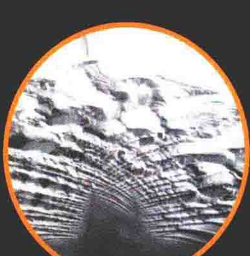
STEPHEN W. FREIMAN JOHN J. MECHOLSKY JR.

THE FRACTURE OF BRITTLE MATERIALS

Testing and Analysis



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A John Wiley & Sons, Inc., Publication

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

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Library of Congress Cataloging-in-Publication Data:

Freiman, S. W.
The fracture of brittle materials : testing and analysis / by Stephen Freiman, John Mecholsky.
p. cm.
Includes index.
ISBN 978-0-470-15586-8 (cloth)
1. Ceramic materials–Fracture. 2. Fracture mechanics. 3. Materials–Fatigue. 4. Fractography. I. Mecholsky, J. J. II. Title.
TA430.F74 2012
620.1'126–dc23

2011028937

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

The Fracture of Brittle Materials

This book is dedicated to our two Susans who supported the efforts of their husbands.

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Preface

The purpose of this book is to bring together the background, testing procedures, and analysis methods needed to design and use materials that fail in a brittle manner. In this context, we define ceramics quite broadly as any inorganic nonmetal. Such a definition includes diverse materials, such as semiconductors (e.g., Si, GaAs, InP), other single crystals (ZnSe, CaF, etc.), cements and concrete, and of course the oxides, carbides, nitrides, and so on that we normally think of as ceramics. Ceramics are also used in composite form, either by dispersing one phase in another or by crystallizing phases from a glassy matrix. Most test procedures designed for monolithic bodies can be used here as well. However, continuous fiber-reinforced composites behave quite differently, and will not be discussed herein. Ceramics are also increasingly used in films and coatings, but determining the mechanical properties of materials in these forms is more complex, and will not be addressed in this book.

This book addresses testing and analysis at temperatures at which the material behaves in a brittle manner. At elevated temperatures, other modes of failure often are important. These include creep, as well as general plastic deformation. Both of these topics are outside the scope of this book.

In this book, we provide the reader some of the background needed to understand the brittle fracture process, as well as a basis for choosing the proper test procedures. The mathematical development of the expressions used to calculate the various properties will be kept to a minimum; the reader will be referred to fundamental references. We intend to provide sufficient examples to allow the reader unfamiliar with the tests to be able to perform the test procedures properly. Questions to test comprehension for self-evaluation will be given at the conclusion of each chapter.

Chapter 1 is a general introduction to the concept of brittle failure. Chapter 2 provides a condensed background into the basic principles of fracture mechanics that underlies most of the test and analysis procedures. Linear elastic fracture mechanics (LEFM) is the basis for measuring the toughness of materials. Chapter 3 gives some background into the theory and mechanisms of environmentally enhanced crack growth, a process that is particularly important for designing components to survive over long periods of time. Chapter 4 provides extensive details on fracture mechanics tests used to both determine the resistance to fast fracture of a material, as well as to determine the parameters associated with environmentally enhanced crack growth. Chapter 5 addresses the test and analysis methods to determine the strength of ceramics. Chapter 6 provides a background and discusses the methods of understanding the fracture process based on quantitative measurements made on the fracture surface. Chapter 7 discusses an important topic with respect to polycrystalline materials, namely the effect of the microstructure of the specific material. Chapter 8 provides the background, test methods, and analytical procedures needed to confidently predict the safe lifetimes of brittle components under stress. Finally, Chapter 9 summarizes the critical issues with respect to brittle fracture.

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Acknowledgments

We gratefully acknowledge the work of Nicholas A. Mecholsky in preparing many of the illustrations in this volume. We also appreciate the numerous technical discussions with George D. Quinn and Jeffrey Fong. Finally, we would like to express our gratitude to Roy Rice for introducing us to many of the topics discussed in this book, particularly those focused on the effects of microstructure.

S.W.F.
J.J.M.

Contents

CHAPTER 1

Introduction

The properties of ceramics have made them extremely attractive to society in uses such as electrical and thermal insulators, high temperature crucibles for steel fabrication, elegant dinnerware, etc. More recently, their applications have become even more extensive and sophisticated, ranging from complex electronic devices to thermal protection for aircraft engines. However, the brittleness of ceramics has at times limited more extensive use. Everyone knows that traditional ceramics, such as dishes and glasses, are brittle: drop a teacup or a plate, break a window, and you experience the brittleness. By brittle we mean that there are no mechanisms to relieve or alter the high stresses at crack tips, such as dislocations in metals or crazing in polymers. The lack of any stress relief mechanism results in cracks growing to failure at stresses that are significantly less than those necessary to initiate and propagate cracks in metals.

Despite their brittleness, advanced technical ceramics form the basis for a wide variety of important products. They are used in applications in which they experience significant stresses imposed by not only mechanical loading but also thermal, magnetic, or electronic conditions. One sees ceramics everywhere: the large electrical insulators on poles, sparkplugs, and skyscraper windows that must resist high winds. Some we do not see or are not aware of. Cell phones would not operate without ceramics having special dielectric properties; automobiles contain hundreds of multilayer, ceramic capacitors. Aircraft

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engines depend on ceramic coatings to reduce the temperature of the metal blades. Turbine engines for auxiliary power generation are now being constructed with rotating ceramic blades.

In the 1970s, the development of advanced processing techniques gave materials such as silicon nitride and silicon carbide properties that allowed them to withstand intense stresses at temperatures as high as 900°C. The drive to use these materials in rotating automotive components led to the "ceramic fever" reported in Japan over the next two to three decades. However, the use of a brittle ceramic as the rotating blade in a ceramic turbine engine means that better tests and analysis procedures are needed.

Another use of ceramics that requires complete reliability is aluminum or zirconium oxide hip and knee replacements in the human body. The hardness, inertness, and wear resistance of these materials make them ideal candidates to replace metals in such situations. Particularly when the patient is young, the lesser amount of wear debris produced by the ceramic means that the component can be used in the body for a significantly longer time than one made of metal.

The list of ceramic applications is extensive, including materials that we do not normally think of as ceramics, for example, semiconducting materials, such as silicon, gallium arsenide, and so on, and oxide films crucial for the operation of electronic devices. Because of the brittleness of these materials and their similarity in mechanical behavior to conventional ceramics, we also refer to these materials as *ceramics*. Figure 1.1 shows some prime examples of advanced technical ceramics.

In each of these examples and in the myriad other applications, the brittleness of ceramics necessitates that special care must be taken in determining the mechanical properties of the material and discovering the stresses imposed on the final product during operation. The fact is that unseen, and probably undetectable, defects can lead to catastrophic failure. We will call these defects *flaws*. By a flaw we do not necessarily mean that errors were made in production. While improper processing can lead to pores or inclusions, component failures caused by these are relatively rare. The vast majority of the time, brittle failure begins at the surface of a component from small cracks that are produced during the machining, finishing, or handling processes. All ceramics contain such flaws; there is no perfect brittle material. Even the strongest ceramic, pristine glass fibers, contains small flaws in its surface despite

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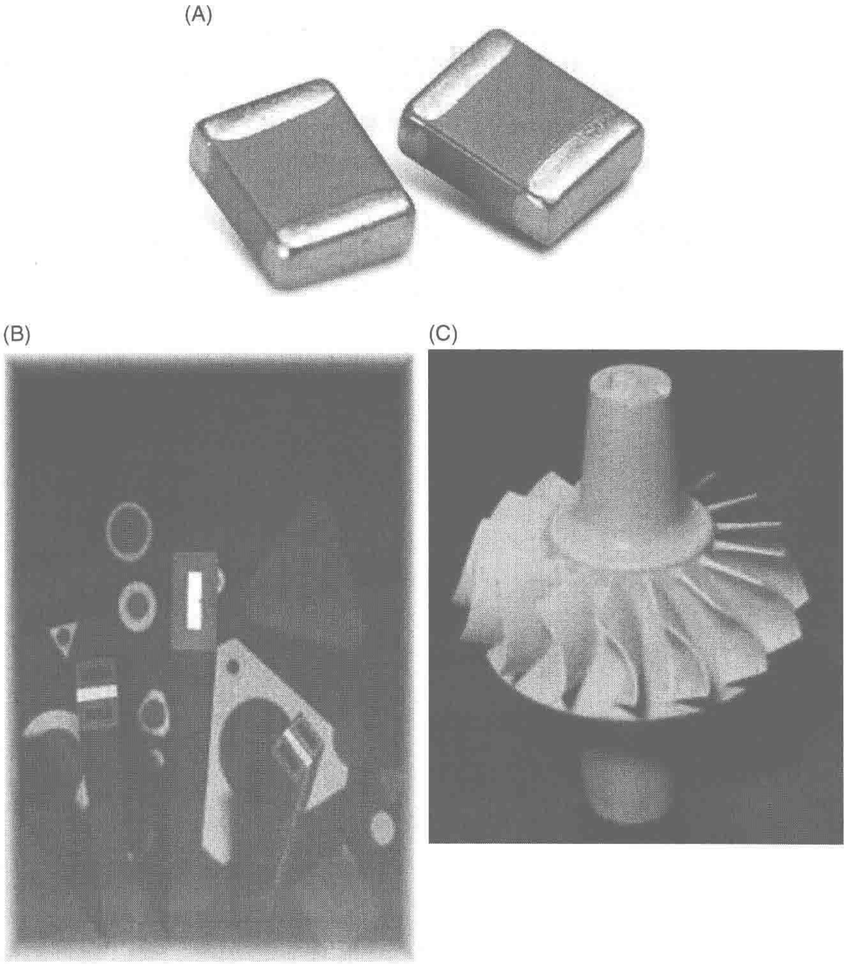

Figure 1.1 Examples of advanced technical ceramics. To the left are barium titanate capacitors (A). In the middle are various silicon nitride components (B). On the right is a silicon nitride turbine wheel (C).

the care taken to avoid any surface damage. It is the size and shape of such flaws, that is, the *flaw severity*, and their location with respect to the tensile stresses, that determine the strength of a component.

Brittle fracture is a statistical process. We usually think of such failure in terms of a "weakest link" model. That is, failure begins from the most severe flaw located in the region of highest tensile stress. Also, the size of flaws in real components, 10–200 μm, means that detection of such defects by some nondestructive means prior to putting the part into service is extremely unlikely.

Another important aspect of most ceramic materials is that even if their strength when placed into service is sufficiently high that failure should not occur, in the presence of certain environments, for example, water or water vapor, surface cracks will grow under the operational stresses, and failure can occur after a period of days, weeks, or even months. Fortunately, we have sufficient knowledge of this behavior, so that with proper testing and analysis, excellent predictions of the safe operating envelope, stress, and time can be given. Nonetheless, the user of ceramic components should recognize that such analysis only pertains to flaws that existed prior to putting the component in service. Other defects can be created during operation, for example, from dust or rain, which may limit useful service life.

Knowledge of the brittle fracture process, most of which has been acquired over the past 30–40 years, has played a major part in our ability to design and use these materials, even in situations where the component is subject to significant tensile stresses. Two developments, which at the time were outside the field of material science, were of major importance in contributing to our ability to safely use these materials. One was the development of the field of linear elastic fracture mechanics. Fracture mechanics provides the framework by which the effect of the stresses imposed on a body can be translated into predictions of the propensity of any cracks or flaws within the body to grow. This has led to the development of test methods and data analysis that permit designers to choose a material, machine it to shape without producing damage that could lead to premature failures, and carry out quality control procedures that provide confidence in the reliability of the part under operating conditions. A second important advancement, allowing us to design with brittle materials, was the development of statistical techniques that account for the uncertainties in the experimental measurements of the various parameters needed to make predictions of reliability.

A third factor that has greatly benefited the use of brittle ceramics in a wide variety of applications is the agreed-upon use of a common test methodology through national, regional, and international standards. Most of these standards have been developed by consensus by private Standards Development Organizations, such as ASTM International and the International Organization for Standardization (ISO). The details of the standards coming out of the deliberation process are based on years of data obtained in laboratories throughout the world.

In this book, we summarize the concepts behind the selection of a test procedure for fracture toughness and strength determination. We explain the importance of the role of microstructure in these determinations and emphasize the use of fractographic analysis as an important tool in understanding why a part failed.

CHAPTER 2

Fracture Mechanics Background

INTRODUCTION

At the most fundamental level, brittle fracture occurs when stresses reach a magnitude needed to break the bonds between the atoms in the material. However, if there were no means of concentrating stress, loads necessary to cause failure would be extremely large. It is the presence of small defects that concentrate applied stresses to a magnitude sufficient to cause them to grow. The materials we discuss in this book are brittle because plastic flow mechanisms in them are insufficient to relieve the stress concentration at the defect.

The science of fracture mechanics allows us to calculate the forces needed to cause defects to grow based on knowledge of specimen geometries and the applied loads. In this chapter, we provide some historical perspective and a summary of the basic principles of fracture mechanics. The reader is encouraged to consult Anderson (1995) and Munz and Fett (1999) for more details.

EARLY BRITTLE FRACTURE RESEARCH

Although fracture studies of ceramics can be traced as far as back as 1867, our current understanding of brittle fracture can be traced to

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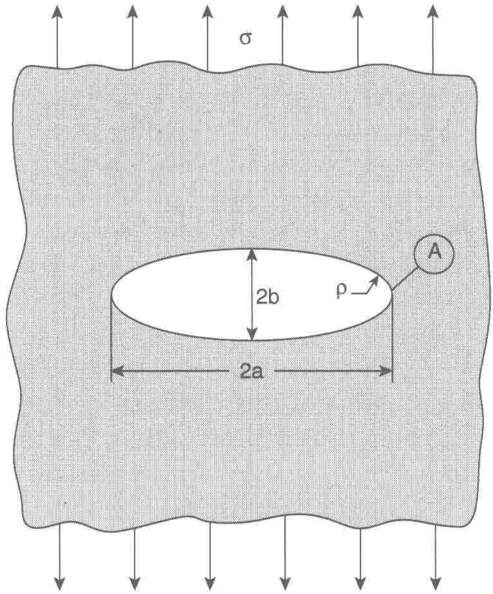

Figure 2.1 Void in a plate in which stresses are concentrated at point A.

Inglis (1913), who initiated the concept of stress concentration at a void in a material as shown in Figure 2.1.

Assuming an elliptically shaped cavity, the concentrated stress, σ_c, due to the presence of the void, is given by the following expression.

$$\sigma_c = \sigma(1 + 2\sqrt{a/\rho}), \qquad (2.1)$$

where $2a$ is the long axis of the ellipse and ρ is its radius of curvature. As ρ approaches zero, that is, the elliptical cavity begins to resemble a crack whose tip radius is of atomic dimensions. The atomistic nature of materials and the nonlinearly elastic or plastic deformation that occurs in the vicinity of a crack tip avoids the problem of $\rho \to 0$, but this approach does not yet allow us to quantify the stress state at an actual crack tip, and says nothing about when the void is likely to grow.

The second important advance in our understanding of brittle failure was made by Griffith (1920) who postulated that brittle failure in glass is a result of the growth of small cracks when the material is subjected to a large enough tensile stress. He put forth the hypothesis that these cracks are present in all glasses in a distribution of sizes, leading to the concept that the smaller the volume (or area) under stress, the less likelihood of finding a large flaw, and therefore the higher the strength. Griffith demonstrated this concept experimentally by measuring the strength of glass fibers of varying diameter, and showing that strength increased with decreasing fiber diameter. The flaw that eventually grows to failure is determined by its severity as well as its location with respect to the highest tensile stress, thereby giving rise to the statistical nature of brittle failure.

Griffith also hypothesized that a material's resistance to the growth of a crack is determined by the energy required to create the two fracture surfaces produced by its extension. This approach assumes that fracture occurs in an equilibrium manner, that is, in the absence of any kinetic effects, and that no energy is lost due to plastic flow or heat. It also neglects the possible effects of the test environment in which the flaw is growing, for example, water. Griffith's expression for glass fracture based upon this approach is given by:

$$\sigma_f = \left(\frac{2E\gamma_f}{\pi a} \right)^{1/2}, \tag{2.2}$$

where σ_f is the fracture strength, E is Young's modulus, γ_f is the energy required to form the crack surfaces (i.e., the fracture energy), and a is the critical flaw size. While Griffith's calculations were not entirely accurate because of his assumption that the fracture energy of the glass could be extrapolated from measurements of surface energy carried out at elevated temperatures, the form of Equation 2.2 accurately depicts the relationship between strength, flaw size, and fracture energy. However, what was still required was a way of translating the external loads on a part into knowledge that could be used to predict its resistance to crack growth. This awaited the development of fracture mechanics.

DEVELOPMENT OF FRACTURE MECHANICS

Credit for the development of the science of fracture mechanics is rightfully give to George Irwin and his colleagues at the U.S. Naval Research Laboratory (Irwin, 1958). Irwin first introduced the concept of a "strain energy release rate," G, which has nothing to do with time

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