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Interaction of a piezoelectric screw dislocation with a blunt mode III crack in a piezoelectric material

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ABSTRACT

The problem of a piezoelectric screw dislocation emitted from a blunt crack is dealt with in this paper. For an arbitrary distribution of the residual dislocation, the series-form solutions are derived. The results show that the electric field strength inside the crack is in direct proportion to the jump value of electric potential, but independent of the jump value of displacement. The force acting on the dislocation decreases with the value of the dielectric constant within the crack increasing. And the increase of the dielectric constant within the crack helps dislocation emission effectively.

1. Introduction

Due to intrinsic coupling behavior, piezoelectric materials are widely used in modern technology such as high power sonar transducers, electro-mechanical actuator, piezoelectric power supplies and micro-positioner. Hence, piezoelectric composites have become an important branch of modern engineering materials with fast development of the intelligent characteristics of piezoelectric composite materials. However, defects are often unavoidable in such materials and affect the performance and reliability of the end products. Thus, in recent years, the study of piezoelectric materials with defects has received considerable interests. Deeg [1] analyzed the dislocation, crack, and inclusion problems in piezoelectric solids. Pak [2] studied piezoelectric screw dislocations and derived the energy configuration force, a generalized Peach Koehler formula, acting on the dislocation. Pak [3] and Suo et al. [4] analyzed the stress and electric fields near a finite crack. Liu et al. [5] derived the solution for a piezoelectric dislocation near an electrically impermeable elliptical cavity. Lee et al. [6] studied the interaction between a piezoelectric screw dislocation and an electrically impermeable mode III crack of semi-infinite. Xiao et al. [7] studied a dislocation emission mechanism for micro-crack initiation at the tip of a semi-infinite rigid line inhomogeneity in a piezoelectric solid.

All the references above supposed that the normal component of the electric displacement could be treated as zero at the upper and lower crack faces. Jackson [8] proposed that the electric boundary conditions along an interface should be the continuity of the normal component of the electric displacement and the continuity of the tangent component of the electric field strength. Using such boundary conditions, Chen et al. [9] discussed the difference of the mechanical and electrical fields produced by a line force, a line charge and a line screw dislocation under electrically impermeable and electrical permeable boundary. Zhang [10–12] studied the crack width effect for piezoelectric materials, showing that the crack width has great influence on the crack growth because of the existence of electric field inside the crack. McMeeking [13] modeled a crack in

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Nomenclature

a, b	lengths of the major semi-axis and minor semi-axis of the ellipse
R, m, c	blunt crack parameters
ρ	radius of the blunt crack tip ($\rho = b^2/a$)
θ	dislocation azimuth angle
C_{44}	shear modulus of the material
e_{15}	piezoelectric constant
ε_{11}	dielectric constant
b_z	jump value of displacement
b_φ	jump value of electric potential
r_d	distance from point o_1 $(a - \rho/2, 0)$ to the surface of the ellipse
σ_{13}, σ_{23}	stress components
γ_{13}, γ_{23}	shear strain components
D_1, D_2	electric displacement components
E_1, E_2	electric field components
u_3	displacement component
ϕ	static electrical potential
K^σ	mode III stress intensity factors for the blunt crack tip
F_1, F_2	force components on the dislocation
$\widehat{\sigma}_{13}, \widehat{\sigma}_{23}$	perturbation stress components at the dislocation
$\widetilde{D}_1, \widetilde{D}_2$	perturbation electric displacement components at the dislocation
F_{imag}, F_Γ	forces on the dislocation produced by image and loads at infinite
$\sigma_{32}^\infty, D_2^\infty$	remote mechanical stress and remote electric displacement
N, θ_0	residual dislocation distribution parameters

an isotropic dielectric material as a sharp elliptical flaw with a low permittivity. He pointed out that neglecting the electric field inside the crack might lead to an erroneous estimate of crack tip fields. McMeeking [14] also analyzed the energy release rate with a capacitor crack model, in which a mechanical load opens the crack, and obtained the similar conclusion that the crack width plays an important role in the energy release rate. Hao and Shen [15] proposed the semi-permeable boundary condition, they found that the electric permeability conditions lead to a decrease of stress intensify factors. Refs. [16–18] calculated the global and local energy release rates. The mechanism of domain switching toughening is discussed in Refs. [19,20].

On the other hand, the behaviour of dislocations near the crack tip has significant effect on the fracture process of piezoelectric materials. Once dislocations are emitted, the crack may be blunted and an internal back stress accommodates the stress intensity due to applied load, causing an increase of fracture toughness of materials. Rice and Thomson [21] obtained a quantitative criterion for ductile verse brittle behavior. Chen et al. [22] investigated the behavior of screw dislocations emitted from a star crack with a central hole. Huang and Li [23] obtained the criterion for an edge dislocation emission from a blunt crack tip. Due to the poor toughness of piezoelectric materials, it is difficult for cracks within piezoelectric materials to blunt themselves and release the stress concentration through emit dislocations. Hence, the purpose of this work is to discuss the behaviour of dislocations near the crack tip with consideration of the electric field within the crack in piezoelectric material. By considering the distributs of the residual dislocation, calculating the generalized Peach–Koehler formulas based on the energy of the system and discussing the influence of the factors on dislocation emission, provide probable ways to help dislocations emission from crack tip which will improve fracture toughness of piezoelectric materials.

2. Problem statement and general treatment

Consider a transversely isotropic material belonging to the hexagonal crystal class 6 mm, the $x_1 - x_2$ plane is the isotropic basal plane. In contracted notation, the governing equations for the anti-plane strain problem (only out-of-plane displacements and in-plane electric fields) can be expressed as:

$$c_{44}\nabla^2 u_3 + e_{15}\nabla^2\phi = 0 \tag{1}$$

$$e_{15}\nabla^2 u_3 - \varepsilon_{11}\nabla^2\phi = 0 \tag{2}$$

where ∇^2 is the two-dimensional Laplacian operator, u_3 is the displacement in the x_3 direction and ϕ is the static electrical potential. c_{44}, e_{15} and ε_{11} are the elastic moduli, piezoelectric constant and the dielectric constant. The governing field equations are given by: