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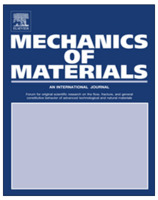

Slip zone model for interfacial failures of stiff film/soft substrate composite system in flexible electronics

Hang Chen, Xue Feng [*], Ying Chen

AML, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China
Center for Mechanics and Materials, Tsinghua University, Beijing 100084, China

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ABSTRACT

Delicate designs of flexible inorganic electronics are based on the composite structure of the stiff film/soft substrate system, which substantially relieves stresses in the stiff inorganic functional units and utilizes the soft substrate to realize flexibility and stretchability. Resulted from the large mismatch of the mechanical properties of each layer in such system, the interface between the stiff electronic film and the soft substrate suffers serious stress concentration so that interfacial failures become more dangerous than material cracks during operating. The existing approaches for interfacial failures do not work well to explain the diverse failure modes, nor give the detailed stress evolution as the increasing of applied loading. In this paper, we employ the slip zone model in composite structure and strength theory to acquire the stress evolution, and then fundamentally and quantitatively explain the interfacial failure behaviors of such flexible electronic devices. The consistence between our theoretical prediction and the experimental results gives adequate supports to our cohesive constitutive relations in the slip zone. The criteria to determine the failure modes have also been established, which are important to guide the design and evaluation of flexible electronic devices.

1. Introduction

Flexible electronics, taking advantages of mechanical assisted integration of traditional inorganic semiconductor and metal films onto soft substrates, have been promoted to be the most potential approach to overcome the stiff, brittle and non-deformable nature of traditional electronic devices, and then attracted rapidly increasing attentions in the last decade (Ahn et al., 2006; Carlson et al., 2012; Chen et al., 2013a,b; Cheng and Song, 2014; Choi et al., 2007; Jin et al., 2004; Khang et al., 2006; Kim et al., 2010; Mayer et al., 2007; Rogers, 2010; Sun et al., 2006). Many emerging applications, such as flexible circuits (Kim et al., 2010), epidermal electronics (Kim et al., 2011b), electronic eye cameras (Ko et al., 2008) and multifunctional balloon catheters (Kim et al., 2011a) are able to sustain substantial and complicated deformation but with the equivalent or even better electronics performance than traditional devices. All of these ingenious designs are based on the buckling of the inorganic films (Li et al., 2010; Sun et al., 2006; Xiao et al., 2010), bridge-island structure (Kim et al., 2010) or serpentine inter-connections (Kim et al., 2011b) on a soft substrate, which relieve large stresses in the stiff inorganic functional units and utilize the soft substrate to realize flexibility and stretchability of the device. Resulted from the large mismatch of the mechanical properties of each layer in such system, the interface between the stiff electronic film and the soft substrate suffers serious stress concentration so that interfacial failures become more dangerous than material cracks during operating

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[*] Corresponding author at: AML, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China.

E-mail address: fengxue@tsinghua.edu.cn (X. Feng).

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(Chen et al., 2014; Dai et al., 2010; Huang et al., 2011; Wang et al., 2000; Kao et al., 2010; Park et al., 2008; Peng et al., 2010; Peng and Chen, 2011; Shen et al., 2009; Suo and Hutchinson, 1990). There exist common and complete theories to calculate the maximum stress in the layered structure (Timoshenko and Gere, 2012), which have no effect the interfacial analysis in this paper. Therefore, we do not give more details about it in this paper.

Two theoretical approaches have been proposed to deal with the fracture of interface in such layered structure in flexible electronics. First, represented by Chen and Nelson (1979), Jiang et al. (1997) and Wang et al. (2000), they used different assumptions and simplifications to approximately solve the peeling stress and shear stress in the imagined or actually existing adhesive layer, which showed well consistency with finite elements methods (FEM) results or preliminary experiments. However, almost all of their theories were aimed to deal with the thermal residual stresses and not combined with the practical operating process. The experimental results given by Park et al. (2008) showed the complicated and diverse behaviors of such stiff film/soft substrate interface under increasing bending strains in typical flexible devices, and gave a strength theory to describe the phenomena. But they did not give a clear explanation of the stress evolution so that the critical loading for each failure mode, which is meaningful to evaluate the mechanical performance and reliability of such devices, cannot be well predicted.

The second approach, represented by Suo and Hutchinson (1990), is to analyze a semi-infinite interface crack lying between two infinite isotropic elastic layers under general edge loadings. The deformation energy in the treated double self-balancing beams is considered as the energy release rate to give the stress intensity factors. This also indicated a simple approach to measure and characterize the interface toughness (Huang et al., 2011), i.e. critical energy release rate. Along this point, the theory of Chen et al. (2014) gave an important qualitative conclusion that: the stiff films always slip first to release some of deformation energy but with the continuously increasing remaining part, and then transit to delamination from the soft substrate as the remaining deformation energy excesses a critical value (as the same setup investigated in this paper shown in Fig. 2). However, the critical energy release rate involves the deformation energy related to the failure models (Krishnan and Hui, 2008). Therefore, for such thin stiff film/soft substrate structure under finite deformation, both dimensions and diverse failure modes may introduce unknown difficulties and errors.

In this paper, a slip zone model is introduced to combine the widely used ideal elastic–plastic cohesive constitutive relation (Duser et al., 1999; Hui et al., 2011; Rahul-Kumar et al., 1999) with the strength theory to completely acquire the stress evolution and establish the criteria for interfacial failures, which fundamentally and quantitatively explain the interfacial behaviors of such composite structure under the typically loading configuration in flexible electronics. The mechanical models and criteria for failures are developed and established in Section 2. We compare our theoretical results with the experiments and give a further discussion in Section 3. Section 4 is the conclusion remarks.

2. Mechanical model

To be consistent with the previous reliability analysis of flexible electronics (Chen et al., 2014; Dai et al., 2010; Huang et al., 2011; Park et al., 2008; Wang et al., 2000), we focus on the typical bending configuration of such devices as shown in Fig. 1(a). Plane strain problem is considered here, but it also can be used in plane stress problem with placement the moduli as plane stress case. The top and bottom layers are the inorganic electronic film and the substrate, respectively. There is an adhesive layer between them. The corresponding thickness and plane strain moduli are donated by h_f, $\bar{E}_f$; h_s, $\bar{E}_s$; and h_a, $\bar{E}_a$, where the subscripts "f", "s" and "a" represent film, substrate and adhesive, respectively. One end of the substrate is under the compressive displacement load dL, while the other is fixed. The length of the film and the substrate are donated by l and L ($l \ll L$), and the film is in the middle of the substrate. The applied strain is defined as $|\varepsilon| = dL/L$. The theory of elastic stability (Timoshenko and Gere, 2012) gives the critical applied strain for buckling: $|\varepsilon^C_{Buckling}| = \pi^2 h_s^2/12L^2$, which means the smallest applied strain to induce buckling. The moments and axial force at layered part are considered constants because the length of the film is negligible compared to the bending curvature:

$$P_m = -\frac{4}{3}[K(p)]^2 \frac{\bar{E}_s h_s^3}{L^2}, \quad \text{and} \quad M_m = \frac{2p}{3}[K(p)] \frac{\bar{E}_s h_s^3}{L}, \tag{1}$$

where $K(\cdot)$ is the complete elliptic integral of first kind, $p = \sin\alpha/2$, and α is the maximum slope rotation angle (absolute value) determined by

$$\frac{2E(p) - K(p)}{K(p)} = 1 - |\varepsilon|, \tag{2}$$

where $E(\cdot)$ is the complete elliptic integral of second kind.

Due to the mismatch of the mechanical properties between the film and the substrate, there exit interfacial stresses on both sides of the adhesive, which transfer the loads from the substrate to the film to satisfy the compatibility of deformation. According to the experimental observations from Park et al. (2008) and the fracture analysis from Chen et al. (2014), the edges of the film slip first from the top surface of the substrate, which is easier to observe for a smaller film/substrate thickness ratio, and finally transit to delamination from the substrate as the increasing applied loading, which is schematically illustrated in Fig. 2. The difference between the critical applied strains for the occurrence of the slippage and its transition dramatically approaches zero as the increase of the thickness of the film. Our subsequent mechanical model is based on the assumption of this failure evolution setup. However, our theoretical derivation in this section and further corresponding analysis in Section 3 will provide enough justifications and supplements to support this reasonable assumption and demonstrate how common such a setup is.