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978-1-107-13186-6 — The Mechanics and Reliability of Films, Multilayers and Coatings
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Excerpt
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1 Introduction

A ‘generic’ system consisting of bonded layers of different materials and illustrations of various failure modes are shown in Figure 1.1. Arguably, the two dominant technological applications with this type of geometry are microelectronic devices and protective coatings in extreme environments (e.g., thermal barrier coatings). These applications involve layers with very disparate properties and are subjected to rather aggressive external stimuli. Cracking happens either between the layers (interface delamination or debonding) or within a layer (tunneling or channeling cracks). Delamination can occur regardless of whether the stresses are tensile or compressive, while buckling-driven delamination occurs only in layers experiencing compressive stress, and channeling or tunneling cracks require tensile stress in the layers.

Failure can be driven by a variety of factors, but it is probably fair to state that the integrity of the vast majority of multilayered devices is controlled by the layers' tendency to expand at different rates in response to thermal, mechanical or chemical stimuli. In essence, when left by their lonesome, the layers expand differently in response to temperature fields, mechanical loading and so forth. However, in the multilayer component they are not alone: they are constrained to experience conformal deformation where they are bonded. This constraint generates stresses (both tensile and compressive) and stored elastic energy that drive system failure. Crudely speaking, the layers would be happiest and in their lowest energy state as separate pieces, and they seek to return there – even if it means splitting themselves into pieces and leaving part of themselves stuck to another layer.

As with the development of any predictive framework, the initial challenge is to reduce the complexity of the actual system to produce a model that captures the salient features of the system, while ignoring those details that have little effect on the behavior of interest. This can be a critical step in the development of multilayered systems, because their geometrical and multimaterial complexity can make full numerical representations extremely costly. Make no mistake: this is an art.[1] Further, it can be highly problem specific. Nonetheless, there are some central idealizations that are widely applied to thin film systems that have served to generate considerable general insight regarding failure. These idealizations involve eliminating at least one, and very often

[1] As epitomized by the late Tony Evans, the Michaelangelo of knowing what to paint and what not to paint in a multilayer problem.

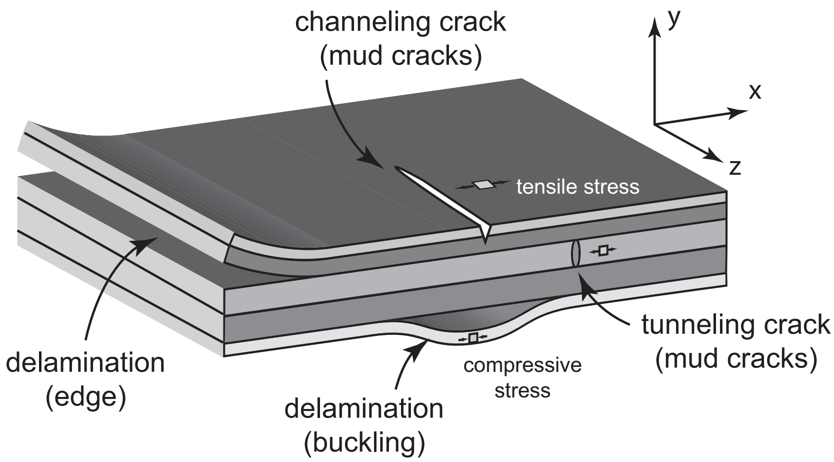

Figure 1.1 A general multilayer made up of thin films and common failure modes; some failure modes occur regardless of the sign of the stresses in the layers (e.g., delamination), while others require either tensile stress in the layer (e.g., channeling and tunneling cracks) or compressive stress in the layer (e.g., buckling-driven delamination). In some failure modes (e.g., edge delamination or channeling cracks), the driving force for crack growth becomes independent of crack length for very long cracks and scales with the layer thickness: this is referred to as ‘steady-state’ cracking.

two (or even more), of the length scales associated with the failure modes shown in Figure 1.1.

Consider the edge delamination crack shown in Figure 1.1. The most common step is to eliminate from consideration the dimension in the z-direction, either because the structure is very thin in that direction (plane stress) or very wide (plane strain). The problem is now two-dimensional, but still with (at least) three length scales: the (x, y) dimensions of the component and the crack length. We fully enter the realm of ‘multilayer analysis’ (as it is commonly used) when we assume the x dimension is much larger than either the y dimension or the crack length. In such cases, the problem consists of ‘thin’ layers bonded together. If the crack length and y dimensions are comparable, we are left with a two-dimensional problem with (at least) two characteristic length scales. Still, it is common to go a step further: suppose the crack length is much larger than the y dimensions: we now have a two-dimensional problem dominated by y dimensions (i.e., layer thickness).

This is arguably the central reference point in the multilayer failure universe: the semi-infinite crack in a semi-infinite plane of thin layers. Herein, this geometry is referred to as consisting of *blanket films*, since the only relevant dimensions are layer thickness. In this reduced problem space, many important aspects of the response – such as the stresses in the layers away from the crack tip and the energy released by crack advance – can be solved for analytically or with highly efficient one-dimensional numerical tools. (As will be discussed, a critical feature of the response – the behavior near the crack tip – will require a two-dimensional numerical analysis.) Cracking in this scenario is referred to as ‘steady-state’ because a change in the crack length does not

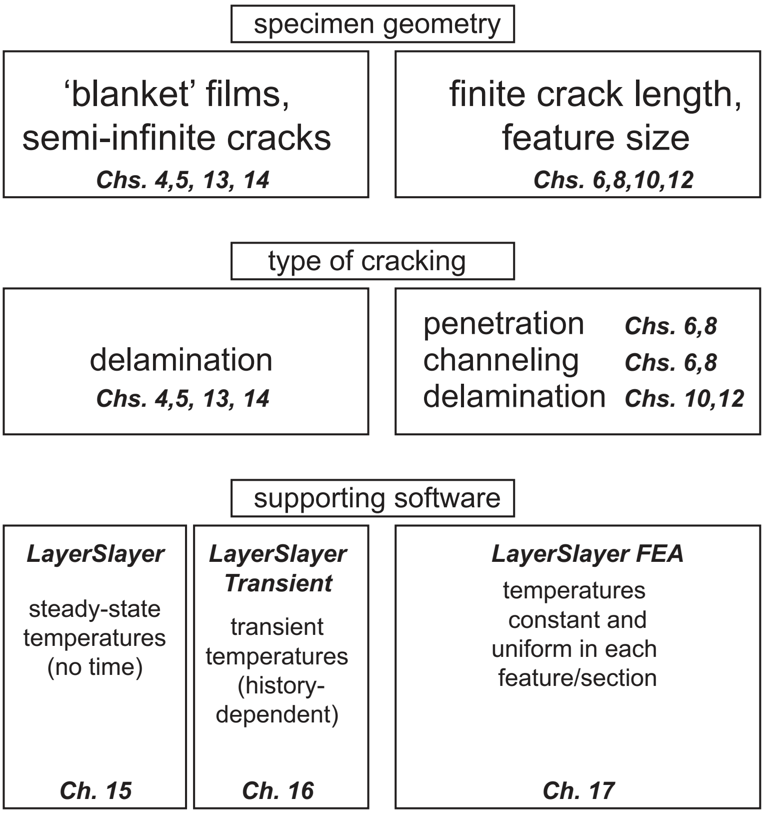

Figure 1.2 A snapshot view of the multilayer problems addressed in this book, the chapters covering each subject and the supporting LayerSlayer software that is provided to analyze various failure modes.

impact the problem: the geometry and solution are self-similar as the crack advances. In many instances, steady-state cracking results in the maximum possible driving force for cracking, which means this idealization plays a central role in conservative designs. In summary, the blanket film scenario is the easiest to analyze and most pessimistic (i.e., it is assumed that a large interface flaw exists) and therefore takes center stage in multilayer design.

Because this process of reducing the dimensionality of the problem is so central to analysis, it is worth repeating for a different failure mode. Consider the channeling crack shown in Figure 1.1. Here, we assume that the length of the crack in the z-direction is much larger than the dimensions in the (x, y) plane, and that the total dimension of the multilayer in the z-direction is even larger still. Thus the device is 'infinite' in the z-direction while the crack is 'semifinite'. Since the problem is self-similar in the z-direction, the channel crack is at steady state with regard to propagation in this direction. It turns out that one can get the relevant quantities that control propagation of the crack in both the z *and* y directions (i.e., growth through the stack) by analyzing the (x, y) planes ahead of the crack in the intact layer, and far behind the crack tip (where the crack is open). In some cases, the analysis can be analytical: in others, numerics are required. As you might expect, it is easiest to illustrate whether analytical analysis or numerical analysis is needed by presenting the assumptions associated with the analytical approach and then discussing when these assumptions are likely violated.

Once the geometry has been suitably simplified (if possible), the question then arises: what to compute? The answer in the simplest terms includes stresses, displacements and the strain energy associated with those quantities. The strain energy plays the central role, as it creates the driving force for failure because energy is released by crack advance. The rest of this book is basically just an illustration of what to compute, how to compute it and then how to use these results to predict whether or not something will fail. The associated theory is discussed principally in the context of examples involving blanket films, and then extended to more complicated geometries for which numerical analysis is required.

A powerful feature of this book is that software is provided to compute the parameters controlling failure modes such as those shown in Figure 1.1, complementing the text, which focuses largely on theory. Figure 1.2 provides an overview of the book's content, organized by geometric idealization, cracking mode and associated software – with indications of the chapters that provide the underlying theory. The chart in Figure 1.2 is intended as a handy reference for readers to identify the location of theory and software that addresses a specific type of problem.