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Book Reviews

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Thin Film Materials—Stress, Defect Formation and Surface Evolution

L. B. Freund and S. Suresh, Cambridge University Press, New York, 2004, 750 pp., $75.00

This treatise emphasizes internal stresses and their effects on fracture, delamination, and permanent deformation of thin films. Thin films have a wide range of engineering applications such as microelectronic devices, microelectromechanical systems (MEMS), and surface coatings intended for various functions such as thermal, tribological, optical, electrical, magnetic, or biological functions. Understanding the evolution of stresses in thin films is of significant importance in predicting their performance and, more important, their failure. The nine chapters cover topics that will be of interest to both applied mechanicians and material scientists. The topics range from mechanics of thin films, including fracture, delamination, and buckling, to dislocation mechanics and thermodynamic equilibrium and stability.

The book begins with an introduction and overview of the subject. A classification of various thin-film configurations and methods of fabrication are discussed in the introductory chapter. Physical and chemical vapor deposition and thermal spray deposition are some of the methods described. The principles are illustrated using thermal barrier coatings as an example. The relation between the microstructure and processing methods is explained using the principles of thermodynamics. In addition to the deposition methods, processes that are used to impart fine features in thin films are discussed. Various processes used in the fabrication of microelectronic and MEMS devices are explained. The chapter concludes with a detailed description of the origin of stresses in thin films. The stresses include both growth stresses and induced stresses. An overview of the consequences of stresses and subsequent chapters form the last section of this introductory chapter.

The second chapter, "Film stresses and substrate curvature," is devoted to the relation between curvature and stresses in thin films. A detailed derivation of the famous Stoney formula is presented using the energy method for the axisymmetric case and is illustrated with numerical examples. Effects of film thickness on curvature are discussed by considering the problem of stresses in a bimaterial (bilayer) structure. Practical methods of measuring curvature in thin films are included in this chapter. Some of the methods are the scanning laser method, multibeam optical stress sensor, grid reflection method, and coherent gradient sensor method. It has been found that grading the material composition in thin films (functionally graded films) can reduce the stresses and hence the probability of failure. Stresses in graded films and the resulting curvature are derived in this chapter. Because of their large aspect ratio (ratio of lateral dimension to thickness) thin films may undergo large deflections. Hence linear theories may not be applicable when the strains are large compared to unity. This chapter discusses the effects of large deformation on stresses, equilibrium shape, and curvature of thin films. The exercise problems at the end of the chapter will be valuable if the book is adopted as a textbook for a graduate course in thin films.

The third chapter, "Stresses in anisotropic and patterned films," is concerned with not only anisotropic film materials but also films of isotropic materials that exhibit apparent anisotropy due to inhomogeneities that may arise due to cracks, film patterning, composite films, etc. A Stoney-type formula is derived for an anisotropic film on an isotropic substrate. This chapter also includes fundamentals of anisotropic elasticity so that the subsequent discussion can be easily followed. Several worked examples are provided for understanding the concepts introduced in various sections. X-ray diffraction is one of the experimental methods that can be used to measure stresses in thin crystalline films on substrates. Expressions are derived for stresses and strains as a function of the distance between crystallographic planes, which are referred to as d-spacing. Piezoelectric thin films are used in many MEMS devices, and hence the substrate curvature due to an electric field is also derived. When a periodic array of cracks develops in thin films, the films exhibit an apparent anisotropy at macroscopic scale. A similar situation arises when periodic patterns are imparted on thin films. In such cases the actual curvature will be quite different from their isotropic counterpart. Methodologies are described for estimating the effects of periodic arrays of cracks on the curvature. The methods can be easily extended to periodic array of parallel lines or stripes.

Delamination and fracture are the dominant modes of failure in thin films, and they are the subject of Chapter 4. There are two main sites of fracture: regions of film containing defects or features such as sharp cracks, abrupt change in properties and/or cross section, and the second, more important site, the free edge where the film intersects the substrate. The nature of singularity at the free edge is discussed. Energy release rate based on the Griffith criterion is used to predict the failure of thin films due to free-edge effects. The fracture mechanics concepts are explained by deriving the crack tip stress field, stress intensity factors, and the phase angle (mode mixity) for various crack configurations. The physical mechanism of separation of surfaces (the film and the substrate) and its relation to the work of fracture are discussed in great detail. The fracture concepts are used to derive conditions under which a thin film will delaminate due to residual stresses. The procedures are illustrated for both plane delamination as well as axisymmetric (circular) delamination. Another interesting problem is that of an internal delamination approaching the free edge. The variation of crack driving force and phase angle as the delamination approaches the free edge are discussed. Although the crack driving force can be calculated using analytical or numerical methods, the interfacial fracture toughness has to be determined by performing fracture tests on some bimaterial specimens consisting of the film and substrate materials. Configurations such as double cantilever beams, four-point flexure beams, and Brazilian disks are some of the specimens discussed in this chapter. Fracture mechanics principles are used to analyze various crack configurations in thin-film structures. Some of the problems illustrated are surface cracks due to residual stresses, tunnel cracks in a buried layer, and arrays of periodic transverse cracks. Expressions for energy release rate are derived and presented in the form of nondimensional charts. Discussion on crack deflection in and out of the interface forms the last section in this chapter.

The fifth chapter, entitled "Film buckling, bulging and peeling," deals with the out-of-plane deflection of a thin film and its consequence on stability, separation, and propagation of the delaminated film. Obviously, buckling and postbuckling response are part of the discussion. Equations are derived for both plane (buckling of a strip) and axisymmetric (buckling of a circular patch) delaminations. The results are used to derive expressions for crack driving force and phase angle in postbuckled thin films. A variety of experimental observations reported in the literature are presented and discussed.

Chapters 6–9 have a distinctly different flavor compared to the preceding chapters that dealt mostly with mechanics-related issues. The later chapters discuss conditions for dislocation formation, inelastic deformation of thin films, equilibrium and stability of surfaces, and evolution of surface morphology.

This book represents a monumental effort by the authors in creating a classic on the topic of thin films that has many technological applications. The book's uniqueness arises from example problems and sample calculations to illustrate the theoretical concepts and many case studies that relate theory to practice. Scientists and design engineers working on thin films and related areas such as microelectronic devices, MEMS, and surface coatings for various applications will find this book a valuable reference. In addition, each chapter concludes with challenging problems that will be useful if the book is adopted as a textbook, and it would be excellent for a graduate-level course in thin films. Currently, few universities offer such a course, and it is hoped the publication of this book will encourage development. This will be a valuable addition to libraries in universities, industry, and research institutions.

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