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Fracture-mode map of brittle coatings: Theoretical development and experimental verification

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ABSTRACT

Brittle coatings, upon sufficiently high indentation load, tend to fracture through either ring cracking or radial cracking. In this paper, we systematically study the factors determining the fracture modes of bilayer material under indentation. By analyzing the stress field developed in a coating/substrate bilayer under indentation in combination with the application of the maximum-tensile-stress fracture criterion, we show that the fracture mode of brittle coatings due to indentation is determined synergistically by two dimensionless parameters being functions of the mechanical properties of coating and substrate, coating thickness and indenter tip radius. Such dependence can be graphically depicted by a diagram called 'fracture-mode map', whereby the fracture modes can be directly predicated based on these two dimensionless parameters. Experimental verification of the fracture-mode map is carried out by examining the fracture modes of fused quartz/cement bilayer materials under indentation. The experimental observation exhibits good agreement with the prediction by the fracture-mode map. Our finding in this paper may not only shed light on the mechanics accounting for the fracture modes of brittle coatings in bilayer structures but also pave a new avenue to combating catastrophic damage through fracture mode control.

1. Introduction

To protect vulnerable materials against external mechanical impacts, engineers and Mother Nature apply a similar strategy-coating. While the engineering examples include the thermal barrier coatings and cutting tool coatings, natural coatings are exemplified by the enamel layer of teeth (He et al., 2013; Lee et al., 2009) and cuticles of various bioarmors (Bruet et al., 2008; Yao et al., 2010). However, no material is invincible. Upon sufficiently high loading, these protective coatings will also fracture through cracking. Interestingly, previous studies on the fracture of coating/substrate systems revealed that brittle coatings in coating/substrate systems under indentation tend to fracture through either radial cracking or ring cracking, depending on factors such as the coating thickness (Chai and Lawn, 2004), coating-substrate modulus mismatch (Chai et al., 1999), indenter size and so on. While ring cracking occurs at the perimeter of the contact area between the indenter and coating, the radial cracking initiates right below the contact center at the coating-substrate interface. Transition between these two fracture modes may happen upon the alteration of some structural parameters. For instance, Chai and Lawn investigated the evolution of fracture mode as a function of the coating thickness in a model

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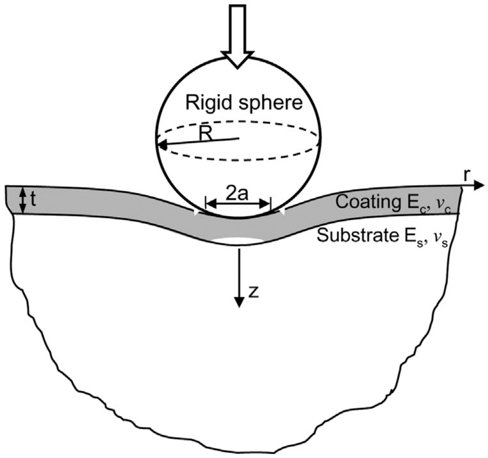

Fig. 1. Schematics of a coating/substrate system under indentation by a rigid spherical indenter.

ceramic/polymer bilayer. It was showed that the fracture mode undergoes transition, from ring cracking to radial cracking and finally back to ring cracking as the coating thickness decreases (Chai and Lawn, 2004). However, so far little is known about the mechanics accounting for such transition between different fracture modes, much less the strategies to control the fracture modes. In this paper, we study the conditions for cracking by rigorously analyzing the stress field developed in the brittle coating of a bilayer material under indentation in combination with the application of fracture criterion. The occurrence conditions for ring cracking and radial cracking are revealed and given in terms of two dimensionless parameters that characterize the contact system, giving rise to a fracture-mode map. Experimental verification of the fracture-mode map is carried out by exploring the indentation-induced fracture of a model bilayer material made of fused quartz and cement. The remain of this paper proceeds as follows. In Section 2, the contact problem between a rigid spherical indenter and a bilayer material is formulated and rigorously solved by using a Hankel transform-based analytical approach. Based on the obtained solution, in Section 3, the stress field developed in the coating is calculated to identify the maximum tensile stress and the corresponding locale and direction. With the application of the maximum-tensile-stress fracture criterion, the conditions for ring cracking and radial cracking are determined in Section 4, resulting in a fracture-mode map. The experimental verification of the fracture-mode map is performed in Section 5. The whole paper is concluded by summarizing the obtained results in Section 6.

2. Theoretical modeling

We consider a bilayer material consisting of an elastic coating of thickness t perfectly attached to an elastic half-space substrate, as shown in Fig. 1. The elastic moduli and Poisson's ratios of the coating and substrate are denoted by E_c, E_s, ν_c and ν_s, respectively. A rigid spherical indenter is compressed onto the bilayer by external compression, resulting in a circular contact region of radius a. Friction between the indenter and coating is neglected. Following the convention in contact mechanics, the profile of the spherical indenter is approximated by a paraboloid of revolution $f(r) = r^2/2R$, where R stands for the tip radius of the indenter.

It is the major objective of this paper to determine the fracture mode of the coating in the posed problem when the external compression is high enough. For a material free of pre-existing cracks, fracture due to external loading tends to start from crack initiation, followed by crack propagation. The locale of the crack initiation and the orientation of the resulting crack plane depend on the stress field developed as well as the nature of the material or the fracture criterion. Brittle materials generally rupture along the plane with maximum tensile stress while the ductile materials tend to fail along the plane having maximum shear stress. In this paper, we focus our attention on brittle coatings and therefore adopt the maximum-tensile-stress criterion (Rankine, 1857), which states that crack is initiated when the maximum principal stress, σ_1, exceeds material's fracture strength σ_f. Here, we assume, as the first order approximation, that the fracture strength σ_f of the coating is a constant rather than a function of the indenter size as deduced from the well-known empirical Auerbach's law (Auerbach, 1891). The plane of the initiated crack prior to growth is supposed to be perpendicular to the direction of the maximum principal stress. Prediction of the fracture modes of the coating in Fig. 1 can be made if the locale and direction of the greatest σ_1 in the coating are known.

In the past a few decades, different analytical approaches have been proposed to solve the contact problem of layered materials. At the beginning, most approaches (Gao et al., 1992; Li and Chou, 1997; Schwarzer, 2000) were approximate as the distribution of contact pressure was empirically assumed rather than rigorously solved from the governing equations and boundary conditions. To tackle this problem, Periot and Barthel applied two auxiliary functions (Perriot and Barthel, 2004), giving rise to a rigorous solution to the contact problem of a rigid indenter of any shape indenting a coated elastic half-space.