Chapter 1

Introduction

In the last 25 years there has been a strong movement to use ceramics in new technological applications and a key facet of this work has been directed at understanding the mechanical behavior of these materials. First, let us consider the various **technological functions** of ceramics as shown in Table 1.1. The diverse properties of ceramics are not always appreciated. For structural functions, adequate mechanical properties are of prime importance. Ceramic materials that are considered for these applications are termed **structural ceramics**. In some cases, such as engine parts, the choice is based on their high-temperature stability and corrosion resistance. These factors imply the engine temperature could be raised, making the overall performance more efficient. Unfortunately, ceramics can be brittle, failing in a sudden and catastrophic manner. Consequently, there has been a strong emphasis on understanding the mechanical properties of ceramics and on improving their strength, toughness and contact-damage resistance. Indeed, it is appropriate to state that there has been a revolution in the understanding of these properties and the associated research has led to the discovery of new classes of structural ceramic materials.

It is important to realize that mechanical properties can also be critical in non-structural applications. For example, in the design of the thermal protection system of the space shuttle, highly porous, fibrous silica tiles are used. The microstructure of these materials, shown in Fig. 1.1, consists of a bonded array of fibers, usually based on silica glass. Clearly, the prime reason for using these materials was their low thermal conductivity but the resistance to thermal and structural stresses was a key item in the final design. In some non-structural applications, mechanical properties can be important in determining the lifetime

Table 1.1 *Functions and technological applications of ceramics*

(Adapted from Kenney and Bowen, 1983, reproduced courtesy of The American Ceramic Society.)

Function	Primary characteristic	Examples of applications
Electrical	Electrical insulation (e.g., Al_2O_3, BeO)	Electronic substrates and packages, wiring, power-line insulators
	Ferroelectricity (e.g., $BaTiO_3$, $SrTiO_3$)	Capacitors
	Piezoelectricity (e.g., PZT)	Vibrators, oscillators, filters, transducers, actuators, spark generators
	Semiconductivity (e.g., $BaTiO_3$, SiC, ZnO–Bi_2O_3, CdS, V_2O_5)	NTC thermistor (temperature sensor)
		PTC thermistor (heater element, switch)
		CTR thermistor (heat sensor)
		Thick-film thermistor (IR sensor)
		Varistor (noise elimination, surge arrestors)
		Solar cells, furnace elements
	Ionic conductivity (β-alumina, ZrO_2)	Solid state electrolytes (batteries, fuel cells, oxygen sensors)
	Superconductivity (YBCO)	Magnets, electronic components
Magnetic	Soft magnets (ferrites)	Magnetic recording heads
	Hard magnets (ferrites)	Magnets, electric motors
Optical	Translucency (Al_2O_3, MgO, mullite, Y_2O_3, PLZT)	High-pressure sodium-vapor lamps, IR windows, lighting tubes and lamps, laser materials, light memory, video display and storage, light modulation and shutters.
	Transparency (silicate glasses)	Optical fibers, containers, windows
Chemical	Chemical sensors (ZnO, Fe_2O_3, SnO_2)	Gas sensors and alarms, hydrocarbon and fluorocarbon detectors, humidity sensors

Table 1.1 (*cont.*)
(Adapted from Kenney and Bowen, 1983, reproduced courtesy of The American Ceramic Society.)

Function	Primary characteristic	Examples of applications
	Catalyst carriers (cordierite, Al_2O_3)	Emission control, enzyme carriers, zeolites
	Electrodes (titanates, sulfides, borides)	Electrowinning, photochemical processes
Thermal	Thermal insulation (fiberglass, aluminosilicate fibers)	IR radiators, thermal protection systems for aerospace vehicles
	Thermal conduction (diamond films, AlN)	Heat sinks in electronic devices
	Thermal stability (AZS, Al_2O_3)	Refractories
Structural	Hardness (SiC, TiC, TiN, Al_2O_3)	Cutting tools, wear-resistant materials, mechanical seals, abrasives, armor, bearings
	Stiffness and thermal stability (SiC, Si_3N_4)	Ceramic engine parts, turbine parts, burner nozzles, radiant tubes, crucibles.
Biological	Chemical stability (hydroxyapatite, Al_2O_3)	Artificial teeth, bones and joints
Nuclear	Nuclear fission (UO_2, PuO_2)	Nuclear fuels, power sources,
	Neutron absorption (C, SiC, B_4C)	Cladding and shielding

Notes:
PZT – lead zirconium titanate
YBCO – yttrium barium copper oxide
PLZT – lead lanthanum zirconium titanate
AZS – Alumina zirconium silicate
NTC – negative temperature coefficient
PTC – positive temperature coefficient
CTR – critical temperature resistance
IR – infra-red

of the component. For example, the sodium–sulfur battery, that has high energy and power density, has been developed for transportation and energy-storage applications. This battery is based on the use of a solid ceramic electrolyte known as β-alumina, but cracking during recharging can lead to a limited lifetime. Clearly, improvements in the mechanical properties of the electrolyte could significantly impact the economic viability of the battery.

Before launching into the details of the various aspects of mechanical properties, it is worthwhile considering the overall philosophy of **materials science and engineering**. Figure 1.2 shows an overview of the way this discipline is used in developing technological applications. An understanding of the possible properties of materials allows a particular application to be identified and a design put forward. This is usually in the realm of engineering and it is important to be able to identify and measure all of the critical properties required in the design. In materials science one is also concerned with properties, but here it is usually the optimization of properties, structure and processing that is the key item. The aim is often to adjust the processing so that a particular structure, that gives the best set of properties, is obtained. *The search for new or improved materials is an*

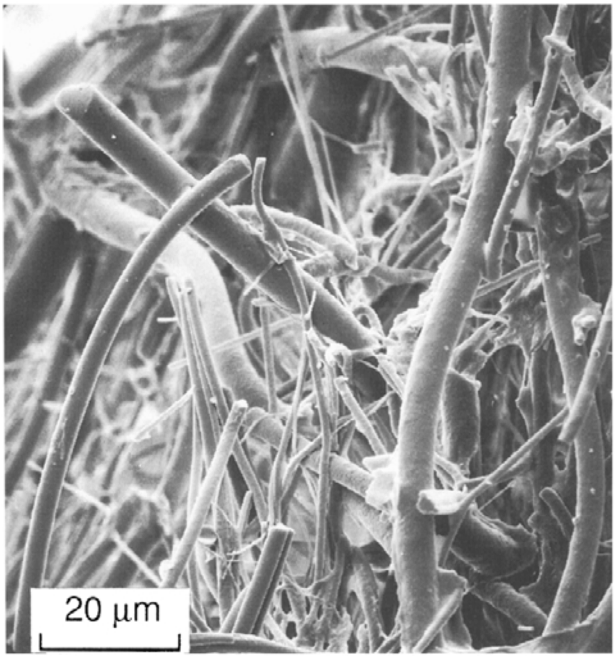

Figure 1.1 Microstructure of space shuttle tile material, a high-porosity fibrous silica; secondary electron image using the scanning electron microscope (SEM). (Reproduced courtesy of Plenum Press, New York.)

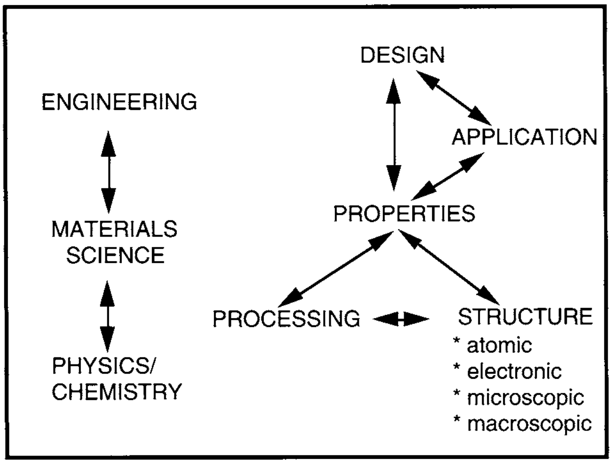

Figure 1.2 Overview of scientific approach for the development of materials for technological applications.

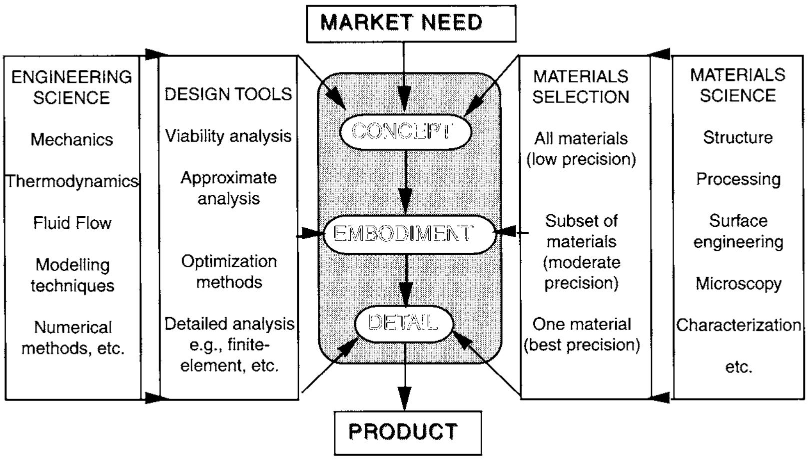

Figure 1.3 A flow chart showing how design tools and materials selection enter the design process. (Adapted from Ashby, 1992. Reproduced courtesy of Heineman Publishers, Oxford, UK.)

essential aspect of the field. The structure of the material that controls a particular property can occur at different scale levels: from the electron and atomic structure through to the macroscopic structure. For example, elastic properties are basically dependent on the chemical bonding, which determines the stiffness of the atomic bonds. Thus, one approach to changing the elastic behavior would be to adjust the composition by adding a solute. It is, however, also possible to change the elastic properties of a material by adjusting the microstructure, i.e., at a larger scale. For example, adding other phases or changing the amount of porosity at the microscopic level will also change the elastic properties. The introduction of ceramic fibers into glass, polymers or metals can substantially increase stiffness and has led to the development of **fiber composites**. At the macroscopic level, the use of different materials in particular configurations and geometries can be important. For example, in laminated structures the elastic behavior can be controlled by placing a stiffer component in the region of highest stress, such as in **sandwich structures**. As indicated in Fig. 1.2, materials science often plays an intermediary role between engineering and the basic sciences of physics and chemistry.

Figure 1.3 shows a flow chart that describes the overall design process. As the design moves from concept to product, design tools of increasing sophistication are needed from engineering science. Concurrently, materials science needs data on the properties of materials with increasing degrees of precision, in order to select the best candidate. In the early stages, approximate data are useful to identify the best group of materials but, later, standard test procedures and in-house testing are often required. The material selection process is becoming more

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sophisticated as computer databases are being developed. Such databases are expected to increase in sophistication and 'intelligence'. This latter aspect is particularly important in being able to check and correct any input errors. Clearly this process will be influenced by many other factors, such as the economics and the aesthetics of the design. It is important to realize that there are often many different processing routes to produce a particular material. Shifting economic patterns and the development of new processing techniques can strongly impact the final decisions. There is also greater concern over 'greener' processing and industrial processes are now being studied from an ecological viewpoint (**industrial ecology**).

To illustrate techniques that have been introduced to improve **mechanical reliability**, it is useful to consider some examples for a particular material, say alumina (Al_2O_3). The microstructure of hot-pressed alumina, which consists of fine equiaxed grains (~5 μm), is shown in Fig. 1.4. Polycrystalline alumina has found applications from electronic circuit substrates through to armor plating. It is now established, however, that the strength and toughness of alumina can be substantially improved by several techniques. For example, adding zirconia as a second phase gives microstructures similar to that shown in Fig. 1.5. In this approach, a mechanism known as **transformation toughening** can be introduced which increases toughness and strength. The toughness of alumina can also be

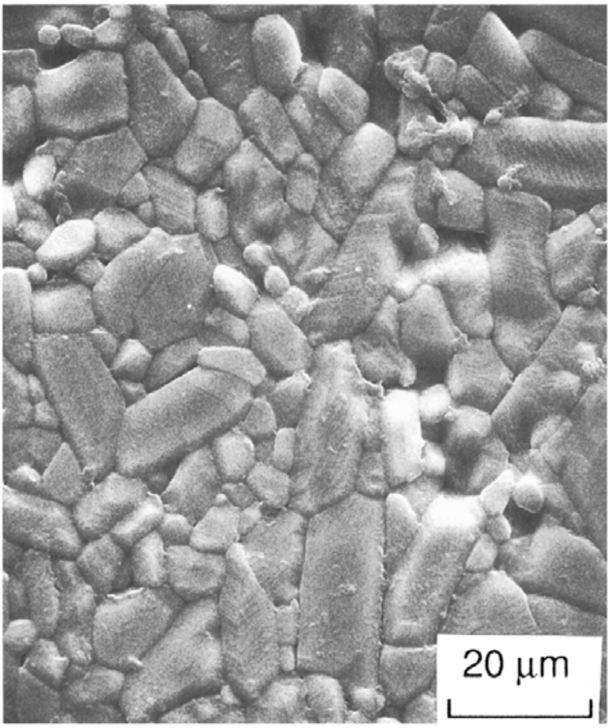

Figure 1.4 Microstructure of hot-pressed polycrystalline aluminum oxide; secondary electron image using the SEM.

increased by incorporating ceramic fibers, whiskers or platelets into the microstructure. For example, Fig. 1.6 shows the microstructure of Al_2O_3 containing SiC platelets. As shown in Chapter 8, **crack bridging** and the frictional pull-out of the reinforcements is often the source for the improved properties of these **ceramic-matrix composites**. The structure of an alumina product can also be manipulated at the macroscopic level. For example, Fig. 1.7 shows the loading of an alumina ceramic sandwich panel. The incorporation of a porous alumina core between dense alumina plates can be used to produce materials with maximum strength or stiffness at minimum weight, especially in flexural loading modes. There is also a current interest in producing ceramic hybrid laminates in which layers of different compositions are interspersed. For example, Fig. 1.8 shows a laminate consisting of alternating alumina and zirconia layers and such a structure can significantly influence the crack-propagation behavior. The above approaches emphasize the use of composites in controlling the structure. There is, however, a push to produce materials in which **self- reinforcement** is 'grown' into the microstructure. For example, Fig. 1.9 shows the microstructure of alumina, in which grain shape and texture are used to control the physical properties and Fig. 1.10 shows the microstructure of self-reinforced silicon nitride in which the production of 'fibrous' grains is found to increase fracture toughness.

The way a particular material is processed is also very important in deter-

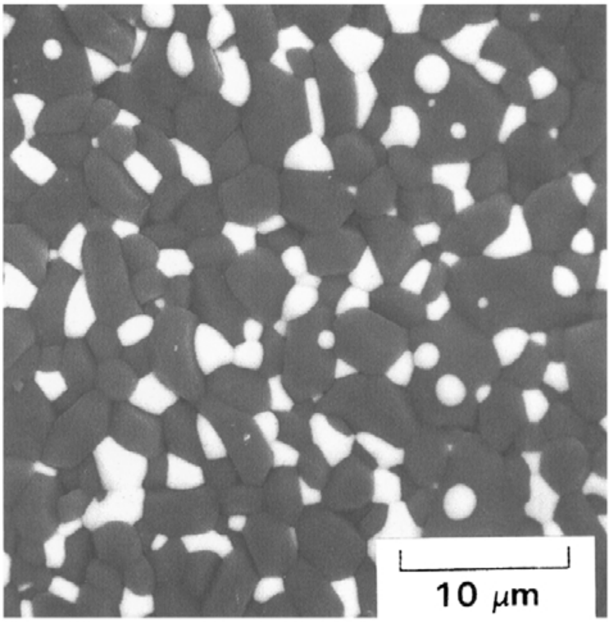

Figure 1.5 Microstructure of a zirconia-toughened alumina; back-scattered electron image using the SEM. The bright phase is zirconia.

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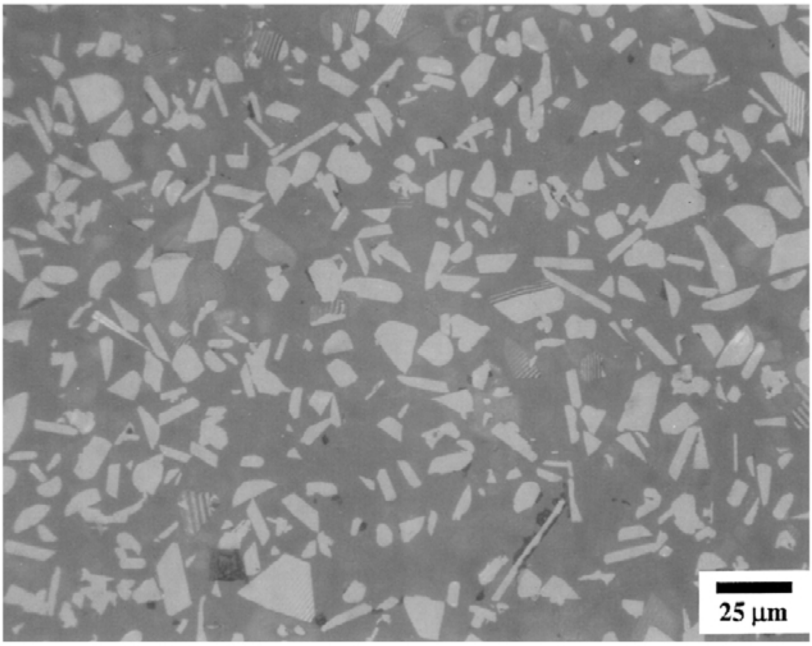

Figure 1.6 Microstructure of a SiC platelet-reinforced alumina; optical micrograph. (Courtesy of Matt Chou.)

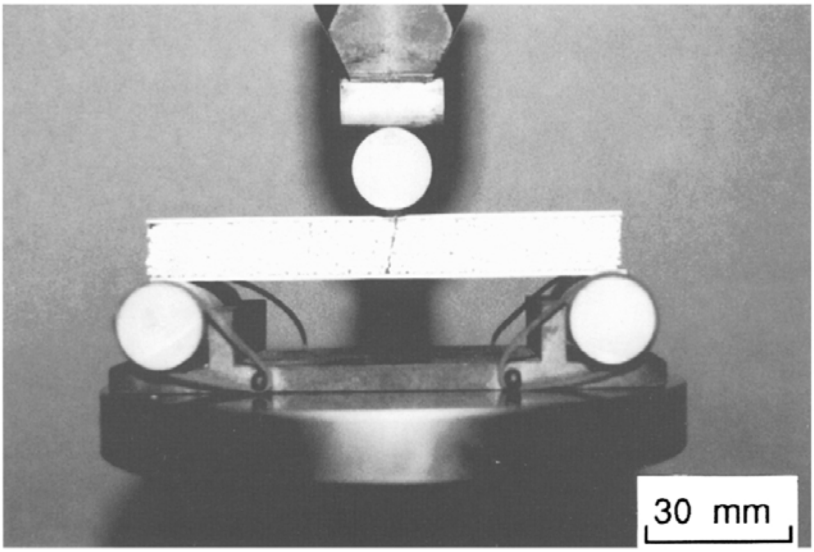

Figure 1.7 Three-point bending of an alumina sandwich panel, consisting of a porous, cellular core and dense faceplates. (Reproduced courtesy of The American Ceramic Society, Westerville OH.)

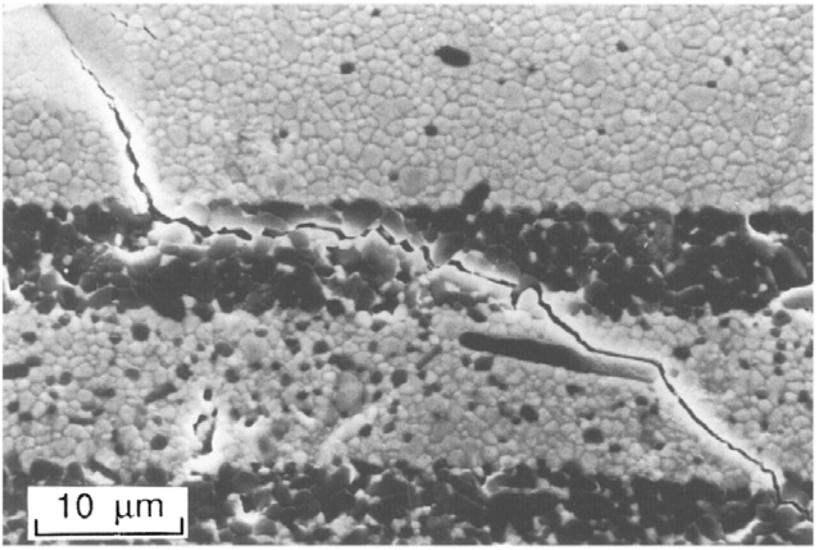

Figure 1.8 Crack deflection in an alumina–zirconia hybrid laminate. The layered structure was produced by electrophoretic deposition; scanning electron micrograph. (Courtesy of P. Sarkar and P. S. Nicholson.)

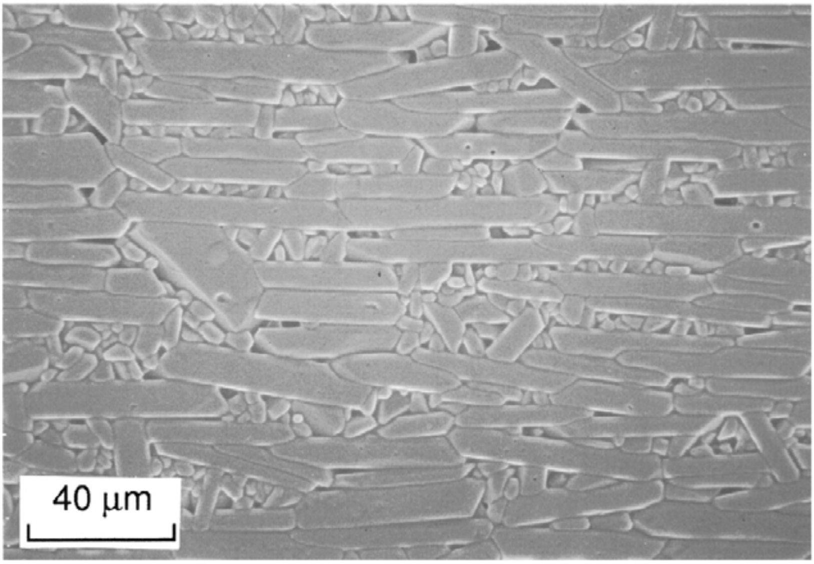

Figure 1.9 Microstructure of alumina in which grain shape and texture are used to control physical properties. (Courtesy of Matthew Seabaugh and Gary L. Messing.)

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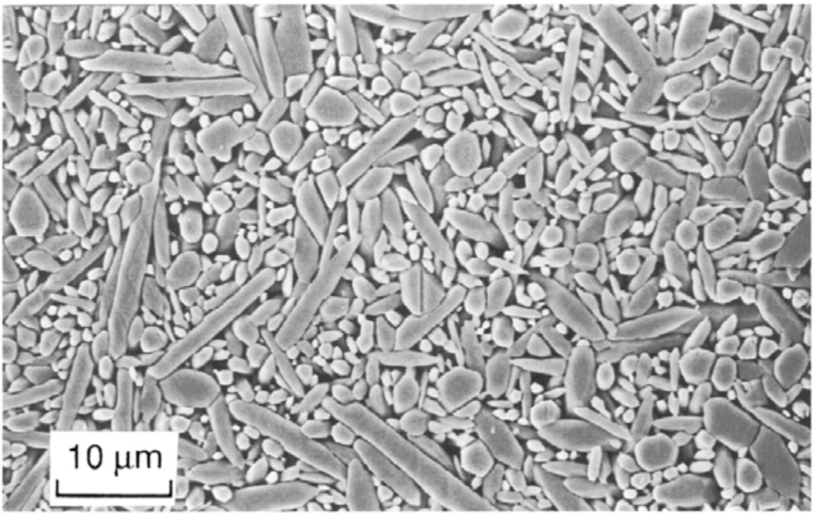

Figure 1.10 Microstructure of self-reinforced silicon nitride in which grain shape is used to control mechanical reliability. (Courtesy of Chien-Wei Li, Allied–Signal Corp.)

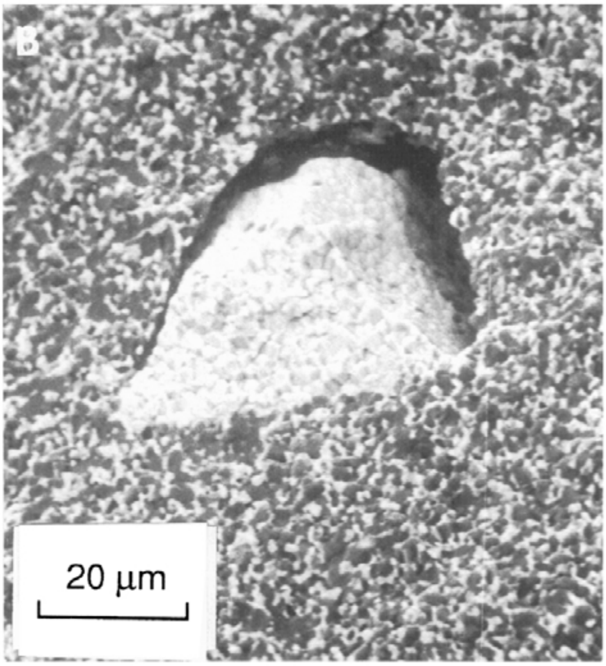

Figure 1.11 Failure origin in a zirconia-toughened alumina, caused by the presence of a zirconia aggregate in the starting powder. (Reproduced courtesy of CRC Press, Boca Raton, FL.)