FRACTURE
IN
CERAMIC MATERIALS

Toughening Mechanisms, Machining Damage, Shock

Edited by

A.G. Evans

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Foreword

This book presents recent studies on the mechanisms of fracture in ceramic materials–the effects of toughening, machining, and shock. Research on toughening mechanisms, machining and surface damage, thermal shock and general aspects of fracture in ceramic materials is described. Quantitative models of the various fracture processes have been developed. Special emphasis has been placed on the toughening that occurs in the presence of microcracks.

During the last decade, research on the fracture of monolithic single phase and multiphase ceramic polycrystals has attained a maturity which now permits many fracture phenomena to be quantitatively described. Specifically, the predominant fracture-initiating flaws have been identified and the fundamental mechanics and statistics related to their fracture severity have been determined. In addition, the crack growth resistance exhibited by common ceramic microstructures can now be expressed in quantitative terms, through the development of micromechanics models of transformation toughening, microcrack toughening, and deflection toughening.

As a result, the next research frontier in the field of advanced monolithic ceramics undoubtedly resides in studies of the processing of optimum microstructures (as identified by the mechanics descriptions). Progress in this area is summarized in this book.

The four main subject areas of the book are toughness/microstructure interactions, machining damage, thermal fracture and reliability, and impact damage. Each part contains papers describing work completed in 1983 by researchers in that particular subject area.

The information in the book is from *Micro and Macro Mechanics of Fracture in Ceramics*, edited by A.G. Evans of the University of California Department of

Materials Science and Mineral Engineering for the U.S. Office of Naval Research, November 1983.

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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NOTICE

Contents and Subject Index

PART V
APPENDIX

INTRODUCTION

Research on the fracture of monolithic single phase and multiphase ceramic polycrystals during the last five to ten years has attained a maturity that now permits many fracture phenomena to be quantitatively described. Specifically, the predominant fracture initiating flaws have been identified and the fundamental mechanics and statistics related to their fracture severity have been determined. In addition, the crack growth resistance proferred by common ceramic microstructures can now be expressed in quantitative terms, through the development of micromechanics models of transformation toughening, microcrack toughening, and deflection toughening. Consequently, the next research frontier in the field of advanced monolithic ceramics undoubtedly resides in studies of the processing of optimum microstructures (as identified by the mechanics descriptions). Some of this research progress is summarized in the present report.

1) Toughness/Microstructure Interactions

The crack resistance phenomena studied during this period have included transformation toughening, microcrack toughening and crack deflection, as summarized in the paper by Evans and Evans and Fu. The first two toughening mechanisms have received particular attention and expressions have been developed that uniquely relate the toughness to the size of the process zone. Both processes induce toughness by exhibiting non-linear, irreversible stress-strain behavior, (which may be regarded as pseudo plasticity). The form of the stress-strain law

that pertains to transformation or microcracking is readily amenable to crack growth analysis. Hence, more rapid progress has been achieved with toughening mechanisms in ceramics than the corresponding processes in metals. Furthermore, the importance of the irreversible nature of the deformation (fig. 1) has emerged, because of the dominant influence of the wake on the near tip opening displacement or, equivalently, the residual energy density. The residual energy in the wake also manifests itself in the presence of R-curve effects (fig. 2).†

Transformation toughening has been analyzed by McMeeking and Evans[1] and by Budiansky, Hutchinson and Lambropolous.[2] These analyses have revealed that the maximum toughness due to dilatation, for a fully developed wake, has the form,

$$K_c = K_c^m + 0.25\, E e^T V_f \sqrt{h}/(1-\nu) \qquad (1)$$

where K_c^m is the toughness of the transformed product in the process zone ahead of the crack, h is the transformation zone width, E is Young's modulus, ν is Poisson's ratio, V_f is the volume fraction of transformed product and e^T is the transformation volume change. Available comparisons with independent measurements of the transformation zone width indicate that most of the toughness can be described by eqn (1), due to dilatation, coupled with deflection effects associated with K_c^m (discussed below).

†Similar R-curve effects in metals may also be wake related, but have not yet been recognized as such.

Some additional effects of shear are expected, but certainly do not dominate the toughening. These comparisons reveal that the basic character of transformation toughening is contained in the micromechanics models, as expressed in terms of the zone width.

It remains to understand relations between the zone width and the nucleation criteria for the transformation. This is a formidable undertaking, because observatons of the nuclei and of the progress of the transformation cannot be made, due to the existance of a substantial nucleation barrier. It is deemed unlikely, therefore, that significant progress in understanding the problem can be achieved, within the next several years, beyond semi-quantitative descriptions of size effects, based on stress concentrations at the corners of facetted particles.[3] The onus for optimizing transformation toughening thus appears to reside in fabricating materials with varying particle size, shape and chemical composition and studying effects on the transformation zone width etc.

Microcrack toughening has been analyzed,[4] using the same techniques developed for the transformation problem, to give;

$$K_c \approx K_c^m + 0.25\, E f_s \theta \sqrt{h} \qquad (2)$$

where f_s is the area fraction of material that microcracks at saturation and θ is the dilatation induced by microcracking. Generally $\theta < e^T$ and since, $f_s < 1$, microcrack toughening is less potent than transformation toughening. The dilatation θ is known to be related to the thermal expansion strain due to expansion anisotropy

or mismatch. However, it remains to develop a fully quantitative relation between θ and the expansion properties of the material. Additionally, further study is needed to define f_s in single phase polycrystals.† Such studies would be of merit, in order to model important R-curve effects in rocks and refractories, and to further understand microcrack toughening in various two phase ceramics (such as Al_2O_3/ZrO_2).

Contributions to the effect of grain size on microcrack toughening have also been made by analyzing the conditions needed to sustain a discrete microcrack zone ahead of a primary crack.[5] This analysis, based on the scale and amplitude of the residual strain field associated with thermal expansion anisotropy, reveals that a microcrack process zone can only be supported above a critical grain size. A grain size dependent toughness of the type depicted in fig. 3 thus ensues. The peak toughness coincides with the grain size at which thermal cracking occurs, upon cooling, because the thermally induced cracks do not contribute toughening (c.f. transformation toughening). The toughening described by eqn (2) thus pertains in the intermediate grain size range, wherein the toughness increases with increase in grain size. Based on this research[5] and previous work,[6] grain size effects on toughness and related specimen geometry effects[4] now seem to be adequately understood, for most purposes.

† In materials containing a second phase f_s is related to the volume fraction of the phase.

Deflection toughening is dictated exclusively by effects occurring at the crack tip. Analysis suggests[7] that the twisting of cracks between deflecting phases in most potent in reducing the crack driving force. Hence, rod-shaped deflecting phases yield the maximum toughening (fig. 4). These predictions are in good accord with observations on Si_3N_4, SiC and Al_2O_3. Hence, further analysis of deflection effects is not regarded as requiring a high priority. However, the second phase characteristics needed to induce deflection, such as residual strain, cleavage resistant planes etc., require further study. Processing of materials with rod-shaped deflecting phases should also receive attention, especially since the toughening mechanism is temperature independent and can be used to optimize high temperature toughness.

ii) Machining Damage

Recent research has highlighted the essential similarities and differences between machining damage and indentation cracks, thereby establishing the final requirements for predicting machining damage either form the machining load or from surface acoustic wave measurements.[8] The similarities pertain to the dominant influence of the residual stress on both the depth of the damage and the effect of the damage on the fracture stress. Furthermore, the dominant material parameters (toughness, hardness and modulus) enter the final expression for the failure stress, such that the failure stress for a machined specimen is given by;