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Propagation of a semi-infinite conducting crack in piezoelectric materials: Mode-I problem

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ABSTRACT

In this paper, the mode-I transient response of a semi-infinite conducting crack propagating in a piezoelectric material with hexagonal symmetry under normal impact loading is investigated. The integral transform methods together with the Wiener–Hopf technique are used to solve the mixed boundary value problem under consideration. The solutions of the coupled fields are derived for two cases, i.e., generalized Rayleigh wave exists or not. The dynamic stress intensity factor and dynamic electric displacement intensity factor as well as their universal functions are obtained in a closed form. The numerical results for two universal functions are provided to illustrate the characteristics of dynamic crack propagation. It is found that the universal functions for the dynamic stress and electric displacement intensity factors vanish when the crack propagation speed reaches the generalized Rayleigh speed which is the propagation speed of surface wave in a piezoelectric half-space with metallized surface. It is noted that the electro-mechanical coupling coefficient has an important influence on the dynamic fracture characteristics.

1. Introduction

Piezoelectric materials, especially piezoelectric ceramics, have been widely used in modern technologies because the piezoelectricity can convert mechanical energy into electrical energy and vice versa. Typical examples illustrating the use of these materials include transducers, sensors, delay lines, filters and actuators as well as sensing and actuating elements embedded in smart structures (Loewy, 1997). Piezoelectric ceramics are very brittle. Their static fracture toughness is usually only 0.5–2 MPa $\sqrt{m}$ while the dynamic fracture toughness is about 10–12 MPa$\sqrt{m}$ (Chen et al., 2013b), therefore they are susceptible to fracture during service. The reliability and durability of the piezoelectric devices or structures call for a better understanding for the fracture behavior of piezoelectric materials. During the past two decades, a larger number of theoretical and experimental investigations on the static fracture mechanics of piezoelectric materials have been carried out. Some advances on this research topic can be found in the review papers by Zhang et al. (2002), Zhang and Gao (2004), Chen and Lu (2003), Chen and Hasebe (2005), Kuna (2010) as well as the monograph by Fang and Liu (2013).

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In practical applications, many piezoelectric devices operate under dynamic mechanical or electrical pulse loads (Kuna, 2010). Therefore, the study on the dynamic fracture behaviors of piezoelectric media is of great importance for both academics and industrialists. In recent ten years, some investigations on the dynamic fracture problems of piezoelectric materials have been reported. These mainly include the transient responses of cracked piezoelectric solids under mechanical and electrical impacts (Chen and Karihaloo, 1999; Chen, 2006; Enderlin et al., 2005; Gu et al., 2002a; Kwon and Lee, 2001; Lei and Zhang, 2012; Li and Fan, 2002; Nguyen-Vinh et al., 2012; Shindo et al., 1999; Wang and Mai, 2007; Wang and Noda, 2001; Wang and Yu, 2000), the electroacoustic wave scattering induced by cracks (Gu et al., 2002b; Gross et al., 2007; Huang and Wang, 2006; Li et al., 2005; Meguid and Wang, 2000; Narita and Shindo, 1998; Singh et al., 2011; To et al., 2005; Ueda, 2003; Zhang et al., 2011) and the electroelastic fields produced by the a fixed length moving crack at a constant speed (Chen et al., 1998, 2013a; Herrmann et al., 2005; Hou et al., 2001; Kwon and Lee, 2003; Lapusta et al., 2011; Li et al., 2000; Piva et al., 2007; Rokne et al., 2012; Shin and Lee, 2010; Soh et al.,2002; Wang et al., 2003; Yan and Jiang, 2009).

In the above mentioned studies on the dynamic fracture, the cracks in piezoelectric materials subjected to impact loads and electroacoustic waves are stationary. For the moving crack problems, although a crack propagates at a constant velocity, its length is assumed to be unchanged. Up to now, the work on the dynamic crack extension of piezoelectric materials under impact load is very limited. Li and Mataga (1996a,1996b) first studied the transient response of a semi-infinite anti-plane crack propagating in a hexagonal piezoelectric medium. They used two types of electrical boundary conditions on crack faces, i.e. one is the conducting type and the other a permeable vacuum free space, in which the electrostatic potential is nonzero. In their work, the exact closed-form expressions for dynamic stress intensity factor, dynamic electric displacement intensity factor and dynamic energy release rate were derived. Their numerical examples show that the Bleustein - Gulyaev (B-G) waves (Bleustein, 1968; Gulyaev, 1969) control the crack propagation speed. To et al. (2006) analyzed the propagation of a mode-III interfacial conductive crack along a conductive interface between two dissimilar piezoelectric half-spaces. They showed that the Maerfeld–Tournois (M–T) wave dominates the dynamic fracture behaviors of the interfacial crack. Chen et al. (2008) studied the dynamic fracture problem of an elastic-piezoelectric bi-material containing a semi-infinite crack along the interface. The transient stress fields and the dynamic stress intensity factor are analyzed numerically. The aforementioned four researches were devoted to the crack propagation problems under anti-plane deformation, where only out-of-plane mechanical displacement and in-plane electric fields exist. To the best of our knowledge, the dynamic crack propagation of piezoelectric materials under in-plane deformation has not yet been considered.

In this paper, the dynamic growth of a semi-infinite mode-I conducting crack in a piezoelectric material under mechanical impact is considered. In Section 2, the governing different equations are given and the considered problem is described. In Section 3, the electroelastic fields in the transformed domain are derived. In Section 4, the dynamic intensity factors of the stress and electric displacement are obtained in closed-form expression. In Section 5, the numerical examples based on the analytical solutions are presented and discussed in detail. The conclusions are given in Section 6.

2. Problem statement and basic equations

Consider the problem shown in Fig. 1. A semi-infinite crack propagates at a constant speed v in an infinite transversely isotropic piezoelectric medium. We choose a fixed Cartesian coordinate system x_i $(i=1, 2, 3)$ such that the crack is placed on the x_1-axis, and assume the plane is perpendicular to the x_3-axis. The crack tip is initially at $x_1=0$ and it begins to move at time $t=0$. The position of the crack tip at any time $t>0$ is at $x_1=vt$. It is assumed the crack propagation speed is subsonic in order to maintain the ellipticity of the differential equations. All conclusions are therefore limited to subsonic crack propagation.

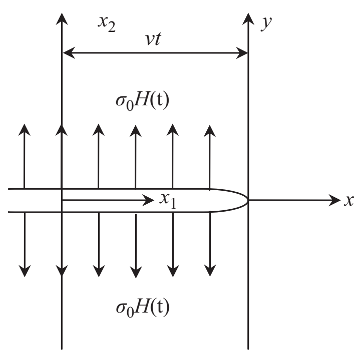

Fig. 1. A semi-infinite crack propagating in an infinite piezoelectric medium under normal loading.