International Journal of Solids and Structures 48 (2011) 2743–2754

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Indentation responses of piezoelectric films ideally bonded to an elastic substrate

J.H. Wang [a], C.Q. Chen [b,*]

[a] MOE Key Laboratory for Strength and Vibration, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, PR China
[b] Department of Engineering Mechanics, AML & CNMM, Tsinghua University, Beijing 100084, PR China

ARTICLE INFO

Article history:
Received 7 February 2011
Received in revised form 15 April 2011
Available online 22 June 2011

Keywords:
Indentation
Piezoelectric film
Elastic substrate
Numerical analysis
Finite element method

ABSTRACT

The influences of elastic substrate on the indentation force, contact radius, electric potential and electric charge responses of piezoelectric film/substrate systems are investigated by the integral transform method. The film is assumed to be ideally bonded to the substrate and the contact interaction between the indenter and the film is assumed to be frictionless, with three kinds of axisymmetric insulating and conducting indenters (i.e., punch, cone and sphere) considered. Obtained results show that when the ratio of the contact radius to the film thickness is close to zero, the influences of the elastic substrate disappear and the indentation behaviors converge to the piezoelectric half space solutions while the indentation responses approach the corresponding ones of elastic half space as the ratio gets to infinity. The transition between the piezoelectric and the elastic half space indentation solutions for the film/substrate system is quantified in terms of the film thickness and the elasticity of the substrate. Finite element analysis on an insulating sphere indentation is conducted to verify the numerical calculations and good agreement is observed. The obtained results are believed to be useful for developing experimental techniques to extract the material properties of piezoelectric film/substrate systems.

1. Introduction

Piezoelectric materials in the form of film bonded to substrate are widely used in microelectromechanical systems (MEMS) as actuators and sensors, due to their attractive mechanical and electric coupling effects (Mason, 1950; Uchino, 1997). The film thickness can range from a few nanometers to several millimeters. To measure the mechanical and electric properties of the piezoelectric materials used in applications that they are prone to contact in thin-film and bulk forms, the instrumented indentation techniques, which are based on the methods developed by Oliver and Pharr (1992, 2004) originally for elastic half space, can offer a powerful tool (Bahr et al., 1999; Sridhar et al., 1999; Zheng et al., 2003; Delobelle et al., 2004; Rar et al., 2006). However, successful application of the techniques to piezoelectric films depends to a large extent upon the availability of reliable closed-form exact or approximate indentation models.

Indentation responses of piezoelectric materials, when compared to those of elastic materials, are more complicated owing to the directional dependence and mechanical–electrical coupled characteristics of the materials. A number of theoretical and experimental studies on this subject are available. Using the Hankel transformation method, Matysiak (1985) obtained the solution for a linear piezoelectric half space penetrated by a rigid conducting punch. Following the same methodology, Giannakopoulos and Suresh (1999) investigated the axisymmetric indentation of a piezoelectric half space pressed by three different types of insulating and conducting indenters (i.e., punch, cone and sphere) within the context of fully coupled, transversely isotropic models. Yang (2008) presented a closed-form solution of the axisymmetric indentation for a semi-infinite transverse isotropic piezoelectric material by a rigid-conducting indenter of arbitrary-axisymmetric profile. Effective contact stiffness and piezoelectric constant were obtained. Alternatively, the potential theory technique was adopted by Wang and Zheng (1995), Chen and Ding (1999), Chen et al. (1999), Ding et al. (2000), and Kalinin et al. (2004) to derive analytical indentation solutions of a transversely isotropic piezoelectric half space. Karapetian et al. (2009) studied the piezoelectric indentation of flat and non-flat indenters with arbitrary form, under normal force (centrally or non-centrally applied) and electric charge distributions prescribed at the base.

Similar to successful implementation of traditional indentation of elastic materials (Busby et al., 2005), experimental studies on piezoelectric materials were conducted by many researchers. The indentation force response of lead zirconate and barium titanate piezoelectric ceramics to spherical micro-indentation was experimentally investigated by Ramamurty et al. (1999). The electric responses during indentation of piezoelectric materials was studied experimentally by Sridhar et al. (1999) and the experimental results were larger than the theoretical prediction, which was likely due to the occurrence of inelastic deformation and the time-dependence of the piezoelectric interaction. Delobelle et al. (2004) used the traditional indentation method to measure the

* Corresponding author. Tel./fax: +86 10 62783488.
E-mail address: chencq@tsinghua.edu.cn (C.Q. Chen).

0020-7683/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijsolstr.2011.05.023