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 such as multilayer capacitors and ultrasonic transducers to thermal protection for aircraft engines and applications in the dental and medical fields. However, the brittleness of ceramics, making them subject to sudden failure without prior warning, 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

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The Fracture of Brittle Materials: Testing and Analysis, Second Edition.
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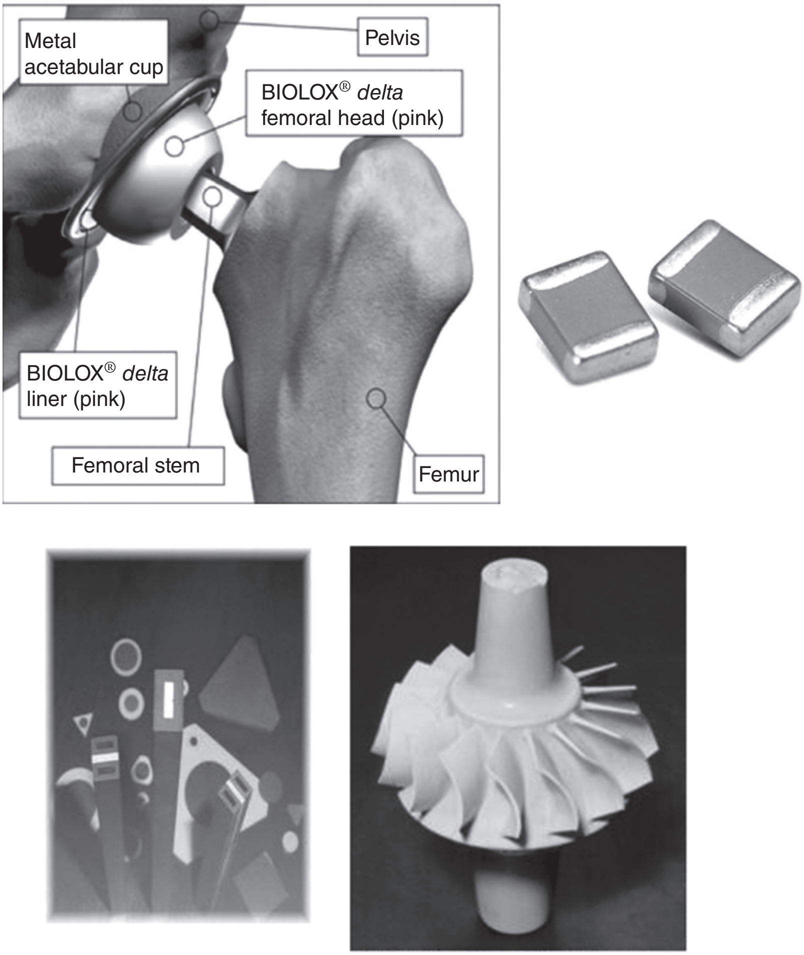
mechanical loading but also thermal, magnetic, or electronic conditions. One sees ceramics everywhere: the large electrical insulators on poles, spark plugs, and skyscraper windows that must resist high winds. Some we do not see or are not aware of. Cell phones would not operate without ceramics having special dielectric properties; automobiles contain hundreds of multilayer ceramic capacitors. Aircraft 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.

Another use of ceramics that requires complete reliability is aluminum or zirconium oxide hip and knee replacements in the human body. Dental ceramic prosthetic composites are routinely implanted in many patients. 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, e.g. semiconducting materials, such as silicon, gallium arsenide, etc., 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 refer to each of 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. For 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



A 16-blade silicon nitride turbine wheel for use in small turbogenerators

Figure 1.1 Examples of advanced technical ceramics. From the left to right are an example of a ceramic hip replacement, barium titanate capacitors, various silicon nitride components, and a silicon nitride turbine wheel.

the care taken to avoid any surface damage. It is the size and shape of such flaws, i.e. 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, e.g. 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, e.g. 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 materials 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 second edition of the book, we summarize the concepts behind the selection of a test procedure for fracture toughness and strength determination and go into some detail in how the statistics of fracture can be used to assure reliability. 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. We have included a significant quantity of material related to the fracture of biomaterials. We have also included new chapters, one devoted to thermal shock and the other to the modeling of the fracture process. In addition, the portion of the book discussing how to treat the statistics of fracture strength data to ensure reliability has been greatly expanded.