Fracture mechanics for thin-film adhesion

by M. D. Thouless

The essential elements of the mechanics of delamination are reviewed and their implications for design are discussed. Two important concepts for the prediction of the reliability of thin-film systems are emphasized: 1) limiting solutions for the crack-driving force that are independent of flaw size, and 2) "mixed-mode fracture." Consideration of the first concept highlights the possibility of *flaw-tolerant* design in which the statistical effects associated with flaw distributions can be eliminated. The significance of mode-mixedness includes its effect on crack trajectories and on the interface toughness, two key variables in determining failure mechanisms. Theoretical predictions are given for some cases of delamination of thin films under compressive stresses, and the results are compared with experimental observations to illustrate appropriate design criteria for the model systems studied.

Introduction

The measurement of adhesion is a subject that has attracted much attention at both practical and theoretical levels. As a result, many techniques for measuring adhesion have been proposed [1]. In some situations, a measurement of adhesion is made only to provide a qualitative and comparative index of different materials and processing methods. Under these conditions, it does not matter if the results are dependent on the geometry of the sample or the nature of the test. However, an adhesion measurement is frequently made in the expectation of some predictive capability. In fact, one of the issues underlying a substantial portion of research on adhesion is whether adhesion measurements can provide a reliable indicator of actual performance in service. In these cases, it is important to use a measurement technique which ensures that the measured quantity is one that has some meaning outside the immediate context of the test. One fundamental quantity that characterizes an interface is the energy, 2γ, required to separate a unit area of the two bonded surfaces. This is often referred to as the thermodynamic work of adhesion (and denoted as W_A), and is defined as

$$2\gamma = (\gamma_1 + \gamma_2) - \gamma_{12}, \qquad (1)$$

where γ_{12} is the energy of the interface, and γ_1 and γ_2 are the surface energies of the two materials, 1 and 2, on either side of the interface. Another quantity that characterizes the bonding across an interface is the theoretical strength of the interface. One can conceive of a theoretical experiment to measure both quantities in which two bonded materials are separated in a uniform fashion while the load and displacement are monitored [**Figure 1(a)**]. The form of the applied stress versus displacement plot that would be obtained is shown schematically in **Figure 1(b)**, where the area under this curve represents

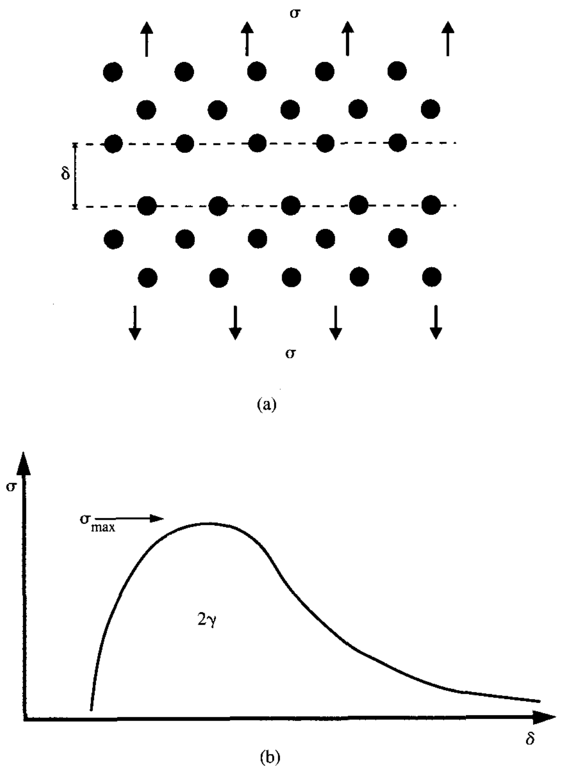

Figure 1

(a) Uniformly separating an interface by an applied stress, σ, would give (b) an idealized stress-displacement (σ vs. δ) plot yielding both the thermodynamic work of adhesion, 2γ, and the theoretical strength of the interface, σ_{max}.

the thermodynamic work of adhesion, and the peak stress, σ_{max}, gives the theoretical strength of the interface. Experimental techniques, such as laser spallation [2], have been developed which generate very high strain rates, and yield values for interface strengths that approach the theoretical strength. However, interfaces do not generally fail in this ideal fashion. More typically, delamination occurs through crack growth: localized breaking of bonds in the highly stressed region at the tip of a propagating crack. This localization results in failure occurring at applied stresses much lower than the theoretical maximum.

The framework for analyzing crack growth has been established by the field of fracture mechanics [3]. One important concept is that the change in the total mechanical energy of a system associated with the propagation of a crack provides the driving force for delamination. This driving force, $\mathcal{G}$, which is also referred to as the energy-release rate, is the energy available to separate a unit area of interface, and is given by

$$\mathcal{G} = \frac{\partial}{\partial A}(W - U), \tag{2}$$

where A is the crack area, W is the work done by any external loads, and U is the elastic strain energy stored in the system. The crack propagates, and delamination occurs, if $\mathcal{G}$ is larger than the energy required to separate a unit area of interface, Γ. This quantity, Γ, is referred to as the toughness, or fracture resistance, of the interface. It is measured experimentally by determining the load required to propagate a sharp crack, performing an elastic calculation to calculate the value of $\mathcal{G}$ appropriate for the load and geometry, and equating the toughness of the interface to this value of the energy-release rate. It can be shown that, ideally, Γ is identically equal to the quantity 2γ defined in Equation (1) [3]. However, this equality is found experimentally only in very weak interfaces, such as when the interfacial bonding is provided by the capillary force of a liquid [4, 5]. More generally, the surface energy represents only a small portion of the total energy consumed in separating an interface by a propagating crack. The bulk of the energy is dissipated by dislocation emission, flow, or other irreversible processes occurring in a process zone at the crack tip.

In homogeneous materials, the toughness can be taken to be a material constant, provided certain restrictions are placed on the size of the sample. This means that a value of toughness determined by measurements made on a laboratory specimen can be used to predict the conditions for crack propagation in a product under service conditions. In the aerospace and pressure vessel industries, particular success has been achieved in incorporating the concepts of fracture mechanics in design against failure by crack propagation. In contrast, the practical use of these concepts in the electronics industry is very rare. However, even if not explicitly stated, one of the questions motivating much of the research on adhesion within the electronics community is whether adhesion measurements can be successfully incorporated in design. This paper therefore reviews some of the issues involved in applying fracture mechanics to one particular geometry of importance for electronic components, namely, the adhesion of films to substrates.

Mechanics of thin-film delamination

As in all fracture problems, the delamination of a film from a substrate to which it is attached can be expected to occur only if there is both a pre-existing flaw and a driving force for crack propagation. In this context it should be noted that, except under special circumstances, the singularities in the stress field that may exist at corners or cut-outs in the film are not strong enough to provide a crack-driving force in the absence of any flaw [6]. Although the initiation of interfacial damage has not been extensively studied, one might imagine that suitable flaws could be introduced by processes such as contamination during deposition of a film, diffusion of corrosive species from the environment onto the interface, localized plastic flow in high-stress regions, or contact damage. For example, interfacial flaws at the edge of a film can be readily introduced by damage occurring during dicing, in which a large coated system is cut into smaller components.

In general, the driving force, $\mathcal{G}$, depends on both the flaw size and the film thickness. There are, however, two limiting cases. For a very small interfacial flaw, one much less than the thickness of the film, the energy-release rate scales with the size of the flaw. In contrast, when the length of the interface crack is substantially larger than the film thickness, $\mathcal{G}$ often exhibits a maximum value which is independent of crack length and scales only with the film thickness. This is illustrated in **Figure 2**, which shows plane-strain, finite-element results of the energy-release rate for a crack developing from the free edge of a film under a uniform residual tension, σ_0 [7]. In this figure l is the crack length, h is the film thickness, E is Young's modulus of the film, and ν is Poisson's ratio of the film. Many other geometries and loading conditions also share the important characteristic of a maximum energy-release rate that scales with the film thickness. For example, **Figure 3** shows how the crack-driving force varies with crack length for an axisymmetric geometry in which a circular region of delamination spreads under a uniform tension from an initial circular defect within the film [8].

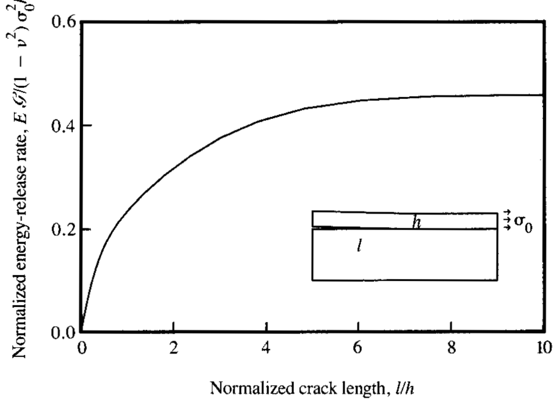

Figure 2

Finite-element results for the energy-release rate of a crack of length l developing from the free edge of a film under a uniform residual stress σ_0. (The substrate depth for this calculation was 30 times the film thickness, h [7].)

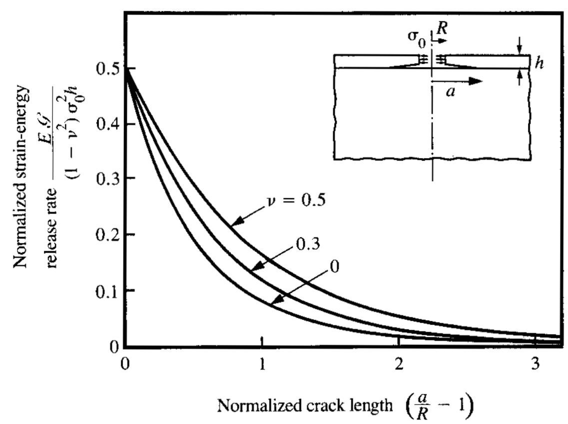

Figure 3

Analytical results for the crack-driving force, $\mathcal{G}$ for an axisymmetric crack of radius a propagating under a residual stress σ_0, from a circular defect of radius R within a film of thickness h. The modulus of the film is E, and the results are plotted for different values of Poisson's ratio, ν, of the film. From [8], reproduced with permission.

- *General solutions for delamination*

Energy-release rates can often be obtained from simple energy-balance considerations, and, as is discussed in a following section, they can provide some basis for establishing failure criteria when designing for mechanical reliability of electronic components. However, because the energy-release rate is a scalar quantity, it provides no information about the distribution of stresses around the crack tip. The information on this field is provided by the stress-intensity factors: components of a vector quantity that characterizes the crack-tip stress field in an elastic body. The stresses at a crack tip exhibit a square-root singularity, and the stress-intensity factors indicate the value of the stresses at a fixed distance from the crack tip. In general, three types of stress must be considered: normal stresses acting across the crack plane, shear stresses, and out-of-plane shear stresses. The stress-intensity factors associated with these stresses are designated the mode-I, mode-II, and mode-III components, K_{I}, K_{II}, and K_{III}, respectively. For the purposes of this paper, geometries for which only the first two components are relevant are considered. Then, for a homogeneous material, the energy-release rate is related to the stress-intensity factors by

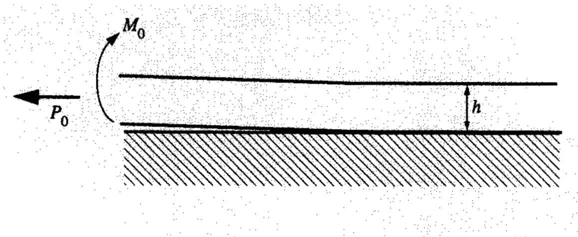

Figure 4

The geometry that provides the basic mechanics for a wide variety of delamination problems. An axial force, P_0, per unit width, acts along the neutral axis of a film of thickness h in conjunction with a bending moment M_0 [9].

$$\mathcal{G} = \frac{(1-\nu^2)K_{\mathrm{I}}^2}{E} + \frac{(1-\nu^2)K_{\mathrm{II}}^2}{E}. \qquad (3)$$

Determining stress-intensity factors generally involves considerably more calculation than obtaining an energy-release rate. However, as is discussed in a later section, it is often important to do so, because many aspects of delamination are dictated by the symmetry of the crack-tip stress field. Fortunately, there now exist some beautifully general results which can be used to deduce the mechanics of a broad range of two-dimensional and axisymmetric delamination problems [9]. The basic geometry is illustrated in **Figure 4**, which shows a film attached to a substrate with a semi-infinite crack parallel to the free surface of the film. An axial force, P_0, per unit width, acts along the neutral axis of the film with a bending moment, M_0, per unit width. The elastic properties and the relative thicknesses of the film and substrate can, in general, be different; the only requirement is that both the film and substrate should be linearly elastic and isotropic. Indeed, using standard techniques of simple beam theory for analyzing composite beams, both the film and the substrate in this figure can represent multilayer structures [10, 11]. The general utility of the solutions to the type of problem illustrated in Figure 4 arises because any arbitrary stress state acting on a film can be recast in terms of the two parameters, P_0 and M_0, when the crack length is much larger than the film thickness. Therefore, the fracture mechanics analysis of many geometries can be reduced to a determination of the appropriate values of the effective axial force, P_0, and the bending moment, M_0.[1] Examples can be found in the literature for a number of stress distributions and loading conditions such as those occurring in the peel test [12], the blister test [13, 14], the cut-film test [15], buckling-driven delamination [16, 17], and substrate cracking [10, 11, 18].

For a full discussion of the solutions to the general problem of Figure 4, the reader is referred to the recent review paper by Hutchinson and Suo [9] and to the associated original research papers [18, 19]. For the purposes of this paper, attention is focused on the limiting solution in which the substrate is infinitely thick and has the same modulus as the film. The mode-I and mode-II stress-intensity factors, K_{I} and K_{II}, acting at the crack tip are then [7]

$$K_{\mathrm{I}} = -0.434P_0h^{-1/2} + 1.934M_0h^{-3/2},$$
$$K_{\mathrm{II}} = -0.558P_0h^{-1/2} - 1.503M_0h^{-3/2}. \qquad (4)$$

Often, it is more convenient to express this result in terms of an energy-release rate given, for plane-strain conditions, by

$$\mathcal{G} = (1-\nu^2)(P_0^2 + 12M_0^2/h^2)/2Eh \qquad (5)$$

and a phase angle ψ defined [9] as

$$\psi = \tan^{-1}(K_{\mathrm{II}}/K_{\mathrm{I}}) = \frac{\sqrt{12}(M_0/P_0h) + \tan\omega}{-\sqrt{12}(M_0/P_0h)\tan\omega + 1}, \qquad (6)$$

where ω is a constant, which in the present case of interest is equal to 52.1°. This phase angle indicates the relative magnitudes of the shear and normal components of the crack-tip deformation. For example, $\psi = 0°$ represents a pure mode-I (opening) deformation, and $\psi = 90°$ represents a pure mode-II (shear) deformation.

Mixed-mode fracture

In an isotropic material with no interfaces, a crack propagates along a path that locally maximizes the energy-release rate. This trajectory is one for which K_{II} is essentially zero. In contrast, a crack forced to grow along an interface between a film and substrate is generally subject to some shear. One consequence of this [20, 21] is that the crack-driving force is greater in a direction other than along the plane of the interface, and there is a possibility that the crack may be forced off the interface. It is this effect that is frequently responsible for what is sometimes termed "cohesive" failure (when fracture occurs in the vicinity of the interface, but leaves the interface intact) rather than "adhesive failure" at the interface itself. The direction in which the crack leaves the interface depends on the sign of K_{II}. As defined in Figure 4 and Equation (6), a negative value of K_{II} causes the crack to kink into the film, whereas a positive value of K_{II} causes the crack to kink into the substrate. Consequently, an

[1] This is valid when delamination occurs as a result of applied or residual loads, or a combination of both. If the effect of a residual load is being considered, P_0 and M_0 are the load and moment required to appropriately relax the constraint imposed by the substrate. For example, if a film delaminates from the edge of a sample under the influence of a residual, tensile, and uniform stress, σ_0, then $P_0 = -\sigma_0 h$ and $M_0 = 0$. The same values of P_0 and M_0 are appropriate for the case in which the film delaminates under the influence of a uniform applied compressive stress, $-\sigma_0$. If the residual stress is not uniform but, for example, varies linearly from $-\sigma_0$ at the interface to σ_0 at the top surface, then $P_0 = 0$ and $M_0 = \sigma_0 h^2/6$.

interfacial crack propagating under a film subjected to a residual tensile stress may crack the substrate, whereas an interfacial crack propagating as a result of a peel force tends to crack the film. Whether the crack actually leaves the interface depends on a number of factors: the relative toughness of the interface and surrounding materials, the existence of pre-existing defects in the region of the interface, kinetic considerations of crack propagation in the interface and surrounding materials, and whether there are any stresses that may stabilize the crack at the interface.

An important example of failure occurring away from the interface can be seen when metals or polymers under residual tension are bonded to brittle substrates such as glass, ceramics, or silicon. Assuming that the tension is uniform through the thickness of the film, an interfacial crack will be driven into the substrate unless the substrate is about four times as tough as the interface [20, 21]. Once the crack has left the interface, it follows a trajectory along which $\psi = 0°$ (pure mode I). This then evolves into a steady state at a fixed depth beneath the interface, as illustrated schematically in **Figure 5** [10, 22]. The depth at which the crack propagates depends on the relative moduli of the film and substrate, and on the stress distribution within the film [7, 11, 18]. If the modulus of the film is much less than that of the substrate, the crack depth will be shallow, and if the film is stiffer than the substrate, it will be much deeper. **Figure 6** gives a plot of how the crack depth varies with the modulus ratio for the case of a uniform, tensile residual stress [11]. Although this geometry is of great practical importance to electronic applications, and the predictions for the steady-state trajectory have been confirmed experimentally [10, 11], there appear to be other situations, for example in some peel tests of polyimides from metal surfaces [23], in which a steady-state trajectory is established in contradiction to mechanics predictions. The steady-state trajectory away from the nominal interface in these cases would seem to indicate that an interphase zone has been established by the processing, and that the crack is in fact running along a new interface.

Even if it does not drive the crack off the interface, a mode-II component of the stress-intensity factor can still have an important influence on the fracture behavior. There is considerable evidence that the toughness of an interface depends on the relative amounts of shear to normal deformation at a crack tip, with the toughness generally increasing with the magnitude of ψ [24–27]. **Figure 7** shows an example of such a dependence for a model interface between a sheet of mica and a thermosetting resin. There are a number of explanations for why the toughness might increase with shear stress, including the possibility of frictional interactions [28] and

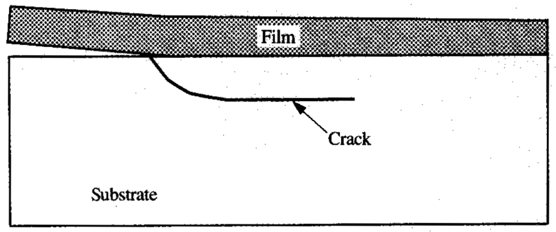

Figure 5

Schematic illustration of substrate spalling under a film with a residual tension. An interface crack is driven into the substrate by the mode-II component of the stress-intensity factor. The crack then grows in a $K_{II} = 0$ trajectory parallel to the interface.

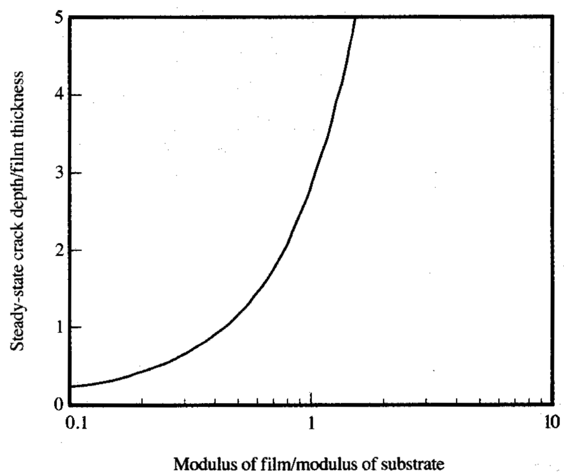

Figure 6

Steady-state depth of the $K_{II} = 0$ trajectory for a crack propagating in a substrate beneath a film with a uniform residual tension [11].

changes in the size and shape of any energy-dissipation zone at the crack tip. The fact that interfacial toughness is not a constant but depends on the nature of the loading has important ramifications. In particular, accurate predictions about the failure of an interface can be made only if the appropriate toughness for the loading conditions is known. Therefore, any program to characterize the adhesion of an interface should encompass toughness measurements over a wide range of phase angles.

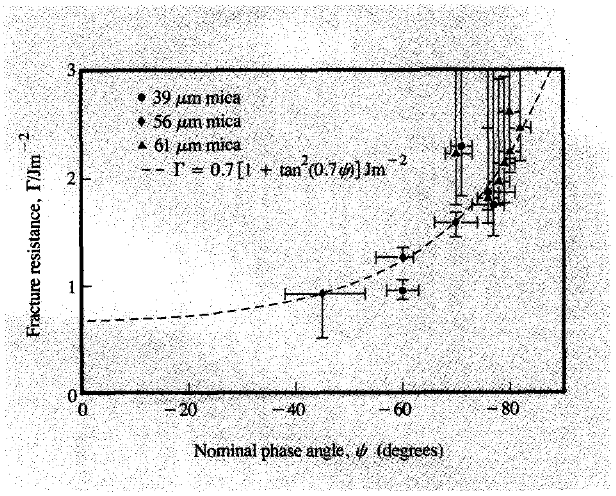

Figure 7

Apparent toughness, Γ, as a function of phase angle, ψ, for a mica–resin interface measured by a blister test. The dashed line represents an empirical fit to the data used in subsequent failure predictions. From [14], reproduced with permission.

Design issues

In general, the strength of a brittle material depends on the size and location of any defects. This dependence introduces a statistical element into designing against failure by crack propagation: Assumptions have to be made either about the nature of the flaw distribution or about the probability of detecting a critical flaw. In contrast to this, the energy-release rate for the delamination of a film has an upper bound which is dictated by a well-characterized dimension: the film thickness. This dependence on the film thickness suggests a possible framework on which to base design criteria for the reliability of film–substrate adhesion. If an appropriate value for the interfacial toughness, Γ, is known, the upper bound for $\mathcal{G}$ can be used to establish a conservative criterion for limiting either the thickness of the film or the maximum allowable stress.

A first approximation for predicting the failure of an interface might involve setting $\mathcal{G}$ to the mode-I toughness of the interface, Γ_{Ic}. However, more sophisticated predictions can be made if the variation of Γ with ψ is known. For example, by fitting the data of Figure 7 for a mica/resin interface to a purely empirical relationship of

$$\Gamma = \Gamma_{\mathrm{Ic}}[1 + \tan^2 0.7\psi], \qquad (7)$$

where $\Gamma_{\mathrm{Ic}} = 0.7\ \mathrm{Jm}^{-2}$, predictions have been made and successfully compared to experimental observations for different delamination mechanisms which can occur when the bonded mica sheet is subjected to a compressive stress. This was chosen as a model system to study because mica can be obtained in films of very uniform thickness. It is elastic and relatively tough normal to the laminar interfaces. It is also optically transparent, which permits the delamination to be monitored. Furthermore, the compressive stress in the film can be readily controlled, either by applying an external load or by relying on a thermal-expansion mismatch between the mica and substrate [16, 17]. Two particular examples of using the mixed-mode failure criterion to predict the conditions for delamination are illustrated: an axisymmetric geometry in which a circular defect of radius R exists at the mica/resin interface, and a plane-strain geometry. In the axisymmetric case, the circular defect spreads under a biaxial compressive stress of magnitude σ_0 and eventually develops into the wavy delamination pattern characteristic of films under compression (**Figure 8**) [29–31]. In the case of the plane-strain geometry, a strip of delamination of width $2b$ spreads in response to an applied compressive stress of magnitude σ_a (**Figure 9**).

Figure 10 shows experimental data of the conditions required for circular defects to spread. Superimposed on this plot is the theoretical prediction for delamination based on the failure criterion of Equation (7) [16]. It can be seen that there is a limiting condition of

$$\sigma_0^2[(1 - \nu)h/E] \simeq 4\Gamma_{\mathrm{Ic}}, \qquad (8)$$

below which fracture is predicted not to occur. Experimental data for the conditions at which delamination was observed to spread from a plane-strain blister are plotted in **Figure 11**, along with the theoretical prediction for delamination, again based on the failure criterion of Equation (7). As in the previous example, the predictions for failure are in excellent agreement with the experimental observations and, for design purposes, there is a lower bound for delamination below which failure will not occur [17]:

$$\sigma_a^2[(1 - \nu^2)h/E] \simeq 3.2\Gamma_{\mathrm{Ic}}. \qquad (9)$$

Finally, the design process must also consider the possibility of failure by mechanisms other than those that involve the interface. Examples include cracking of a brittle film [32–34], as well as cases in which a crack is driven off the interface in response to the stress state. This possibility of competing failure mechanisms cannot be ignored in the design process. The example given earlier of an interface crack under a film subjected to a uniform residual tension σ_0 illustrates some of the range of behavior that must be considered. The first requirement for avoiding failure is that the stress should be sufficiently low so as not to cause delamination of the interface, i.e.,

$$\sigma_0^2[(1 - \nu^2)h/E] < 2.0\Gamma_{\mathrm{i}}\{\psi = 52°\}, \qquad (10a)$$

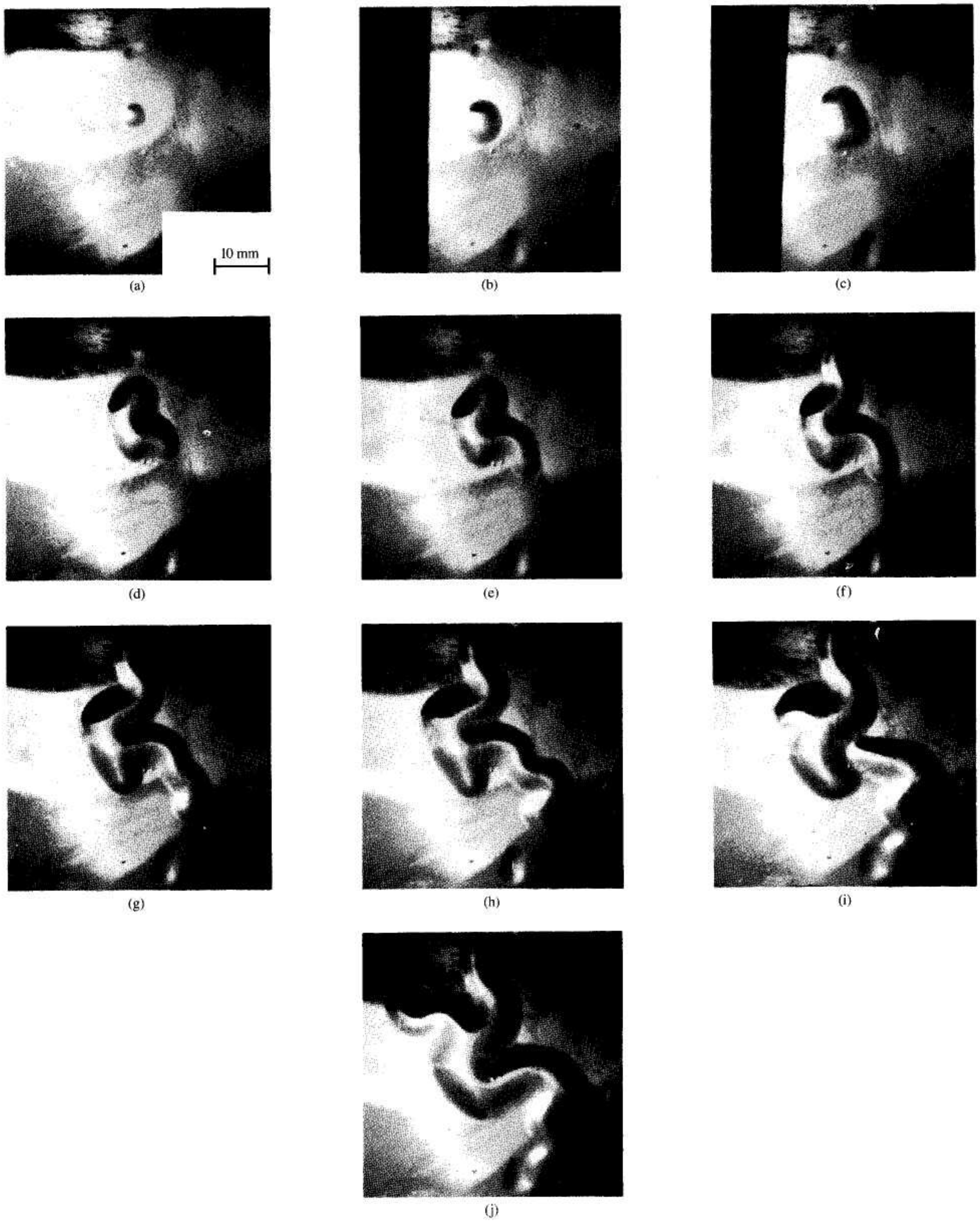

Figure 8

Failure sequence from a circular defect at a mica–resin interface. The mica film is under an equi-biaxial compressive stress σ_0. The sequence illustrates (a) the initial defect, (b, c) its loss of axisymmetry, and (d–j) the eventual development of ''worm-like'' delamination patterns characteristic of compressively stressed films. From [16], reproduced with permission.

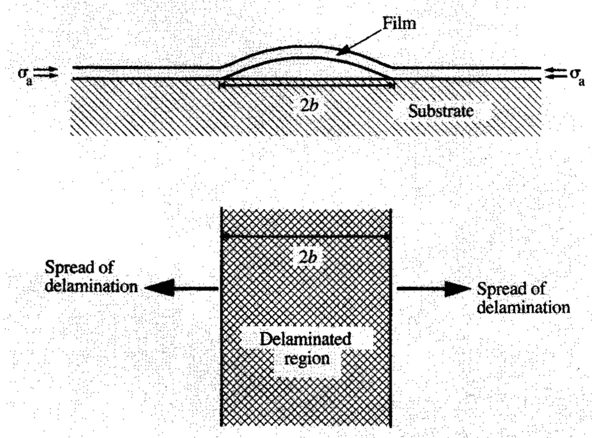

Figure 9

A schematic illustration of buckling-driven delamination for a plane-strain geometry. A compressive stress, σ_a, is applied to the film and results in the film buckling above a strip of delamination of width $2b$. The buckling then provides a driving force for further delamination which increases the width of the blister [17].

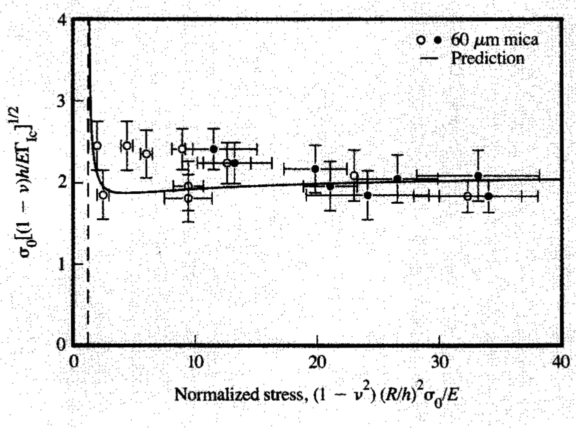

Figure 10

Comparison between theoretical predictions and experimental results for delamination from a circular defect of radius R when the film is under a biaxial compressive stress σ_0 [16]. The modulus of the film is E, Poisson's ratio is ν, and the thickness is h. The predicted curve is based on the mixed-mode failure criterion of Equation (7) established by the data of Figure 7. Γ_{Ic} is the mode-I fracture toughness of the interface, taken to be 0.7 Jm^{-2}. The open and closed symbols are for data obtained for the initiation and arrest of delamination, respectively. Redrawn from [16], reproduced with permission.

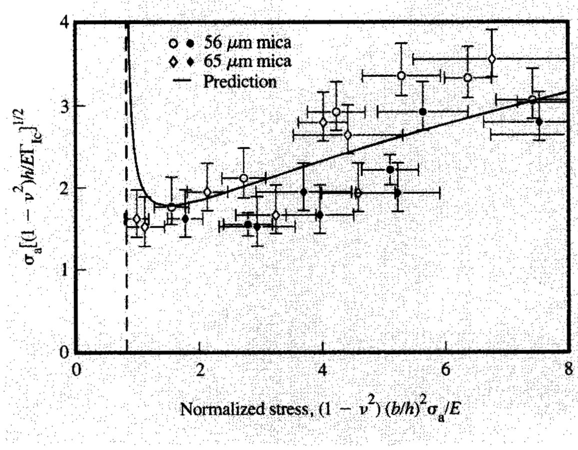

Figure 11

Comparison between theoretical predictions and experimental results for delamination from a plane-strain blister of width $2b$ when the film is under an applied stress σ_a [17]. The modulus of the film is E, Poisson's ratio is ν, and the thickness is h. The predicted curve is based on the mixed-mode failure criterion of Equation (7) established by the data of Figure 7. Γ_{Ic} is the mode-I fracture toughness of the interface, taken to be 0.7 Jm^{-2}. The open and closed symbols are for data obtained for the initiation and arrest of delamination, respectively.

where $\Gamma_i\{\psi = 52°\}$ is the interface toughness at a phase angle of 52°, appropriate for these conditions. If the crack leaves the interface and enters the substrate, it follows a $K_{II} = 0$ trajectory to the steady-state depth discussed earlier. As the crack goes along this path, the energy-release rate decreases until it reaches the steady-state depth. Therefore, under certain conditions the crack can be drawn out of the interface and arrested within the substrate. Although mechanical failure is then avoided, this limited cracking could cause electrical failure if it occurs within an electrically active site. Therefore, if this possibility of electrical failure is an issue, the stress must be kept below a value that satisfies

$$\sigma_0^2[(1 - \nu^2)h/E] < 1.2\Gamma_s\{\psi = 0°\}, \tag{10b}$$

where $\Gamma_s\{\psi = 0°\}$ is the mode-I toughness of the substrate, which is about 4 Jm^{-2} for silicon in air [35]. At the other limit, catastrophic substrate cracking occurs if

$$\sigma_0^2[(1 - \nu^2)h/E] < 2.9\Gamma_s\{\psi = 0°\}. \tag{10c}$$

These three conditions can be expressed graphically on a map of failure mechanisms, as shown in **Figure 12,** and similar maps can also be drawn for other mechanisms of film failure [36–38].

Conclusions

The primary concern in the design of electronic components is obviously to maximize electrical performance. However, another important consideration should be component reliability. This paper has shown how an appreciation of the mechanical issues, especially the causes of delamination of the constituent layers of a component, can be used to enhance reliability. The fundamental concern is simply to prevent mechanical failure from occurring. This goal could, in principle, be pursued by controlling the processing to such a degree that all defects that could initiate failure are eliminated. The inherent danger of such an approach, however, is that it does not make provisions for unforeseen perturbations in processing. A more productive approach is the possibility of developing *flaw-tolerant* design criteria based on the geometry and mechanics of thin-film adhesion. This may perhaps allow the elimination of the statistical element associated with any flaws introduced during processing or service.

The possibility of using this approach arises because the maximum energy-release rate for delamination scales with the well-defined dimension of film thickness rather than depending on the more uncertain parameter of crack length. Provided that appropriate values of the toughness are known, the maximum energy-release rate provides a conservative bound for the maximum stress or film thickness that can be tolerated in a given system. In general, such an approach could provide a means of setting a maximum limit on the allowable tolerances for the film thickness. In a more restrictive design, it might suggest the point at which alternative processes should be developed to limit the stresses or to enhance the appropriate toughness. For such an approach to be successfully utilized, many issues in the characterization of adhesion must be addressed. One of the key issues—the response of the interfacial toughness to mixed-mode loading—has been discussed above. Some of the others, such as the interpretation of adhesion measurements and time-dependent failure, are briefly discussed in the Appendix and suggest possible directions for future research in thin-film adhesion.

Appendix: Additional considerations for adhesion measurements

Probably the best-recognized problem in measuring adhesion is that many measurement techniques result in large amounts of plastic deformation within the film. The most notorious of these are the peel test and various forms of the blister test. For example, analyses by Kim et al. [39–41] have shown that in the peel test of copper films, energy dissipated by plastic deformation can swamp any quantity that could reasonably be considered to be a value of the interfacial toughness. The problem is sufficiently severe that any such values are rendered useless for design purposes. Only if adhesion is very poor, or if the films are very hard, can a peel test provide a measure of adhesion that is useful for any purposes other than comparing different processing techniques. A related problem is that, for thin-film geometries, the small-scale yielding conditions required for geometry-independent toughness measurements may be violated. In thin films, it must be expected that any nonlinear process zone at the tip of an interface crack may extend through a significant portion of the film. The size and shape of the process zone are then controlled by geometrical considerations in addition to the elastic stress field. Since the toughness of an interface is generally dominated by this process zone, it may change with the film thickness and be affected by the presence of additional layers above the film. Thickness-dependent values of toughness have been noted for copper films bonded between brittle substrates[2] and in some studies of

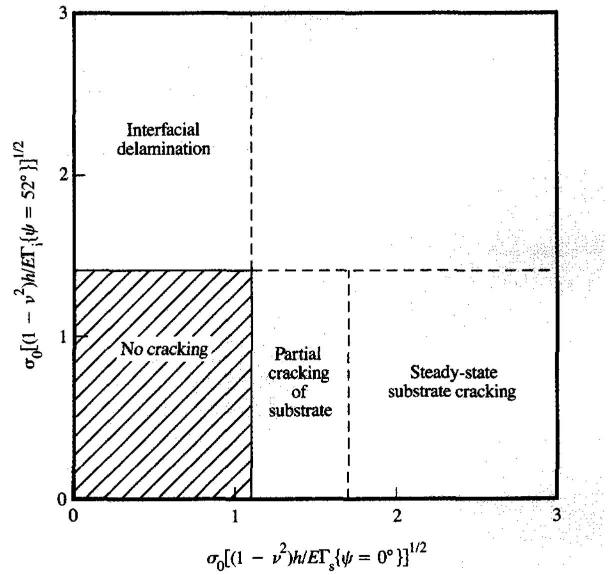

Figure 12

A map of possible failure mechanisms for a tough film bonded to a substrate with the same elastic properties, and subjected to a uniform, tensile stress of σ_0. The phase angle for delamination along the interface under these conditions is $\psi = 52°$ (approximately equal shear and normal components), so the appropriate toughness is the interfacial toughness measured at $\psi = 52°$, $\Gamma_i\{\psi = 52°\}$. The appropriate toughness when fracture occurs in the substrate is that of the substrate, $\Gamma_s\{\psi = 0°\}$, measured under pure mode-I conditions. From [36], reproduced with permission.

[2] R. M. Cannon, Lawrence Berkeley Laboratory, private communication, 1992.

adhesive layers [42]. An important and unresolved issue is, therefore, whether there are conditions when values of toughness measured in regimes where small-scale yielding is violated can be interpreted with sufficient accuracy to provide at least some guidance in design and failure prediction.

A final concern that must be mentioned in this Appendix is the possibility of time-dependent failure of interfaces. The discussion in this paper has been predicated on the assumption that there is a critical value of energy-release rate required for crack growth. In practice, it must be appreciated that subcritical crack growth can occur under both static and cyclic loading. The crack velocity depends not only on the crack driving force, but also on the nature of the environment [43, 44]. Under these circumstances, the question of lifetimes must enter the design considerations, and crack velocities must be determined for the appropriate conditions.

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