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Mechanics of non-slipping adhesive contact on a power-law graded elastic half-space

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ABSTRACT

In previous work about axisymmetric adhesive contact on power-law graded elastic materials, the contact interface was often assumed to be frictionless, which is, however, not always the case in practical applications. In order to elucidate the effect of friction and the coupling between normal and tangential deformations, in the present paper, the problem of a rigid punch with a parabolic shape in non-slipping adhesive contact with a power-law graded half-space is studied analytically via singular integral equation method. A series of closed-form analytical solutions, which include the frictionless and homogeneous solutions as special cases, are obtained. Our results show that, compared with the frictionless case, the interfacial friction tends to reduce the contact area and the indentation depth during adhesion. The magnitude of the coupling effect depends on both the Poisson ratio and the gradient exponent of the half-space. This effect vanishes for homogeneous incompressible as well as for linearly graded materials but becomes significant for auxetic materials with negative Poisson's ratio. Furthermore, influence of mode mixity on the adhesive behavior of power-law graded materials, which was seldom touched in literature, is discussed in details.

1. Introduction

Mechanics of functionally graded materials (FGMs) with spatially varying elastic moduli is of significance to many applications in tribology (Enomoto and Yamamoto, 1998; Donnet and Erdemi, 2004), adhesion (Giannakopoulos and Pallot, 2000; Chen et al., 2009b), geology (Holl, 1940; Booker et al., 1985a,b), biomechanics (Pompe et al., 2003; Hedia and Nemat-Alla, 2004), fracture mechanics (Suresh, 2001), thermo-mechanical systems (Pindera et al., 1998; Nemat-Alla, 2003), energy storage/conversion systems (Kambe and Shikata, 2003; Kato et al., 2006) and nanotechnology (Li et al., 2009; Sioh, 2010). In particular, the contact mechanics of FGMs has received considerable attention in the past (Giannakopoulos and Pallot, 2000). Early studies on the contact mechanics of FGMs focused on the settlement of foundations on soils with elastic moduli varying linearly with depth (Holl, 1940; Lekhnitskii, 1962; Gibson, 1967; Gibson and Sills, 1975; Calladine and Greenwood, 1978; Booker et al., 1985a,b). More recent studies have demonstrated that FGMs can be designed to have substantially improved resistance to contact damage compared to their homogeneous counterpart (Suresh and Mortensen, 1998; Suresh, 2001). Suresh and coworkers made systematic investigations on the mechanics of indentation on graded elastic solids (Giannakopoulos and Suresh, 1997a,b; Giannakopoulos and Pallot, 2000; Choi et al., 2008; Prasad et al., 2009), and proposed a theoretical framework for frictionless contact of graded materials under concentrated point loads and axisymmetric indenters (Giannakopoulos and Suresh, 1997a,b). The plane strain problem of a rigid cylinder in contact with a power-law graded half-space was also examined by Giannakopoulos and Pallot (2000).

With the rapid development of nanotechnology, micro- and nano-indentation has become a powerful tool to characterize mechanical properties of a variety of biological/soft materials with sizes approaching molecular or atomic dimension. For such application, the adhesion forces between contact surfaces induced by capillary, electrostatic and van der Waals interactions will come into play and may affect the contact behavior significantly. Recent years have witnessed a continuously growing interest in adhesive contact between soft materials from different branches of engineering and applied sciences. Compared with studies on adhesive contact mechanics of homogeneous materials (Johnson et al., 1971; Derjaguin et al., 1975; Barquins, 1988; Maugis, 1992; Chaudhury et al., 1996; Baney and Hui, 1997; Greenwood, 1997; Barthel, 1998; Hui et al., 2001; Chen and Gao, 2006a,b, 2007a,b), there is so far only limited work (Giannakopoulos and Pallot, 2000; Chen et al., 2009b; Jin and Guo, 2010) on adhesive

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