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Interface behavior of a thin-film bonded to a graded layer coated elastic half-plane

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ABSTRACT

The interface behavior of a thin-film adhering to an elastic half-plane with an arbitrarily graded transition layer is analyzed by a linearly unified model when the interface between the thin-film and the graded layer is subjected to a mismatch strain. A series of continuous but piecewise linear functions are adopted to describe different graded variation laws of the transition layer's modulus. The fundamental solution of a graded-layer coated half-plane under a pair of normal and tangential concentrated forces is obtained first, and then the mismatch problem of a thin-film bonded to an elastic half-plane with an arbitrarily graded transition layer is further investigated. Solving the obtained integral governing equation of Cauchy singularity leads to the interfacial shear stress, the normal stress in the film, as well as the stress intensity factor near the bonded edge. It is found that the interfacial mechanics of a thin-film bonded to a graded layer is significantly affected by varying gradient law, stiffness of the film, ratio of shear modulus and length scale of the graded transition layer. The results should be helpful for the design of systems with thin-films and functional graded materials and could guide engineers to choose proper graded materials for particular applications.

1. Introduction

Functionally graded materials (FGM) have been widely used in high-tech industries and engineering practices, which can be synthesized by at least two kinds of material particles with volume fractions varying in a spatial direction. Used as a coating or a transition material, it tends to increase the bonding strength, alleviate residual stresses, prevent surface from fracture and fatigue, possess excellent thermal shielding function and provide protection against adverse chemical environment, etc [1]. Due to its multifunction, surface contact is often involved during applications, through which various kinds of loadings are transferred between or among different solids, for example, cylinder linings, turbines, brake discs and data storage devices. Great attentions have been paid to the contact behavior of FGMs [2].

In the past two decades, contact mechanics between an elastic graded material and a rigid punch or stamp has been extensively investigated. Mechanical properties of FGMs, such as the yield strength, the Young's modulus, hardness and fracture toughness, were investigated experimentally and theoretically [3–5]. Giannakopoulos and Suresh [6,7] considered an axisymmetric contact problem of a graded half-space loaded by flat, spherical and conical indenters. It was found that the distribution of contact stress could be significantly altered by different gradient variations and a suppressed Hertzian crack near contact edges could be induced. The surface sliding behavior of a FGM coated substrate under a rigid punch was well analyzed by Guler and Erdogan [2,8]. Ke and Wang [9,10] proposed a well-defined linear multi-layered model to explore the contact mechanics between FGMs and rigid punches. Considering the thermal effect, Choi and Paulino [11] and Chen and Chen [12] analyzed the thermoelastic contact behaviors of FGMs. The surface partial slip contact model about FGMs were investigated by Elloumi et al. [13] and Chen and Chen [14]. Recently, Chen et al. [15] studied the sliding contact behavior of a rigid cylindrical punch on an elastic half-plane with shear modulus varying gradiently in an arbitrary direction. All the above studies on graded materials belong to Hertzian contact. Considering the interface adhesion, Chen et al. [16,17] gave a closed-form analytical solution for a rigid cylinder or sphere in adhesive contact with a graded half-space, which could be well reduced to the classical JKR solution. Using a similar JKR-DMT transition, the axis-symmetrically adhesive contact problem between rigid punches and graded half-spaces was successfully analyzed by Guo and his colleagues [18–20].

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All the above investigations are related to contact mechanics of graded materials, in which rigid solids are introduced as stamps or punches. In another practical applications, graded materials should be protected by thin-films, for example, in micro-electro-mechanical systems (MEMS), biomedical components, sensors and actuators, integrated circuit, high power tunable microwave devices, flip-chip microprocessor packages, etc [21–23]. The complicate interface behavior between an elastic film and a homogeneous elastic substrate has been well studied [23–29]. However, the adhesion problem of a thin film bonded to an FGM substrate is seldom involved. Guler and his co-authors [30,31] analyzed the bonded problem of an elastic film on a graded layer coated half-plane, in which the graded feature of the coating layer abides by an exponential variation law. Recently, Chen et al. [32] investigated the non-slipping adhesion model of a mismatch film bonded to a finite-thickness graded substrate, whose shear modulus also abides by an exponential function. How about other graded materials and how could we choose a graded material in real applications? Comprehensive comparison of interface behaviors formed between thin-films and different graded materials should be carried out.

Based on the fact that a series of continuous but piecewise linear curves can well represent an arbitrary curve [9,33,34], a linearly unified theoretical model is established in this paper in order to evaluate the interface property of a thin-film bonded to an arbitrarily graded material coated half-plane. The fundamental solution of an FGM coated elastic half-plane under a pair of normal and tangential concentrated forces is obtained first. Then, the interface mechanics of an elastic film bonded to a half-plane coated with a graded layer, whose modulus abides by an exponential variation law, is re-analyzed in order to verify the present unified model. The non-slipping contact model of a half-plane coated with a power law graded layer and a thin-film is mainly investigated. Not only the interface stress and the normal stress in the thin-film but also the stress intensity factor near the bonded edges is used to assess comprehensively the interface property.

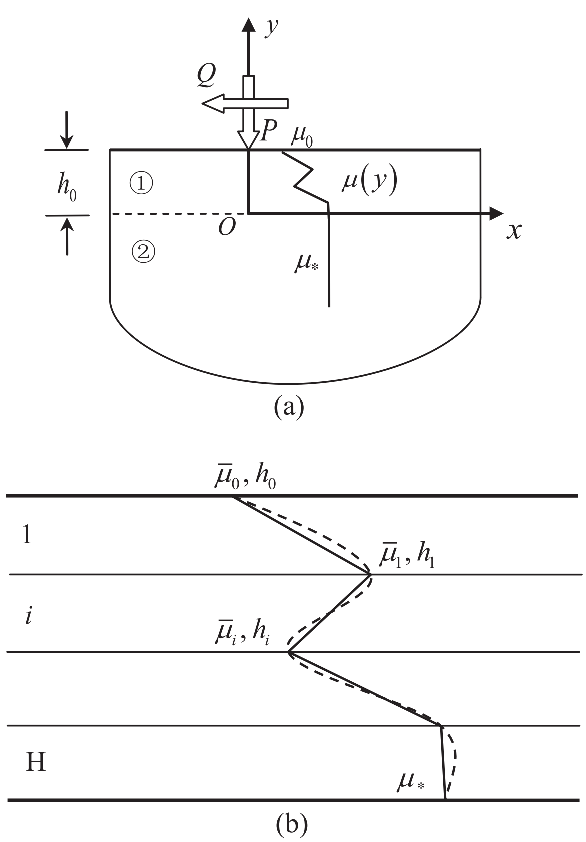

Fig. 1. (a) Schematic of a FGM coated half-plane subjected to a normal concentrated force P and a tangential concentrated force Q; and (b) the linearly multi-layered model for the graded coating layer.

2. Fundamental solution of an FGM coated elastic half-plane

In order to investigate the adhesive problem of a thin-film bonded to an FGM coated elastic half-plane, the fundamental solution of an FGM coated elastic half-plane subjected to a normal or tangential concentrated force is briefly introduced firstly, based on Ke and Wang [9,10]. Fig. 1 is the corresponding plane strain model for the fundamental solution, where both a normal concentrated force P and a tangential concentrated force Q act on the surface of an FGM coated elastic homogeneous half-plane. The shear modulus at the FGM coating surface is denoted as μ_0 and the shear modulus of the homogeneous half-plane is μ_*. Both the Poisson's ratio of the graded coating and that of the homogeneous half-plane are assumed to be constant ν. A multi-linear piecewise function is used to approximate the graded variation law of the coating layer as shown in Fig. 1(b), where the graded coating layer

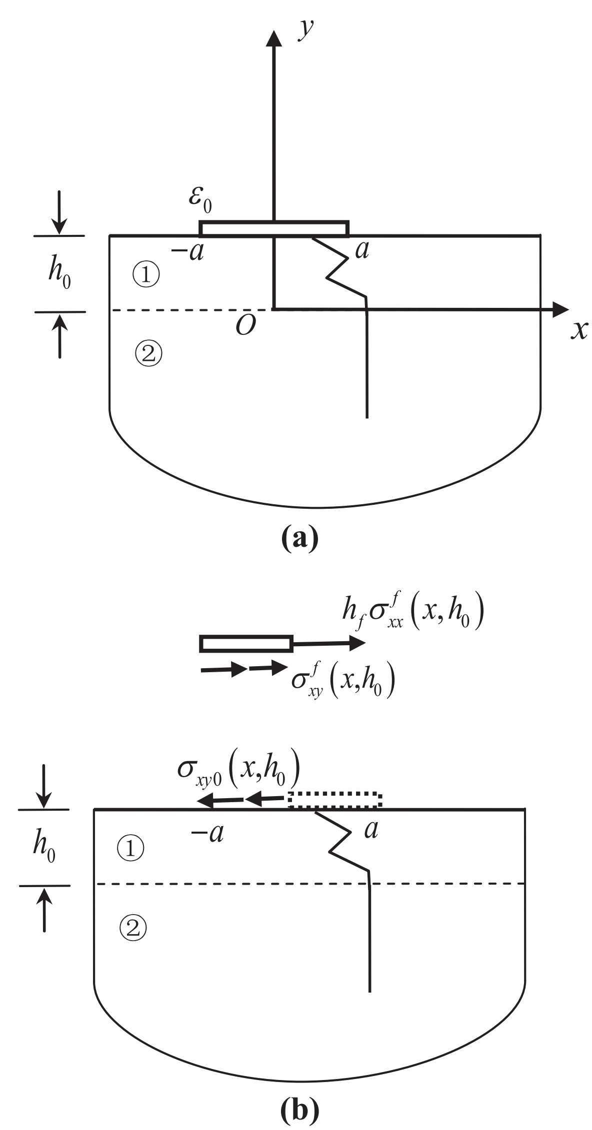

Fig. 2. (a) The adhesive bonded model between a mismatch film and a FGM coated half-plane; and (b) schematic of the stress on the bonded interface.