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Periodic cracking of films supported on compliant substrates

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ABSTRACT

When a tensile strain is applied to a film supported on a compliant substrate, a pattern of parallel cracks can channel through both the film and substrate. A linear-elastic fracture-mechanics model for the phenomenon is presented to extend earlier analyses in which cracking was limited to the film. It is shown how failure of the substrate reduces the critical strain required to initiate fracture of the film. This effect is more pronounced for relatively tough films. However, there is a critical ratio of the film to substrate toughness above which stable cracks do not form in response to an applied load. Instead, catastrophic failure of the substrate occurs simultaneously with the propagation of a single channel crack. This critical toughness ratio increases with the modulus mismatch between the film and the substrate, so that periodic crack patterns are more likely to be observed with relatively stiff films. With relatively low values of modulus mismatch, even a film that is more brittle than the substrate can cause catastrophic failure of the substrate. Below the critical toughness ratio, there is a regime in which stable crack arrays can be formed in the film and substrate. The depth of these arrays increases, while the spacing decreases, as the strain is increased. Eventually, the crack array can become deep enough to cause substrate failure.

1. Introduction

A coating, thin film, or surface layer supported on a substrate can fracture into a pattern of parallel cracks when subjected to a tensile stress (Thouless, 1990; Thouless et al., 1992; Hutchinson and Suo, 1992; Beuth, 1992; Shenoy et al., 2000). The cracks are limited to the surface layer if it is more compliant than the substrate. However, the cracks will penetrate the interface and propagate within the substrate if a stiff film is supported on a compliant substrate (Beuth, 1992; Zak and Williams, 1963). While there have been several studies on the cracking of stiff coatings on polymers (Chen et al., 2002; Jansson et al., 2006; Begley et al., 2005; Gruber et al., 2009; Schalko et al., 2010), the associated analyses have generally assumed that only the coating fractures. Recent experimental observations (Douville et al., in preparation) on a system consisting of a thin metal film on an elastomeric substrate demonstrated stable fracture patterns with cracks clearly propagating within the substrate. This observation was the original motivation for the present analysis to investigate how fracture of the substrate affects the formation of crack arrays (Fig. 1). The results of the analysis show how the crack spacing and depth depend on the ratio between the film and substrate modulus and on the ratio between the film and substrate toughness. In particular, the results help delineate the regimes in which substrate fracture may have a significant effect on

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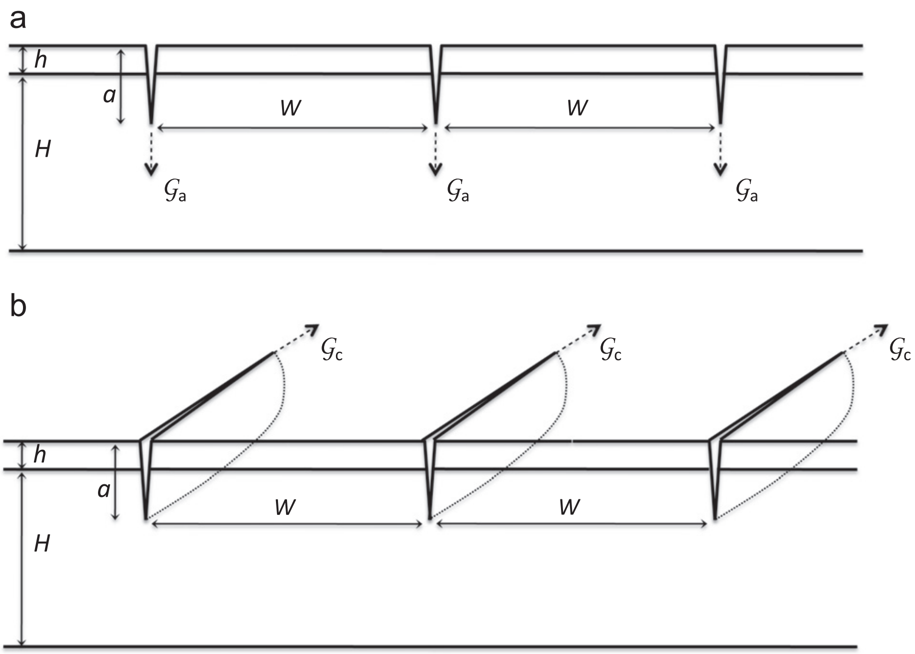

Fig. 1. The geometry considered in this paper. A stiff film of thickness h and elastic constants E_f and ν_f is supported on a compliant substrate of thickness H and elastic constants E_s and ν_s. There is a uniform crack array of depth a and spacing W. (a) The two-dimensional geometry, appropriate for cracks propagating perpendicular to the interface and to the substrate. (b) The configuration for crack channeling (propagation parallel to the interface).

the failure of coated systems from those that do not. Finally, the results establish criteria for when stable fracture patterns do not form, but the propagation of a single crack in the film induces catastrophic failure of the substrate.

The fracture behavior of stiff films on compliant polymeric substrates has relevance for a number of applications. The level of modulus mismatch between the two components for some of these applications can be as extreme as 10^4–1 when a metal film is supported by an elastomer. For example, elastomeric actuators deform in response to a high electric field between thin metal electrodes on the surfaces of elastomeric dielectrics (Pelrine et al., 2000; Begley et al., 2005; Begley and Bart-Smith, 2005). Oxide and metal coatings on a range of different polymers, including elastomers, form the basis of flexible electronics such as organic light-emitting diodes (Burroughs et al., 1990) or solar cells (Forrest, 2004; Günes et al., 2007). Failure of the surface layer is one of the limitations on the flexibility of such devices (Li et al., 2004; Lacour et al., 2003, 2004; Lewis, 2008). More generally, metal-polymer multilayers are commonly used for electronic packaging (Chiu et al., 1994). Metal films have been used as permeability barriers for polymers in the food packaging industry for many years, and there have been recent studies on the use of oxide (Chatham, 1996) and diamond-like carbon films for this purpose (Tsubone et al., 2007). Integrity of the permeability barrier is compromised by cracking. A practical application in which cracking of stiff layers on elastomers is desirable is in the fabrication of tunable biological devices and nano-channels (Zhu et al., 2005; Huh et al., 2007; Mills et al., 2010). Finally, it is well known that a stiff surface layer on a polymer, such as might result from the application of a paint film or from environmental degradation, has a tendency to make the underlying polymer substrate fail in a brittle mode (So and Broutman, 1982, 1986; Verpy et al., 1994). The results of this paper may provide some insight into this particular failure mode.

By way of background, the mechanics of crack formation will be summarized for systems in which the cracks are confined to a surface layer. Below a critical level of strain, ε_c, no cracks can propagate. This critical strain depends on the thickness of the film, h, the thickness of the substrate, H, the elastic constants of the film and substrate, and the toughness of the film, Γ_f:

$$\varepsilon_c = f\left(\alpha, \beta, \frac{\Gamma_f}{\overline{E}_f h}, \frac{H}{h}\right). \tag{1}$$

The Dundurs parameters, α and β, are the non-dimensional parameters which define the modulus mismatch in plane geometries; they are given by (Dundurs, 1969)

$$\alpha = \frac{\overline{E}_f - \overline{E}_s}{\overline{E}_f + \overline{E}_s} \tag{2}$$

and

$$\beta = \frac{\overline{E}_f f(\nu_s) - \overline{E}_s f(\nu_f)}{\overline{E}_f + \overline{E}_s}, \tag{3}$$