ij} = c_{ijks}\varepsilon_{ks} - e_{sij}E_s, \qquad D_i = e_{iks}\varepsilon_{ks} + \alpha_{is}E_s \tag{4}$$

Strains and electric field can be expressed using displacements u_i and electric potential φ in the form

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}), \qquad E_i = -\varphi_{,i} \tag{5}$$

The equilibrium equations are:

$$\sigma_{ij,j} = 0, \qquad D_{i,i} = 0 \tag{6}$$