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# INTERFACE SCIENCE

Volume 3—1996

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## The Mechanics and Physics of Thin Film Decohesion and its Measurement

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**Abstract.** The intent of this review is to utilize the mechanics of thin films in order to define quantitative procedures for predicting interface decohesion motivated by residual stress. The emphasis is on the role of the interface debond energy, especially methods for measuring this parameter in an accurate and reliable manner. Experimental results for metal films on dielectric substrates are reviewed and possible mechanisms are discussed.

### Keywords:

### Notation

$a$	crack half length	$T$	external stress
$a_0$	initial crack size	$U$	stored energy
$A$	section area	$W_{ad}$	work of adhesion
$b$	Burgers vector	$Y$	dimensionless quantity for the $K$ -calibration
$c$	constant $\approx 3$	$\alpha$	Dundurs parameter (Eq. (2.3))
$C_i$	constants related to thin film decohesion	$\beta$	second Dundurs parameter (Eq. (2.3))
$D$	dislocation free zone near crack	$\gamma$	interaction angle (Eq. (2.31))
$E$	Young's modulus	$\delta$	location of neutral axis
	plane strain value of $E$	$\varepsilon$	strain
$E^*$	average modulus (Eq. (2.9))	$\eta$	thickness ratio, $h/H$
$\mathcal{G}$	strain energy release rate	$\theta$	polar angle
$\mathcal{G}_{ss}$	steady-state $\mathcal{G}$	$\kappa$	curvature
$\Delta\mathcal{G}_{ss}$	reduced $\mathcal{G}_{ss}$ caused by bending	$\lambda$	cracking number
$h$	film thickness	$\mu$	shear modulus
$h_c$	critical superlayer thickness	$\nu$	Poisson's ratio
$H$	substrate thickness	$\xi$	loading combination (Eq. (2.38))
$I$	sectional modulus	$\Pi$	non-dimensional $\mathcal{G}_{ss}$
$K$	stress intensity factor	$\sigma_{ij}$	stress tensor
$L$	characteristic length	$\sigma_R$	residual stress
	prescribed length to define the mode mixity	$\sigma_0$	yield strength
$M$	moment	$\sigma^*$	peak stress for the cohesive zone rupture
$P$	constant related to Dundurs parameters (Eq. (2.33))	$\psi$	mode mixity angle
$P$	edge force		mode mixity defined at a prescribed length
$r$	distance from crack tip	$\omega$	relative loading phase
$R_0$	plastic zone size	$\Gamma$	fracture energy
		$\Gamma_i$	interface fracture energy

$\Gamma_s$	substrate fracture energy
$\Gamma_p$	plastic dissipation
$\Gamma_0$	plastic dissipation for the cohesive zone rupture
$\Delta$	normalized location of neutral axis, $\delta/H$
$\epsilon$	oscillation index (Eq. (2.5))
$\Sigma$	modulus ratio, $E_1/E_2$

## 1. Introduction

The number of applications for thin films and multilayers that take advantage of their special mechanical, thermal, electronic and optical characteristics has steadily increased. The associated technologies include multi-chip modules, thermal and oxidation protection coatings, wear and abrasion resistance coatings, etc. In general, the layers are deposited by vapor deposition (either physical or chemical). One of the problems, that has limited the more widespread use of such systems, has been the incidence either of interface decohesion or of delamination within one of the brittle constituents motivated by residual stresses [1–5]. Such stresses are inevitable in vapor deposited layers and are exacerbated when the constituent materials have vastly differing thermomechanical properties, such as polymers on metals and metals on ceramics. The stresses arise for two reasons. (1) Intrinsic stresses develop during deposition [6]. These stresses persist, unless they are relaxed by plastic deformation or annealing. (2) The mismatch in thermal expansion induces stresses when the temperature is changed [7].

Controlling the stress in order to inhibit decohesion and delamination without compromising the functional characteristics of the system is not usually an option. Instead, thermomechanical design of multilayer systems to resist these failure modes is required. This goal is crucially dependent upon the attainment of an adequate interface debond toughness,  $\Gamma_i$ . The toughness requirement is manifest in the fail-safe design solution, [1, 8]

$$\Gamma_i \geq h\sigma_R^2/\bar{E}\lambda \quad (1.1)$$

where  $h$  is the film thickness,  $\bar{E}$  is its appropriate Young's modulus (plane strain or biaxial plane stress),  $\sigma_R$  is the residual stress and  $\lambda$  is a cracking number (of the order unity). When Eq. (1.1) is satisfied, there is insufficient energy stored in the film to permit an interface crack to propagate and the film *must remain attached to the substrate*.

In order to implement this fail-safe criterion, methods for the accurate measurement of  $\Gamma_i$  on the actual interfaces of relevance must exist. The principal intent of the present review is to describe and analyze the available methods with the objective of identifying those capable of providing the quantitative information needed to apply Eq. (1.1). There have been several reviews on aspects of this topic. These include surveys of test methods, [9–12] the thermomechanical integrity of films and multilayers [13], the mechanics of crack growth along interfaces [14], residual stresses and their origin [15]. The present review differs from these by focusing on the quantitative aspects of thin film decohesion and its measurement. Most thin film adhesion tests empirically infer the adhesive strength by subjecting the film to some external loading (like scratching, pulling or inflating) and measuring the load at which decohesion occurs. These tests are simple and effective for routine ranking of bond quality. However, they do not measure  $\Gamma_i$ , because the strain energy release rate cannot be deconvoluted from the work done by the external load [12]. An ideal test should *duplicate* the practical situation as closely as possible and be able to modulate the available strain energy. It must also explicitly incorporate the contribution to decohesion from the residual stress. The test methods are assessed against this ideal.

## 2. Mechanics of Thin Film Decohesion

### 2.1. Basic Principles

Most decohesion problems of interest involve films subject to residual tension. This case is given the major emphasis in the present article. Relatively few remarks are made about the corresponding problem when the films are in compression. Films in tension are able to decohere from the substrate by relaxing the residual stress in the film above the interface crack. For the simplest case of a thin, homogeneous film subject to uniform residual stress on a thick substrate, the steady-state energy release rate,  $\mathcal{G}_{ss}$ , for an interface crack is given by *the strain energy in the film*. The non-dimensional form for a film is,

$$\Pi = \bar{E}\mathcal{G}_{ss}/\sigma_R^2h \quad (2.1)$$

where  $\Pi$  is a non-dimensional quantity of the order unity. The same form arises for other problems, but its numerical magnitude differs, as elaborated below.

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