Mechanics of Materials 92 (2016) 8–17

Contents lists available at ScienceDirect

Mechanics of Materials

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

Modeling surface pressure, interfacial stresses and stress intensity factors for layered materials containing multiple cracks and inhomogeneous inclusions under contact loading

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A R T I C L E I N F O

Article history:
Received 29 April 2015
Revised 29 July 2015
Available online 7 September 2015

Keywords:
Coating
Contact load
Inhomogeneous inclusion
Crack
Stress intensity factor

A B S T R A C T

This work develops a semi-analytic solution for multiple cracks and inhomogeneous inclusions in a two-dimensional multi-layered material subject to contact loading. The solution not only considers the interactions among all the inclusions and cracks but also the surface deformation of the layered material caused by both the surface loading and subsurface inclusions and cracks. The solution strategy is to treat each material layer as an inhomogeneous inclusion with respect to the substrate and then utilize Eshelby's equivalent inclusion method to model each inhomogeneous inclusion as a homogenous inclusion with initial eigenstrain plus unknown equivalent eigenstrain, while using the distributed dislocation technique to model each crack of mixed modes I and II as a distribution of climb and glide dislocations with unknown densities. As a result, the original inhomogeneous or heterogeneous material problem is converted into a new homogenous material problem. The new problem is further decomposed into two sub-problems: a homogenous half-space contact sub-problem in which the unknown surface contact area and normal pressure and tangential traction within it are determined as an inhomogeneous crack and inclusion sub-problem in which the unknown equivalent eigenstrains and dislocation densities are determined. As the two sub-problems are correlated, an algorithm is developed to integrate them and all the unknowns are solved by means of iteration using the conjugate gradient method. The stress intensity factors of cracks are also obtained by the dislocation densities at the crack tips. An accurate description of the surface pressure, the subsurface elastic field of the layered heterogeneous materials and the stress intensity factors of subsurface cracks allows their fracture and delamination analyses to be conducted.

1. Introduction

Over the last few decades, surface coatings have been extensively employed to a variety of mechanical components, cutting tools and instruments to provide heat-, oxidation- and wear-resistance for those parts and structures in the engines, transmissions and the manufacturing industry. The newly advanced deposition techniques, such as chemical vapor deposition and physical vapor deposition, offer a wide range of possibilities to deposit coating layers with many different materials and structures, which were unachievable a decade ago.

However, due to the differences in mechanical properties, thermal expansion coefficient and heat conductivity

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http://dx.doi.org/10.1016/j.mechmat.2015.08.008
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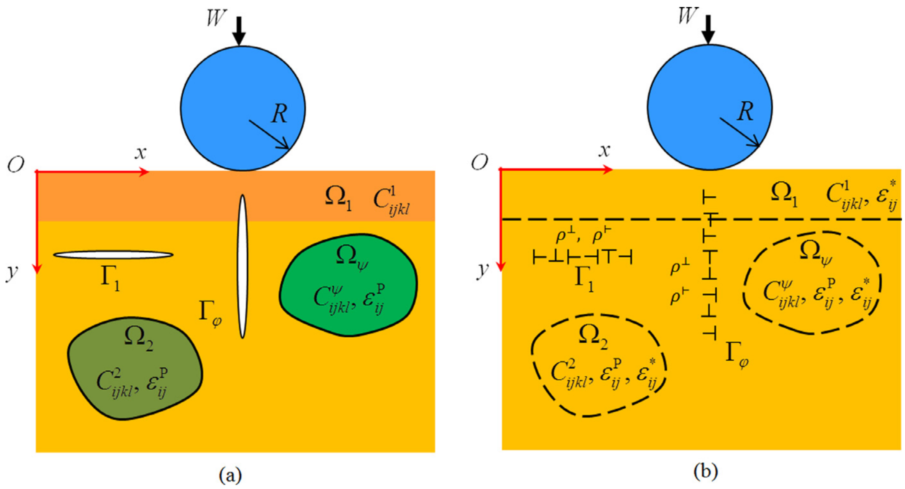

Fig. 1. (a) The original inhomogeneous half-space coating-substrate contact problem, and (b) the equivalent new homogenous half-space contact problem.

between the coating and substrate, the cracking or delamination of a coating layer can be easily induced when thermal or contact loading is applied (Chen et al., 2010; Yi et al., 2012, 2013; Zhou et al., 2011b; Zhuang et al., 2013). The finite element method (FEM) has been widely used to study the coating problems concerning indentation (Kot, 2012; Rash Ahmadi et al., 2008), defects (Andritschky et al., 1999; Bansal et al., 2006; Baragetti et al., 2003; Chen and You, 2014; Fan et al., 2012) and multiple layer structures (Bouzakis et al., 1997; Zhao et al., 2011).

On the other hand, defects near the surface such as inclusions, cracks and dislocations could greatly influence the mechanical properties and behavior of the material. Their presence could cause plastic deformation, crack nucleation or propagation, which may degrade mechanical properties or even lead to the final failure of materials. Considerable research has been conducted to simulate or predict mechanical performance under the influence of subsurface defects (Chen et al., 2013; Fan et al., 2014; Fang et al., 2008, 2009a, 2009b; Feng et al., 2011; Li et al., 2011; Pan et al., 2011; Rodin and Weng, 2014; Tao et al., 2014; Wang and Kishimoto, 1999; Yi et al., 2014; Zhang et al., 2010; Zhao and Weng, 1996). The interactions among the coated layer, subsurface cracks and inclusions must be investigated to predict and prevent damage and failure to the material.

Recently, Zhou et al. employed the equivalent inclusion method (EIM) (Eshelby, 1957) but bypassed the complicated Eshelby tensor to model multiple inhomogeneous inclusions of three-dimensional (3D) arbitrary shape and developed a semi-analytic solution in both full space and half-space (Zhou, 2012; Zhou et al., 2009, 2011a, 2011c). Afterwards, Zhou and Wei (2014) solved a two-dimensional (2D) half-space contact problem for multiple subsurface inclusions and cracks, which are modeled by the distributed dislocation technique (DDT) (Hills et al., 1996; Miller and Keer, 1982; Bryant et al., 1984; Miller et al., 1985). Details of the DDT may refer to Mura's monograph (1987).

This study analyzes a 2D coating-substrate system in the presence of subsurface inclusions and mixed-mode (mode I and II) cracks with the consideration of the interactions among the loading body, subsurface defects and coating/substrate system.

2. Methodology

2.1. Problem description and solution approach

A half-space coating-substrate system contains multiple arbitrarily-shaped inhomogeneous inclusions and cracks, as shown in Fig. 1(a). The surface coating of thickness H is subjected to a contact load, which is applied through a cylindrical isotropic loading body of infinite length and radius R under external load W. The coating with elastic moduli C^1_{ijkl} can be regarded as an inhomogeneous inclusion Ω_1, which should be large enough along the x-axis to neglect the boundary error caused by that portion of the coating outside the simulation domain. Thus, the original coating-substrate problem is converted into a half-space problem with inhomogeneous inclusion $\Omega_\psi(\psi = 1, 2, \ldots, n_1)$ and cracks $\Gamma_\phi(\phi = 1, 2, \ldots, n_2)$.

According to work done by Zhou and Wei (2014), this problem is further decomposed into two sub-problems: (1) the half-space sub-problem to determine subsurface equivalent eigenstrains ε^*_{ij} and dislocations $\rho^\perp$ and $\rho^\vdash$ for a prescribed surface loading, and (2) the homogenous half-space contact sub-problem to determine the surface deformation, contact area and loading distribution for a prescribed external load applied to the loading body. An iterative algorithm has also been developed to solve the two correlated sub-problems.

2.2. Half-space sub-problem with prescribed surface loading

By using the EIM (Eshelby, 1957), each inclusion Ω_ψ can be modeled as a homogeneous inclusion with initial eigenstrain ε^P_{ij} plus unknown equivalent eigenstrain ε^*_{ij} to be determined; using the DDT (Hills et al., 1996), each crack is modeled as a distribution of climb and glide dislocations with unknown densities $\rho^\perp$ and $\rho^\vdash$ to be determined (Fig. 1(b)). When stresses within the equivalent inclusions are considered, the utilization of Hooke's law and stress superposition