Ceramic Containing Systems

Mechanical Aspects of Interfaces and Surfaces

A.G. Evans

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Mechanical Aspects of Interfaces and Surfaces

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Foreword

This book describes mechanical aspects of interfaces and surfaces in ceramic containing systems. Various multicomponent materials were investigated. Systems studied include ceramic matrix composites, metal/ceramic bonded systems and polymer particulate composites, as well as monolithic ceramics.

Fracture behavior has been observed, to develop criteria that identify fracture parameters pertinent to structural design. Micromechanics models of mechanical behaviors have also been developed whenever possible. Matrix cracking in composites and edge effects in metal/ceramic bonded systems are examples of modelled phenomena. This book gives detailed descriptions of interfacial and surface phenomena in these ceramic containing systems.

The information in the book is from *Mechanical Aspects of Interfaces and Surfaces in Ceramic Containing Systems,* prepared by A.G. Evans of the University of California, Berkeley, California, for the U.S. Office of Naval Research, December 1984.

The table of contents is organized in such a way as to serve as a subject index and provides easy access to the information contained in the book.

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ADVANCED CERAMIC MATERIALS Technological and Economic Assessment

Based on Studies by

Charles River Associates Incorporated
U.S. Department of Commerce International Trade Administration
National Research Council National Materials Advisory Board

This assessment of the current competitive status of advanced ceramic materials presents the situation both from the technological aspect and the economic viewpoint. U.S. prospects relative to Japanese technology and the Japanese governmental philosophy, as well as the general international picture, are outlined and discussed.

Five specific applications of advanced ceramic materials—heat engines, capacitors, integrated optic devices, gas sensors, and cutting tools—are covered at length.

A condensed table of contents listing **part titles and selected chapter titles** is given below.

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Introduction

Research during FY 1984 has considered four areas, concerned with the mechanical behavior of materials: monolithic ceramics, ceramic matrix composites, ceramic/metal bonded systems, and polymer matrix materials. Water drop impact damage on brittle systems has also been investigated.

The research on monolithic ceramics represents the conclusion of several years of study related to the fracture toughness of polycrystalline ceramics. The emphasis of the present research (Paper I) has been on the development of a comprehension of microcrack toughening in single phase anisotropic ceramics, such as Al_2O_3. The study illustrates how the stress, strain characteristics of a microcracking system can be derived and then used to predict trends in the fracture toughness. The dilatational strain associated with the microcracking is thereby determined to be the major toughening mechanism. The dilatation is, in turn, related to the thermal expansion anisotropy and the grain size.

Thermal fracture studies (Paper II) describe a technique for evaluating edge flaw populations in ceramic devices: notably, multilayer capacitors. The study, performed on standard capacitors, revealed that the edge flaws are more serious than the surface flaws and hence, that capacitor fracture upon soldering or thermal cycling is strongly influenced by edge damage. The concept of thermal stress testing to obtain flaw populations is also shown to be applicable to other components, such as turbine valves and turbochanger rotors. The procedure may be used for evaluation or proof testing purposes.

The research on ceramic matrix composites (Papers III & IV) presents an analysis of the mechanical behavior of a SiC/LAS composite with uniaxial reinforcement. The study reveals that the tensile properties are dictated by a matrix cracking stress and an ultimate tensile strength, whereas the fracture toughness is not a relevant material parameter. Comprehensive investigation of matrix cracking indicates that, in this composite, the good tensile properties derive from an absence of chemical bonding between the fiber and matrix. Furthermore, the matrix cracking stress is determined to vary with the frictional shear resistance of the interface, the fracture toughness of the matrix and with the thermal expansion difference between fiber and matrix (via the residual stress).

Studies of the mechanical properties of ceramic/metal bonded systems (Papers V, VI, VII) have begun to investigate the effects of thermal and elastic anisotropy and of metal plasticity on the mechanical strength. In particular, plasticity in the metal is determined to profoundly effect several aspects of mechanical behavior. For example, crack blunting has been observed at the interface of Al_2O_3/Nb, due to plastic flow in the metal, resulting in interface strengthening. Additionally, stress, strain hysteresis due to metal plasticity has been used to eliminate residual stress in Al_2O_3/Cu strips. The influence on fracture behavior of stress concentrations at edges, due to mismatch in elastic modulus, has also been studied.

Polymer matrix particulate composites exhibit toughness characteristics similar to those previously studied in ceramics (viz, transformation and microcrack toughening). Hence, models of rubber toughening and glass toughening of polymers have been developed (Papers VIII, IX) using concepts based on stress, strain hysteresis. In these instances, the dilatation of the material due to plastic expansion of the matrix around debonded, or cavitated, second phases has been studied and used to predict trends in the toughness. The trends reveal synergistic effects. Particularly strong synergism was identified in rubber toughened systems wherein toughening by rubber stretching across the crack faces was determined to be multiplicative with debonding and shear banding in the process zone.

Finally, the research studies on water drop impact damage have involved the development of schemes for statistical damage characterization, pertinent to the influence of the damage on infrared transmission losses. Three aspects of this issue have been addressed. Techniques developed for characterizing the spatial variation in crack damage (Papers XI, XII) allow experimental results evaluated for a wide variety of impact conditions and target materials to be unified. In particular, the inner damage radius and the number density of cracks have now been fully characterized. Theoretical studies (Paper X) have involved the development of a computer model to simulate the crack damage. The model is based on the fracture mechanics of cracks engulfed by the short stress pulse generated by drop impact. Inertial effects of the crack faces are a particularly important aspect of the model. The computer scheme thereby allows the stress pulse to activate statistically distributed, small pre-existing surface cracks and create a distribution of crack damage. The simulation has, thus far, successfully predicted the number density of cracks in the damage zone, by incorporating stress pulse attenuation.

PART A

MONOLITHIC CERAMICS

I. Some Effects of Microcracks on the Mechanical Properties of Brittle Solids

I-a. STRESS, STRAIN RELATIONS

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ABSTRACT

An analysis of microcracking in a brittle polycrystalline aggregate is presented. The analysis is based on the combined influence of the residual stress and the applied loads. Microcrack densities are predicted as a function of load and correlated with acoustic emission measurements. The non-linear characteristics of the stress-strain curves of microcracking materials are calculated, as required for subsequent evaluation of microcrack toughening in brittle materials.

1. INTRODUCTION

Localized residual stresses typically form in polycrystalline brittle solids, due to thermal expansion anisotropy.[1-4] The residual field often induces a stress intensity of sufficient magnitude that microcracks nucleate,[5] especially when present in conjuntion with appreciable applied stresses. The resultant microcracks influence the mechanical properties of the material, in addition to having important effects on optical and thermal properties. The intent of this article is to describe the source of the microcracks and to evaluate the stress, strain response of materials subject to stress induced microcracking. The associated effects of microcracks on crack propagation are presented in a companion paper.[6]

In the present paper, the stresses that result from expansion anisotropy are firstly assessed. Then, fracture concepts that account for observations of thermal microcracks are discussed. Thereafter, the concepts are used to predict the microcracking that occurs upon application of applied loads and hence, to predict stress, strain relations for microcracking brittle solids. Experimental measurements that relate to stress induced microcracking are, where available, correlated with the predictions.

2. RESIDUAL STRESSES

The analyses of the residual stress caused by expansion anisotropy were originally concerned with the stresses induced within grains. The results of such analyses, obtained using variational principles, revealed stresses of the form,[2]

$$\sigma_{ij} = M_{ijkl}\,(\sigma_{kl})_o$$

$$(\sigma_{ij})_o = C_{ijkk}(\alpha_o - \alpha_k)\Delta T \qquad (1)$$

where α_o is the thermal expansion coefficient of the polycrystalline aggregate and α_k is the thermal expansion coefficient along the k-axis of the grain, ΔT is the cooling range, C_{ijkl} is a compliance tensor and M_{ijkl} is a relaxation tensor. However, since microcracks in polycrystalline brittle solids typically occur along grain boundaries[5,7], the stresses along boundaries are deemed more pertinent for present purposes.

Grain boundary stresses are conveniently analyzed using the Eshelby procedure.[5,8] In this procedure, the first step entails removal of the microstructural entities, followed by unconstrained straining. Then, surface forces are applied to restore the entities to their original shape, whereupon they are reinserted into the body. Finally, interface tractions are imposed to establish stress continuity in the system. For polycrystalline solids subject to thermal expansion anisotropy, it can be shown[9] that the grain boundary stresses may be adequately assessed using four anisotropic grains, contained within an isotropic matrix with the average properties of the polycrystal (fig. 1). With this approach, the stresses σ_{ij}^T within each grain, due to application of surface forces, are given by

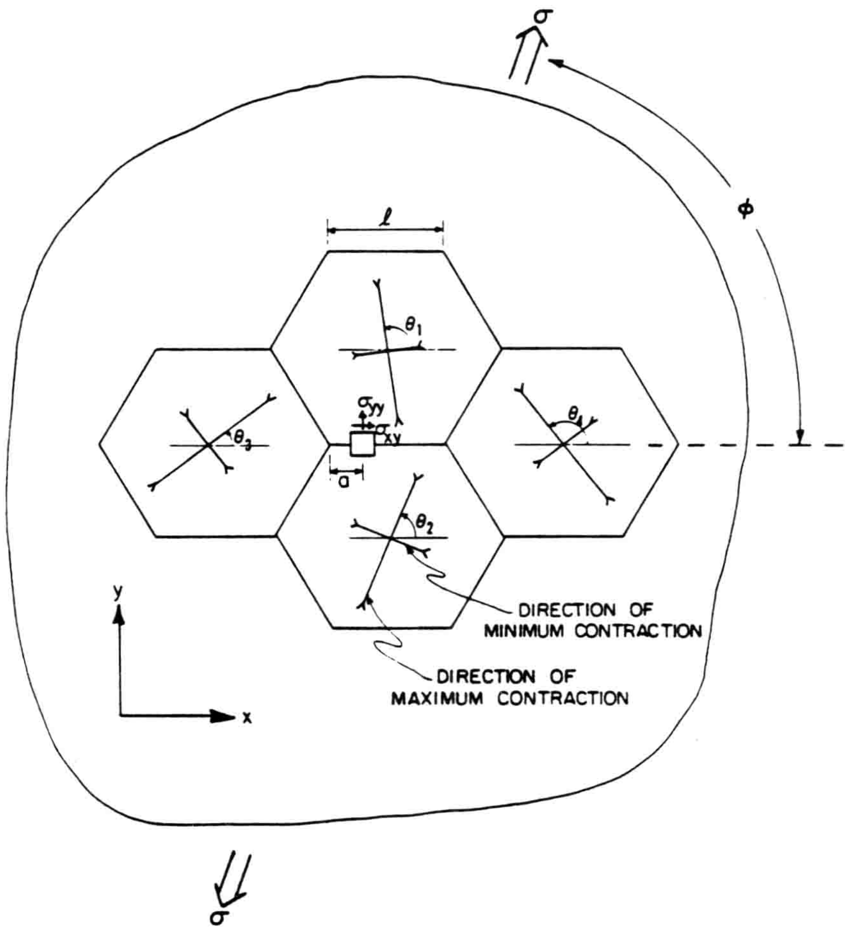


Fig. 1 The four anisotropic grains with an isotropic matrix used for residual stress analysis.

$$\sigma^T_{zz} = E\Delta\alpha\Delta T \cos 2\theta_n/(1+\nu)$$

$$\sigma^T_{yy} = E\Delta\alpha\Delta T \cos 2\theta_n/(1+\nu)$$

$$\sigma^T_{xy} = E\Delta\alpha\Delta T \sin 2\theta_n/(1+\nu) \quad (2)$$

where,

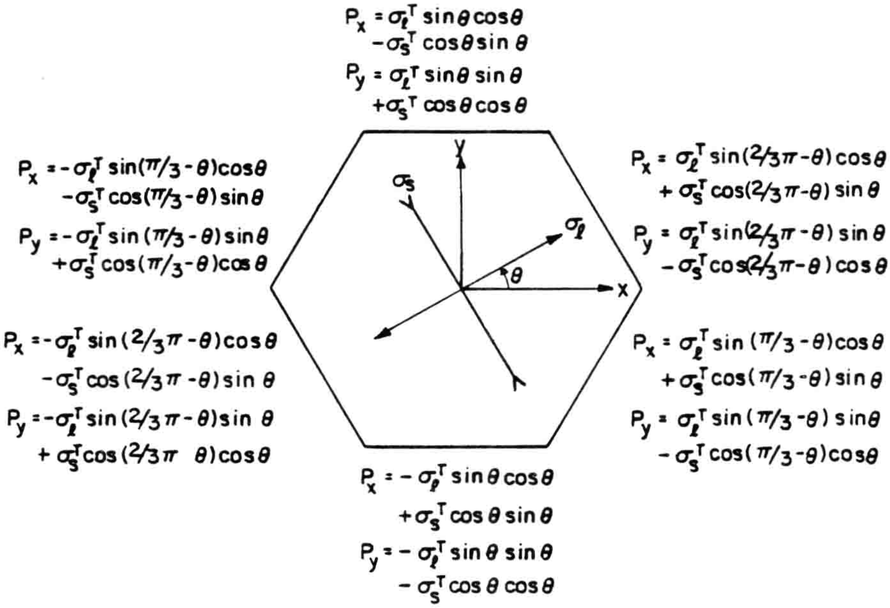
$$\Delta\alpha = \alpha_1 - (\alpha_1 + \alpha_2)/2$$

$$= \alpha_2 - (\alpha_1 + \alpha_2)/2;$$

the subscripts 1 and 2 refer to the principal strains, and θ_n is the angle between the axis of maximum contraction in grain n and the grain boundary plane.

These stresses are modified during the final step in the sequence, when interface tractions P_i (fig. 2) - equal in magnitude but opposite in sign to the surface forces - are applied around the grain boundaries after insertion into the matrix. Resultant stresses, evaluated for two dimensional grain arrays, with several grain orientations, are presented in fig. 3.

The stresses can be considered to comprise of two principal components: uniform stresses at the grain facet center and singular stresses near the grain corner. The uniform stresses, σ^M_{ij}, originate from the mismatch between the two grains adjacent to the grain boundary of interest and are given by;



$$\sigma_{xx} = \sigma_\ell^T \cos^2\theta + \sigma_s^T \sin^2\theta$$

$$\sigma_{yy} = \sigma_\ell^T \sin^2\theta + \sigma_s^T \cos^2\theta$$

$$\sigma_{xy} = (\sigma_s^T - \sigma_\ell^T) \sin\theta\cos\theta$$

Fig. 2 A summary of the interface tractions, P_i, imposed to achieve stress continuity in the final step of the Eshelby sequence.