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Boundary effect on crack kinking in a magnetoelectroelastic strip with a central crack

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ABSTRACT

In this study, the boundary effect on crack kinking in a magnetoelectroelastic strip with a central crack vertical to the boundary under in-plane loadings has been investigated. By using integral transform techniques the mixed boundary value problem of the crack is reduced to the solution of dual integral equations, which can be further reduced to solving Fredholm integral equations of the second kind. Analytical solutions can be obtained when the width of the magnetoelectroelastic strip are of infinite size. The asymptotic fields around crack-tips have been obtained for the electrically and magnetically impermeable and permeable cracks, respectively. Crack kinking phenomenon is investigated by applying the criterion of maximum hoop stress intensity factor. Numerical results show that the material properties, the geometry of the cracked strip and the electric–magnetic-mechanical loading significantly affect the singular field distributions around the crack. Crack kinking is found for the permeable crack case while no kinking for the impermeable crack.

1. Introduction

Because of the intrinsic magnetoelectric coupling effect, magnetoelectroelastic materials have been used in smart structures for a variety of applications. Some defects (such as dislocations and cracks) could be induced during the manufacturing processes or during service by the mechanical, electric, or magnetic loadings, which may adversely influence the performance of the structures. Consequently, it is necessary to develop the understanding of the characteristics of magnetoelectroelastic materials with defects. In recent decades, there are growing interests among researchers in studying fracture mechanics problems in magentoelectroelastic media [1–7]. Crack initiation behavior in a magnetoelectroelastic composite under in-plane deformation has been studied by Song and Sih [8]. Qin [9] obtained two-dimensional (2D) Green's functions of defective magnetoelectroelastic solids under thermal loading, which can be used to establish boundary formulation and to analyze relevant fracture problems. Transient response of a cracked magnetoelectroelastic strip under anti-plane impact has been considered by Yong and Zhou [10], whose results show the electric and magnetic impacts have significant influences on the dynamic stress intensity factor. Feng et al. [11] analyzed the dynamic magnetoelectroelastic behavior induced by a penny-shaped crack in a magnetoelectroelastic layer. Zhao and Fan [12] proposed a strip, electric-magnetic breakdown model in magnetoelectroelastic medium to study the nonlinear character of electric and magnetic fields on fracture of magentoelectroelastic materials. Li and Lee [13] established fundamental solutions for in-plane magnetoelectroelastic governing equations and studied collinear, unequal cracks in magnetoelectroelastic materials. A numerical model based on dual boundary element method has been proposed by Rojsa-Diaz et al. [14] to analyze different crack face boundary

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Nomenclature

C	half crack length
h	half width of the magnetoelectroelastic strip
(r, θ)	polar coordinate system
(x, y, z)	Cartesian coordinate system
$C_{11}, C_{13}, C_{33}, C_{44}$	elastic constants
d_{11}, d_{33}	electromagnetic constants
e_{15}, e_{31}	piezoelectric constants
h_{15}, h_{31}	piezomagnetic constants
μ_{11}, μ_{33}	magnetic permeabilities
u_x, u_z	displacement
$\lambda_{11}, \lambda_{33}$	dielectric permittivities
ϕ, φ	electric potential and magnetic potential, respectively
B_0, D_0, P_0	uniform magnetic induction, electric displacement and normal stress, respectively
$H_0(\eta, t)$	kernel functions of the Fredholm integral Eq. (54)
$H_{ij}^*(\eta, t)$ $(i, j = 1–3)$	kernel functions of the Fredholm integral Eq. (19)
K_D, K_B	EDIF and MIIF, respectively
K_I, K_{II}	Mode I and Mode II stress intensity factors, respectively
$K_{\theta\theta}, K_{r\theta}$	HSIF and SSIF, respectively
L_B, L_D	magnetic loading and electric loading parameters, respectively
$\Phi^0(t)$	unknown function solved from the Fredholm integral Eq. (54)
$\Phi_1^*(\eta), \Phi_2^*(\eta), \Phi_3^*(\eta)$	unknown functions solved from the Eq. (19)
σ_0	uniform normal stress at zero electrical and magnetic loadings
$\sigma_{ij}, \varepsilon_{ij}, D_i, E_i, B_i, H_i$ $(i, j = x, z)$	components of stress and strain, electric displacement, electric field, magnetic induction and magnetic field, respectively
γ_j $(j = 1–4)$	characteristic root
EDIF	electric displacement intensity factor
HSIF	hoop stress intensity factor
MIIF	magnetic induction intensity factor
Re	real part of a complex number
SIF	stress intensity factor
SSIF	shear stress intensity factor

conditions in 2D magnetoelectroelastic media. The moving crack problem in an infinite magnetoelectroelastic body was solved by Hu and Li [5] and crack kinking phenomena are analyzed based on the maximum hoop stress criterion. An opening crack in a magnetoelectroelastic strip under in-plane mechanical, electric and magnetic impact loadings has been considered by Hu and Chen [15], and the crack curving phenomena were observed. Although much attention has been focused on the fracture analysis of magnetoelectroelastic materials, in which most researches are confined to the crack problems in infinite materials, less effort has been paid to study the crack kinking problems in finite size magnetoelectroelastic solids due to the complexity of the mathematical treatment. In this paper we investigate the size effect on crack kinking in a cracked magnetoelectroelastic strip under in-plane mechanical, electric and magnetic loadings.

Crack kinking is an important feature of fracture in brittle materials and several studies on crack kinking have been conducted [16–20]. By using a perturbation technique, an approximate description of crack kinking and curving under mixed loading and in the presence of in-plane stresses has been given by Karihaloo et al. [21]. Crack kinking in anisotropic brittle materials has been investigated by Azhdari and Nemat-Nasser [22,23] considering the hoop and shear stress intensity factors. The problem of crack kinking in piezoelectric materials has received considerable attention. McHenry and Koepke [24] reported the phenomenon of crack kinking in piezoelectric ceramics under electro-mechanical loads based on their experimental study. Park and Sun [25] encountered the crack kinking phenomenon in their experimental work. Zhu and Yang [26] modeled the crack kinking in a piezoelectric solid by a continuous distribution of edge dislocations and electric dipoles and the solution was formulated via the Stroh formalism. Qin and Mai [27] dealt with the problems of crack kinking in a piezoelectric biomaterial system with various material combinations and studied the effect of electric field on the path selection of crack extension. Soh et al. [28] investigated the generalized plane problem of a moving Griffith crack in anisotropic piezoelectric solids based on the extended Stroh formalism and the crack branching is predicted. Hu and Zhong [29] considered a moving mode-III crack in a functionally graded piezoelectric strip, and found that the gradient of the material properties can affect the magnitudes of the stress intensity factors, and a high crack moving velocity may change the propagation orientation of the crack. Beom and Kang [30] investigated the crack kinking induced by domain switching in a ferroelectric material subjected to purely electric loading, and the size and shape of the switching zone has been estimated approximately by using the nonlinear electric theory. The size effect on crack kinking in a piezoelectric strip under impact loading was considered by Hu and Chen [31] and the results show that the geometry of the cracked strip and the electric loading significantly influence the singular field distributions around the crack tip and the crack kinking angle.

In this paper, the boundary effect on crack kinking in a magnetoelectroelastic strip with a central crack vertical to the boundary under in-plane loadings has been investigated. Fourier transforms is employed to reduce the mixed boundary value problem of the crack to solving a system of Fredholm integral equations. Both impermeable and permeable crack assumptions are considered. The asymptotic fields near the crack tip are obtained in an explicit form and the hoop and shear stress intensity factors are determined. Analytical solutions for the infinite cracked magnetoelectroelastic solid can be recovered if the size of the magnetoelectroelastic strip goes to infinity. The crack kinking phenomenon is investigated by applying the criterion of the maximum hoop stress intensity factor. The coupled electro-magnetic effects on the crack-tip fields are investigated. The influence of the geometric size of the magnetoelectroelastic strip on crack kinking is discussed.