Indentation responses of piezoelectric films ideally bonded to an elastic substrate

J.H. Wang, C.Q. Chen

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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 electrical coupling effects (Mason, 1950; Uchino, 1997). The film thickness can range from a few nanometers to several millimeters. To measure the mechanical and electrical 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, Matysiaik (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 transversely 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 electrical 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