38

Industry and the Environment

CHAPTER PREVIEW

Throughout this book we have highlighted the engineering applications for ceramics. In the final analysis, the importance of any material is based on what it can be used for. For example, at the present time, high-temperature superconductors (HTSCs) are of research interest but are not commercially important. Because of the unparalleled range of properties shown by ceramics, they find application in a vast number of areas. This last chapter looks at the field from an industrial perspective. Because it is impossible in one chapter to cover every aspect of the multibillion-dollar ceramic industry, we have chosen to focus on a few topics, mainly through examining case studies. One of the exciting prospects for the industry over the next decade is in nanotechnology. Ceramic nanopowders already represent the biggest segment of the nanopowders market and are used for polishing, sunscreens, etc. With the demonstration of the successful growth of ceramic nanowires, nanoribbons, nanosprings, and nanotubes, etc., there exists the potential for even more applications in critical areas such as solar cells, batteries, and hydrogen storage. As we have often done, we begin with some history.

38.1 BEGINNING OF THE MODERN CERAMICS INDUSTRY

In Chapter 2, we described some of the early history of ceramics and their production. The transition to a large-scale manufacturing industry occurred in Western Europe during the eighteenth century as part of the period that became known as the Industrial Revolution. The great porcelain factories established and subsidized by royal patronage at Miessen in Germany and Sèvres in France began to give way to purely commercial products being made in Staffordshire in the north of England. Later, the factories at Miessen and Sèvres began to imitate English designs. They were certainly helped in this area by immigrant workers. Emigration was a concern for the ceramics industry more than many others, such as iron production, because it relied on secret processes, such as specific body and glaze compositions. Once these became known, a worker would become valuable to a competitor.

SÈVRES

Royal Commission: The factory at Sèvres was commissioned to make an 800-piece dinner service for Catherine II of Russia. It took 3 years to complete.

The development of the Staffordshire area as the prominent pottery center in England was in large part due to the use of coal as a fuel for the kilns. Coal was abundant in this area, as was (and still is) clay. The proximity of raw materials provided an economic advantage over other rural potteries that were still using the diminishing supply of timber. Staffordshire is a long way from the major metropolitan areas of London, Bristol, and Norwich. Early pictures of Tunstall, one of the six towns that formed the Potteries and in 1910 became absorbed into the city of Stoke-on-Trent, show a town surrounded by hilly countryside.

By the mid-eighteenth century there were many separate potteries employing a large number of workers. A petition presented before the British Parliament in 1763 read:

> In Burslem [another of the six towns that made up the Potteries] and its neighborhoods [*sic*] are nearly 150 separate potteries for making various kinds of stone and earthenware, which, together, find constant employment and support for nearly 7,000 people.

In the early days of the pottery industry in England, transport of raw materials in, and products out, was inefficient. The costs of transportation had to be included in the selling price of every article produced. Clearly, quantity production could not be achieved without better transportation.

SIX TOWNS: THE POTTERIES

Tunstall, Burslem, Hanley, Stoke-upon-Trent, Fenton, Longton

C.B. Carter and M.G. Norton, *Ceramic Materials: Science and Engineering*,
DOI 10.1007/978-1-4614-3523-5_38,

Master potter and entrepreneur Josiah Wedgwood was instrumental in organizing a potters' association to push for the development of improved roads and a canal system. Wedgwood realized that cheaper and more regular transport meant an even flow of production, less breakage, lower prices, wider markets, and greater sales. Staffordshire potters lobbied successfully for the development of a canal that would link the rivers Trent and Mersey, which was authorized by an Act of Parliament in May 1766. The project was completed in 1772 at a total cost of £300,000. The completion of the Trent-Mersey Canal ensured that Staffordshire would remain the center of English pottery production. A complex web of railway routes followed, and these developments transformed an isolated rural area into a major industrial center.

Wedgwood made contributions in several areas that helped transform the production of pottery into a major industry. He changed the manufacturing process and adopted mechanization that would enable him to increase production while lowering prices; and the increased productivity would help to maintain a stable wage for his employees. He had many ideas about sales and marketing of his products and was the first manufacturer to introduce the "satisfaction-guaranteed-or-your-money-back" policy, which is now an extensively used tool for selling.

Wedgwood was an advocate of free trade, and a commercial treaty with France was welcomed by many of the ceramic manufacturers as a means of stimulating imports. Industries that had not adapted to new technology (e.g., the use of steam) feared the competition of imports. Wedgwood wrote on this issue of the treaty with France:

> An exchange of the produce of one nation for the manufactures of another are happy circumstances, and bid fair to make the intercourse lasting; but sensible as I am to the interests of trade, manufacturers and commerce, they all give place to a consideration much superior in my mind to them all. I mean the probability that a friendly intercourse with so near and valuable a neighbour [sic], may keep us in peace with her—may help to do away with prejudices as foolish as they are deeply rooted, and may totally eradicate that most sottish and wicked idea of our being natural enemies . . ..

The production of ceramics became an important and growing export industry. Vast quantities of ceramic ware produced in the potteries were exported from the major seaports of London, Bristol, Liverpool, and Hull to America, the West Indies, and all over Europe.

Today, many of the most famous names associated with the Staffordshire Potteries, such as Royal Doulton and Spode, can still be seen. A visit to any department store demonstrates that these names are still associated with some of the highest-quality ceramic tableware. However, most of the Royal Doulton pieces are now made in China, not in the small towns in the Potteries. As with other industries, the ceramic industry has seen much consolidation and acquisition in recent years. Wedgwood merged in 1986 with Waterford Crystal, forming Waterford Wedgwood plc to become the world's largest tableware company, with sales in excess of $1 billion. Unfortunately, the company bearing the great name of Wedgwood went into receivership in 2009, and production at its headquarters in Waterford, Ireland shut down with the loss of several hundred jobs. Also in 2009, the Portmeirion Group acquired Spode; and production still takes place in Stoke-on-Trent.

38.2 GROWTH AND GLOBALIZATION

Although the United Kingdom was a traditional leader in the development of ceramics, there were major changes during the latter half of the twentieth century, when Japan became the major producer of ceramics. Rapid transportation routes meant that manufacturing sites no longer needed to be near mineral resources. For example, Japan has no significant domestic energy supplies but is a major industrialized manufacturing nation. One of the significant changes that led to the growth and dominance of Japan was a shift in its business from traditional low value-added basic ceramics to one that has a large component of high value-added. Table 38.1 shows the market for high-technology ceramics as it was in 1980. Japanese companies satisfied about half of the $4.25 billion demand. In some areas they were dominant, producing over 60% of the worldwide market for integrated circuit (IC) packages and almost 80% of the ferrites. The market for IC packages, which is based on alumina, was established largely by U.S. companies, but there are few remaining that sell on the open market.

The rapid growth in the Japanese production of ferrites in the 1970s and 1980s coincided with a decline in this area in the United States and in Europe. The only serious constraint on the expanded production of ferrites in Japan during this period was a shortage in raw material (secondary iron oxide) caused by weak steel production. In 2011, Japan remains the largest market for advanced ceramics.

TABLE 38.1 1980 Market for High-Technology Ceramics (Excluding Fibers, Nuclear Fuels, Spark Plugs)

Product	*Japan*	*World*
Ceramic powders	$130	$250
Electronic IC packages/substrates	540	880
Capacitors	325	750
Piezoelectrics	295	325
Thermistor/varistors	125	200
Ferrites	380	480
Gas/humidity sensors	5	45
Translucent ceramics	20	45
Cutting tools: carbide, cermet, coated noncarbide	120	1,000
Structural ceramics (heat and wear resistant)	120	250
Totals	$2,065	$4,250

IC integrated circuit.
Markets in millions of dollars.

TABLE 38.2 Challenges Facing the Ceramic Industry According to Percent of Survey Respondants

Environmental standards	39%
Changing markets	33%
Cost of labor	32%
Imports	27%
Health and safety standards	26%
Cost of materials	25%
Quality of labor	20%
Capital for expansion	20%
Quality control	19%
Cost of fuel	19%

Table 38.2 shows some of the challenges that face ceramics companies worldwide. This information was gathered from a survey of over 250 ceramics companies. The major challenges are meeting environmental standards, adapting to changing markets, and labor costs. The ceramics industry, like many others, can establish production facilities where labor costs are lower. For example, KEMET Corporation, based in Greenville, SC, a manufacturer of tantalum electrolytic and multilayer ceramic chip capacitors, has relocated all manufacturing to lower-cost facilities such as in Mexico and China.

CERAMIC IC PACKAGES

Together with substrates, ceramic packages compete with polymers but are superior in terms of thermal conductivity and hermeticity and are used in high-reliability applications.

38.3 TYPES OF MARKET

As we described in Chapter 1, the ceramics industry is generally divided into six distinct markets.

- Glass
- Advanced ceramics
- Whiteware
- Porcelain enamel
- Refractories
- Structural clay

It is in advanced ceramics that many of the exciting developments are occurring. The 2007, U.S. advanced ceramics market was \$12 billion, and by 2015 it is projected to reach \$16 billion. The global market for advanced ceramics is expected to exceed \$56 billion by 2015. The largest growth segments are electronic ceramics, which includes capacitors, piezoelectrics, and ferrites. In chemical processing and environmental-related applications, ceramics are routinely used for automotive catalyst supports and filters that reduce pollutants in response to regulations on both automobile and industrial emissions.

TABLE 38.3 Types of Ceramic Industry

Activity	*Examples*
Ceramic powders	SiC for abrasives
	Nanosized TiO_2 for sunscreen
	Bioactive glasses for bone reconstruction
	Bayer process Al_2O_3 for the production of Al using Hall-Héroult cells
Forming powders into bulk forms	Slip casting of toilet bowls
	Cz growth of Nd:YAG single crystals
	AlN sheets by tape casting
	Glass melting
Fabricating ceramic components	Ceramic chip capacitors
	Packages for integrated circuits
	SiC pressure sensors

38.4 CASE STUDIES

As we described in Chapter 1, the ceramics industry covers a wide range of materials and products. We can generally divide the activities of this industry into three distinct categories, as listed with examples in Table 38.3. In this section, we describe in more detail one example of each activity and some current industrial trends.

38.4.1 Silicon Nitride Powder

Silicon nitride, Si_3N_4, is not a naturally occurring mineral. All the Si_3N_4 that we use must be synthesized, usually by one of the following methods (more details in Chapter 19).

- Direct nitridation of Si
- Carbothermal reduction of silica in N_2
- Vapor phase reaction of $SiCl_4$ or silane (SiH_4) with ammonia

The characteristics of the resulting powder that are important to end-users are:

- Particle size and distribution. Powder compacts containing a few coarse particles produce components with significantly reduced strength and toughness (two of the properties we are often trying to maximize). Milling can be used to reduce particle size but often leads to significantly increased costs and the introduction of unwanted contamination.
- Surface area. Affects how easily the powder can be densified during sintering and the final grain size in the sintered component.
- Purity. Depends on the processing route and wide variations are possible. Oxygen on the surface of the

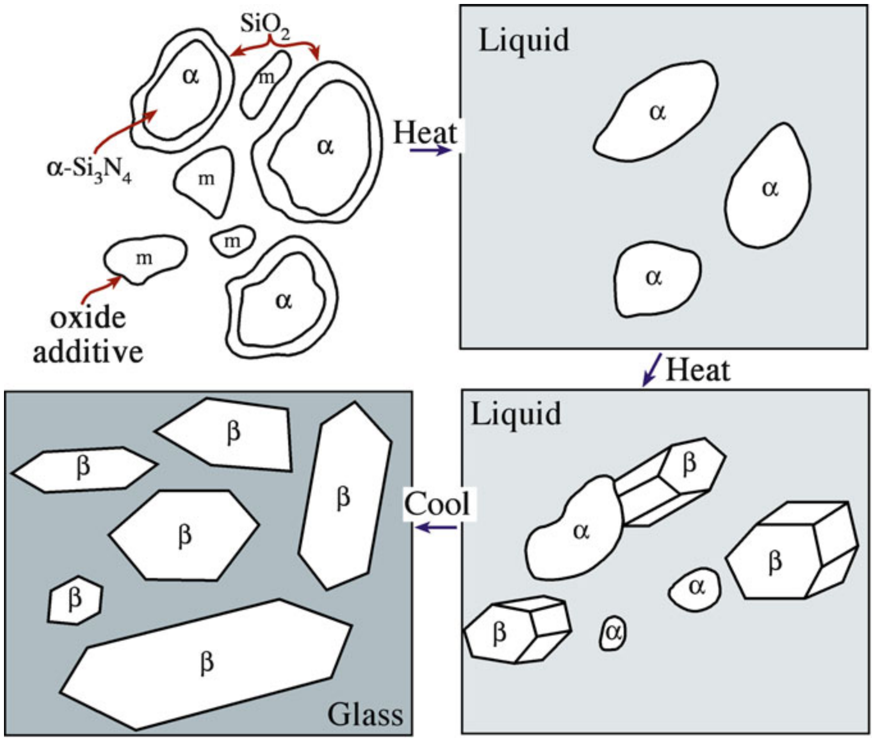

FIGURE 38.1. Schematic showing processing steps in forming Si_3N_4 by LPS. The metal oxide additive (m) would be something like Y_2O_3 and the liquid an oxynitride/silicate.

powders can affect densification; however, we need enough to form the liquid phase during sintering.

- Structure. A high α-Si_3N_4 content is desirable because it favors the conversion to rodlike interlocking β-Si_3N_4 during subsequent processing into bulk components, as illustrated in Figure 38.1.

The cost of Si_3N_4 powders can vary from \$30/kg up to \$150/kg depending on particle size and purity. The high costs of raw material and the subsequent shaping and forming processes have restricted the use of Si_3N_4. Table 38.4 shows a summary of a cost analysis performed for direct-nitrided Si_3N_4 powder. Most of the cost of the powder is due to the raw materials and the process materials (i.e., the milling media). Si_3N_4 milling media is very expensive; it costs about \$150/kg, compared with alumina or steel media at \$16/kg and \$4/kg, respectively.

Some of the present applications for Si_3N_4 parts include cutting tool inserts, bearings and rollers, refractory parts, cam followers in engines blades, vanes in heat engines, and turbocharger rotors. The advantage of using Si_3N_4 for cutting tool inserts should be clear from Figure 38.2. You may see the units given as surface feet per minute (SFM), which is a measure of the distance covered by a rotating tool (traditionally a saw or lathe now used in wear); the surface foot is a linear foot (3.28 SF = 1 m).

There are several powder manufacturers—primarily in China, Germany, and Japan—producing hundreds of tons of Si_3N_4. There are currently no U.S. suppliers of Si_3N_4 powder. GTE, Dow Chemical, and Ford Motor Company developed high-quality Si_3N_4 powders between about 1973 and 1995, but none of these companies is a supplier today.

TABLE 38.4 Summary of Costs for Direct-Nitrided Si_3N_4 Powder

Cost distribution	*\$/kg*	*% of total*
By cost element		
Silicon powder	7.49	25.4
Silicon nitride seed powder	1.71	5.8
Capital equipment	0.49	1.7
Direct labor	1.18	4.0
Energy	1.88	6.4
Process materials	16.74	56.8
Total	29.48	100.0
By process step		
Silicon powder	7.49	25.4
Silicon nitride seed powder	1.71	5.8
Direct nitriding	3.30	11.2
Crushing	6.62	29.3
Fine grinding	8.36	28.4
Total	29.48	100.0

38.4.2 Ceramic Chip Capacitors

We described the structure of a multilayer chip capacitor (MLCC) in Chapter 31. The MLCCs are used in a large number of products, in particular personal computers and

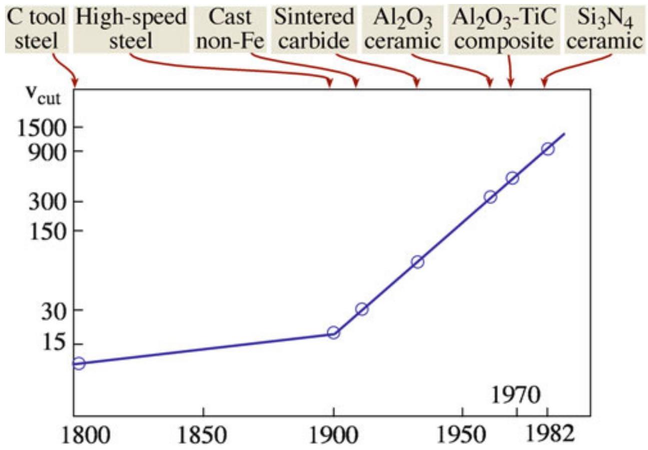

FIGURE 38.2. Improvements in the rate of metal cutting for various cutting-tool inserts.

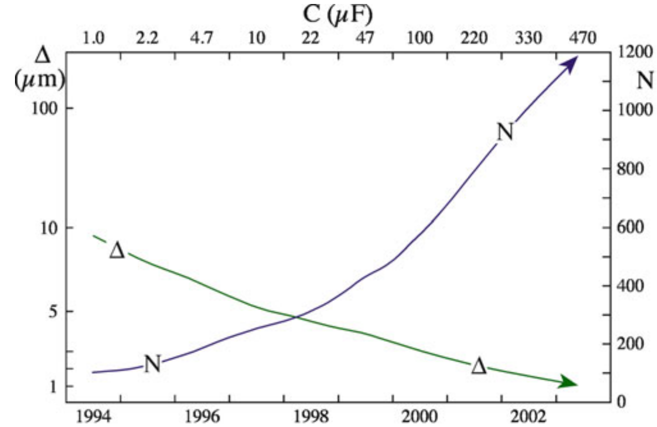

FIGURE 38.4. Trends in number (N) of dielectric layers and thickness (Δ) of the dielectric layer.

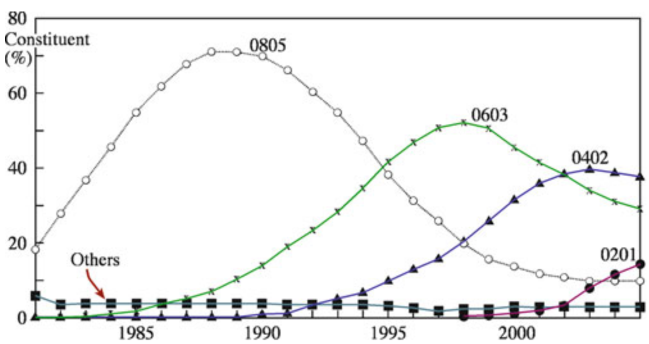

FIGURE 38.3. Multilayer ceramic capacitor-size trends.

cell phones. A typical cell phone may contain 400 MLCCs. The goal is to make smaller components with larger capacitances at a lower cost.

Capacitors are extremely price-competitive because of their relatively simple structure (see Figure 31.19). The following costs are involved.

- Ceramic dielectric. The ceramic capacitor industry uses more than 10,000 t of $BaTiO_3$-based dielectrics (about 90% of the total produced).
- Metal electrodes are usually precious metal-based.
- Labor costs are particularly important in this industry because of the low value-added costs.

Figure 38.3 shows the trend in the size of MLCCs since 1981. The designations used follow the Electronic Industries Association (EIA) guidelines. In the 1980s, most MLCCs produced were either 1206 or 0805 (the two largest sizes). By 2000, the 1206 type accounted for less than 10% of the market, and 30% of the market was the 0402 type: a component with a fraction of the area and using much less material. Since 2000, the very small 0201 captured an increasingly larger market share.

The use of lower operating voltages in handheld devices and microprocessors has allowed dielectric layer thickness (Δ) to be reduced; consequently, higher layer counts (N) are possible within the same overall device dimensions, as shown in Figure 38.4. The trends in N and Δ predicted by the arrows at the end of the lines in Figure 38.4 are consistent with where the industry was in 2011: N > 1,800 and Δ < 1 μm.

You may recall from Chapter 31 that capacitance, C, is given by:

$$C = \varepsilon_0 \kappa \frac{A}{d} \qquad (31.13)$$

By reducing d and increasing the number of layers (effectively increasing A), it has been possible to expand the capacitance of MLCCs into the tantalum and aluminum electrolytic capacitor range.

The ability to cast thin layers (<3 μm) requires highly disperse, uniform, fine-grained ceramic powders (100–300 nm particle diameter). To achieve these particle sizes, extensive milling may be used, or the powder can be made by solution methods such as using metal alkoxides, as we described in Chapter 22.

A major challenge in the MLCC industry has been to replace the

EIA CAPACITOR CODE

The size of MLCCs is defined as "llww": ll is the length of the capacitor and ww is the width, both in thousandths of an inch (a case where Imperial and U.S. units are still widely used in industry!)
Example: 0805 means a capacitor of length 0.080 in (~2 mm) and width 0.050 in (~1.25 mm).

PRECIOUS METAL

In January 2001 Pd prices reached a staggering $1,000 per troy oz. Currently Pd trades for between $750–800 per troy oz.

precious metal electrodes (usually a Pd-Ag alloy) with base metals such as Ni. The MLCC industry accounts for about 75% of the electronic industries' use of palladium.

38.4.3 Nd-Doped YAG Laser Crystals

Yttrium aluminum garnet (YAG) single crystals are the most widely used laser host, with over 100,000 YAG lasers worldwide. The Czochralski process, which we described in Chapter 29, is used to grow single crystals of YAG. Typical growth conditions are pull rates of 0.4 mm/h at temperatures nearing 1,900°C.

One of the most common dopants is Nd^{3+}, which substitutes for yttrium in the crystal lattice. Commercial Nd-doped YAG is regularly produced with Nd concentrations of 0–1.5 substitutional percent (sub %) of yttrium sites. From the chemical formula $Y_{3-x}(Nd_x)Al_5O_{12}$, the substitutional percent Nd is given by $x/3$. For instance, 1.02 sub% Nd = 0.153 at. % Nd. Few crystals beyond 1.5 sub% Nd are available commercially.

The goal for commercial suppliers is to grow highly doped, large-diameter crystals. Increasing the dopant concentration results in a higher absorption coefficient, lower fluorescence lifetime, and greater overall laser efficiency. However, raising the Nd concentration increases the frequency of cracking during growth as we showed in Figure 16.1. If fracture occurs during growth, the process must be halted, which results in significant loss of time because a single boule can take 2 months to grow.

One of the causes of fracture has been shown to be small regions of inhomogeneity in the crystal, as shown in the transmission electron microscopy (TEM) image in Figure 38.5. The widely spaced fringes in the image are moiré fringes caused by interference of the electron beam as it passes through two lattices that have different lattice parameters. The particle shown in Figure 38.5 actually has a larger lattice parameter, corresponding to a local Nd concentration of 2.768%, compared to the matrix, which has an Nd concentration of 1.02% Nd. (There is also a very small misorientation between the particle and the matrix, which affects the spacing of the moiré fringes).

More recently, there has been interest in using nanopowders to make polycrystalline laser hosts, which would avoid the need to use slow single-crystal growth methods. The problem is keeping the grain size small enough during sintering to maintain transparency.

YAG LASERS

The first application for Nd-doped YAG lasers was in laser range finding. Nonmilitary applications include cutting, welding, and drilling of metals for the automobile industry and in medical and dental procedures.

Ce-DOPED YAG

Ce-doped YAG is a scintillator that can be used to detect γ-rays with a high energy resolution (<4% using ^{137}Cs 662 keV γ-rays). The applications include nuclear threat detection and medical diagnostics using positron emission tomography. Ce-doped YAG is yellow; Nd-doped YAG is purple.

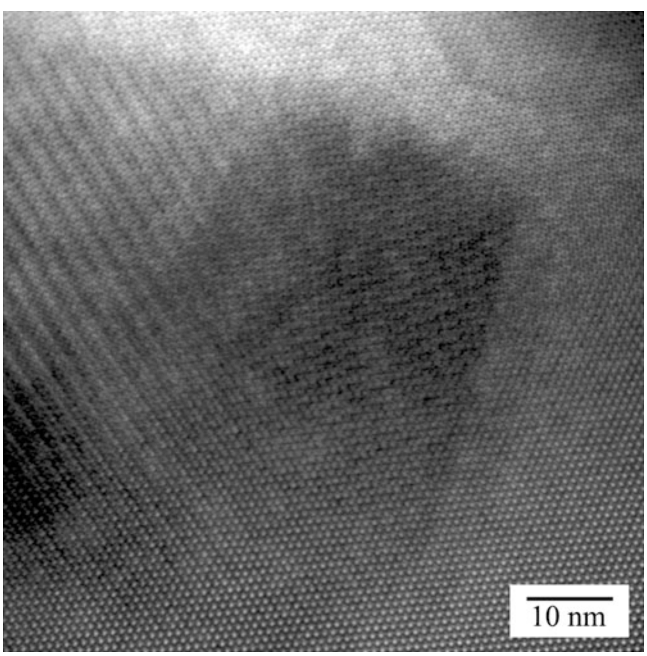

FIGURE 38.5. Moiré fringes observed in a high-resolution transmission microscopy image of an Nd-rich particle in single-crystal YAG.

38.5 EMERGING AREAS

The area of advanced ceramics is exciting as technologies developed in research laboratories and universities become adopted by industry. This market segment shows continued growth offering good employment opportunities for Management Science and Engineering (MS&E) graduates.

In this section we describe three emerging areas: ceramic nanopowders, high-temperature superconductors, and ceramic matrix composites.

38.5.1 Ceramic Nanopowders

Nanotechnology is a "hot" research topic. The field is trendy, popular, and high-tech. Although silica and iron oxide nanoparticles have a commercial history spanning half a century or more, it is really within the last two decades that technologies have been developed for

TABLE 38.5 Current and Emerging Applications for Nanosized Powders

Electronic, optoelectronic, magnetic applications	*Biomedical, pharmaceutical, cosmetic applications*	*Energy, catalytic, structural applications*
Chemical–mechanical polishing (CMR) supports	Antimicrobials	Automotive catalyst
Electroconductive coatings	Biodetection and labeling	Ceramic membranes
Magnetic fluid seals	Biomagnetic separations	Fuel cells
Magnetic-recording media	Drug delivery	Photocatalysts
Multilayer ceramic capacitors	Magnetic resonance imaging contrast agents	Propellants
Optical fibers	Orthopedics	Scratch-resistant coatings
Phosphors	Sunscreens	Structural ceramics
Quantum optical devices		Thermal spray coatings
Solar cells		

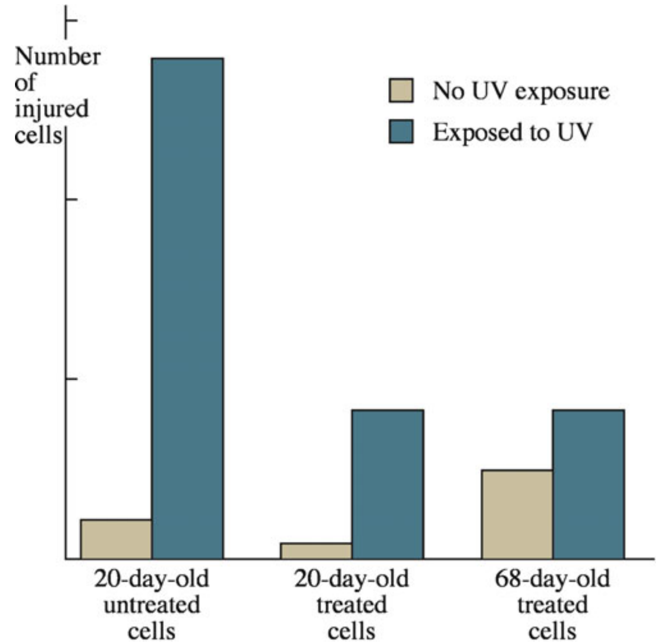

FIGURE 38.6. Effect of nanosized cerium oxide particles on the life-span of rat neurons.

producing ultrapure nanosized powders of a range of ceramics. The global nanoparticle market, which is dominated by ceramics, is now around $1 billion. Current applications for ceramic nanoparticles are summarized in Table 38.5.

- Electronic, magnetic, and optoelectronic applications account for 70%. The biggest single use is slurries of abrasive silica particles (50–70 nm) for chemical–mechanical polishing (CMP).
- Biomedical, pharmaceutical, and cosmetic applications account for 18%. Sunscreens use nanosized powders of TiO_2 or ZnO.
- Energy, catalytic, and structural applications account for the remaining 12%. Uses include catalyst supports (e.g., for low-temperature H_2 production), ceramic membranes, fuel cells, and scratch-resistant coatings.

An example of the potential of nanosized ceramic powders in medicine is the demonstration that 5-nm cerium oxide (CeO_2) nanoparticles can prolong the life of brain cells. Usually these cells live for around 25 days in the laboratory, but after a low dose of the nanoparticles they have been shown to survive and function normally for 6 months. The hope is that this approach might one day be used to treat age-related disorders such as Alzheimer's disease. It was also found that the treated cells had increased protection against damage from ultraviolet (UV) radiation, as shown in Figure 38.6. The implication is that the nanoparticles mop up free radicals—reactive molecules that damage cells and are known to be involved in aging and inflammation. (Look back at Chapter 35—this is just the beginning, but always remember that perhaps the most dangerous asbestos fibers are "nanoparticles").

NANO
Nanosized ceramic powders have grain sizes on the order of tens of nanometers or less; conventional ceramic particles typically have grain sizes of several microns or more.

An energy-related application undergoing extensive testing is the use of 10-nm CeO_2 particles as additives to diesel fuel. The CeO_2 nanoparticles catalyze combustion of the fuel. The claim is that they release oxygen to oxidize carbon monoxide and hydrocarbon gases to carbon dioxide and reduce quantities of harmful nitrogen oxides. The result is a cleaner-burning fuel that converts more fuel to carbon dioxide, produces less noxious exhaust, and deposits less carbon on the engine walls.

The market for nanosized powders is much smaller than for conventional ceramic powders, but the cost per kilogram is much greater. Despite progress in scaling up production and reducing costs, nanosized powders remain relatively expensive (often 100 times more than conventional ceramic powders).

There are growing concerns about the impact of nanoparticles on human health and the environment. Inhaling fine quartz particles is known to cause silicosis, a potentially fatal scarring of delicate lung tissue. Fine particles shed from hip and knee replacements as they wear cause inflammation of the surrounding tissues and may result in the implant having to be replaced. Studies where carbon nanotubes were placed directly into the lungs of mice showed that there was significant damage to the lung tissue. Because many of the potential applications for nanoparticles are in the human body, it is important to determine their safety. It is also necessary to evaluate their environmental impact.

38.5.2 High-Temperature Superconductors

One of the benefits with increasing T_c above 77 K is that liquid nitrogen, rather than liquid helium, can be used as the coolant. Liquid nitrogen is both cheaper and more readily available than liquid helium. You can find the cost of liquid nitrogen described as either less than milk or less than cheap beer! The cost of liquid helium is often likened to fine champagne.

Soon after the discovery of HTSCs and, in particular, the yttrium barium copper oxide (YBCO) compound, there were grand predictions that these materials would revolutionize areas such as a high-speed transportation and power transmission. The applications to date have been a little more modest. Magnetic levitation (maglev) for high-speed transportation has not been achieved with HTSCs but continues to a limited extent with the use of low-temperature materials. The other major application proposed for HTSCs was in power transmission. However, due to the high cost and impracticality of cooling miles of superconducting wire, this has happened only with short "test runs." In May 2001, about 150,000 residents of Copenhagen, Denmark, began receiving their electricity through superconducting cables. The superconductor chosen for this application was bismuth strontium calcium copper oxide (BSCCO) (see Section 7.16) in the form of a tape wrapped around a flexible duct that carries the liquid N_2. The remainder of the cable consists of thermal and electrical insulation. In November 2001, commercial power was delivered to about 30,000 homes in Detroit, Michigan using a similar approach.

One area where HTSCs are is poised to make a significant impact is in filters that improve network performance between wireless (cellular) devices and cell sites. Superconductivity avoids a typical trade-off by filtering out interference from adjacent signal bands without hindering the base station's ability to pick up weak signals. Commercial units using HTSCs are available and have been deployed.

According to estimates by Conectus, the worldwide market for HTSC products is projected to grow to about \$0.5 billion by 2013. It is interesting to compare this projection with the very "bullish" one provided by the same organization and quoted in the first edition of this book! It really goes to show that it is very difficult to accurately predict markets over even short periods of time.

38.5.3 Ceramic-Matrix Composites

Ceramic-matrix composites (CMCs) are being developed to provide an alternative to single-phase ceramic components because of the possibility of designing in higher toughness. The most important CMCs will probably be those with continuous fiber reinforcement. We described some of the processing routes in Chapter 20. CMCs are at a relatively early stage of development compared to polymer-matrix composites (PMCs) and metal-matrix composites (MMCs); and significant research is needed if they are to meet their full potential. Table 38.6 lists some of the priorities.

TABLE 38.6 Priory Needs in CMCs to Address Key Challenges Faced by Ceramic Manufacturers and End Users

Key challenges for CMCs	*Priority needs to address the challenge*
Reduce the cost of precursors	Scale-up/cost reduction of fiber manufacturing Lower-cost interface materials and deposition processes
Improve understanding of failure modes	Basic understanding of interactions between CMC constituents and application environments Micro- and macro-mechanics understanding of interactions of CMC with an applied stress or strain
Increase temperature stability to 1,200–1,500°C	Higher-temperature fibers, matrix materials, and interface coatings Environmental barrier coatings (EBCs) Active cooling designs
Manufacturing scale-up and cost reduction	Larger furnace design and construction Automation/semiautomation of perform fabrication Low-cost tooling Near-net-shape fabrication Low-cost in-process and post-process quality assurance

- *Cost*: Nonoxide fibers cost thousands of dollars per kilogram. Oxide fibers, even those that have been commercially available for years, sell for hundreds of dollars per kilogram. The main reason is that production volumes are small. Most fiber-reinforced CMCs utilize a layer between the fiber and the matrix to optimize mechanical properties. The methods used for depositing this layer tend to be expensive and difficult to scale up for production.
- *Understanding failure modes*: We generally want a weak fiber/matrix interface in CMCs. A propagating crack is deflected around the fibers as shown in Figure 38.7 and does not propagate through the fibers. This is a situation opposite to that in PMCs, where we often want a strong interface so that the load is transferred to the stronger fibers.
- *Increase temperature stability*: Fiber-reinforced CMCs have been demonstrated to survive in the severe environment of a gas turbine engine for 2,500 h at temperatures up to 1,200°C. The use of environmental barrier coatings (EBCs), such as oxide layers, on SiC appears to help extend durability, but more research is

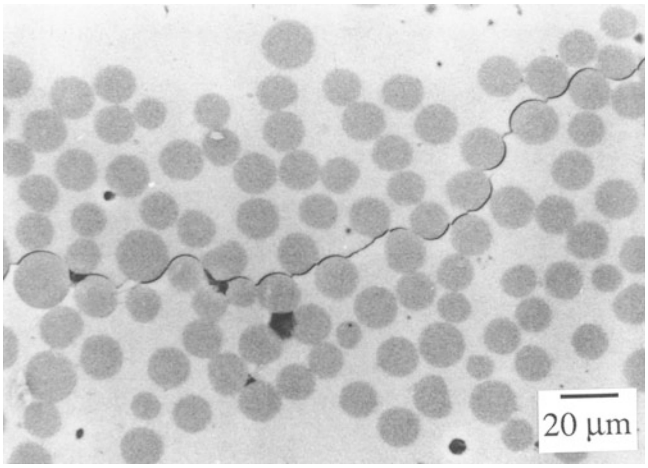

FIGURE 38.7. Crack propagation through a fiber-reinforced composite: SiC fiber in calcium aluminosilicate glass.

needed to determine whether they present a long-term solution.

- *Scale-up*: The high price of finished components made from fiber-reinforced CMCs is a major limitation. Reducing materials' costs and increasing production volume would reduce costs substantially. One of the requirements for large-scale manufacturing of CMCs is the development of quick, inexpensive quality control procedures that can be used during production. The main processing defects are voids, density variations, and cracks. X-ray computed tomography (CT) is a powerful technique for this type of investigation, and high-resolution detectors can detect defects as well as resolve features as small as 5 μm (see Chapter 10). However, the technique remains expensive and slow and is not suitable at the present time for in-line process control.

38.5.4 Ceramics as the Enabling Materials

As you've realized from the discussion of capacitors, glass, data storage, etc., ceramic materials are often the critical part of a program or product even if the consumer never sees them.

Sapphire single crystals are grown for use in substrates, as windows, as infrared (IR)-transparent domes, in jewel bearings, as the "glass" on your watch; but there are other applications of these and other single crystals that most of us never see. Large sapphire crystals are being tested for use in the Laser Interferometer Gravitational-Wave Observatory (LIGO) Fabry-Perot interferometer. The aim of LIGO is to study astrophysical gravitational waves. There are two LIGO sites: one in eastern Washington and one in Louisiana. Sapphire should reduce the thermal noise compared to the fused silica that was initially used. The LIGO requires the crystals to be 35 cm in diameter and 12 cm long, and it uses 5 N-pure alumina powder. The factors studied in assessing the sapphire mirrors for future generations of LIGO include all aspects of the influence of temperature on mechanical properties. The results are compared with the current fused-silica mirrors. In either case, the ceramic is the enabling material and is the topic of very focused research.

38.6 MINING

From the ugliness of an open cast mine, to the health problems of mine workers, to the bitter civil wars fought over mineral resources in Africa, the impact of mining and our search for raw materials are frequently topics in the news media. Many of the ceramic products we use are produced from natural resources. For example, the main component of most glasses is SiO_2, which comes from sand. The main component of traditional ceramic products such as tableware and bricks is clay, which is available in different grades and is usually extracted by opencast mining. These raw materials are abundant and widespread. Data on the United States Geological Survey (USGS) site is fascinating food for thought and is updated annually.

38.6.1 Talc

A mineral that has caught the attention of environmentalists and conservationists is talc. Talc is used in the production of paper and tiles and as coatings in the motor industry for dashboards and bumpers. However, its main use is in beauty products such as eye shadow, lipstick, body lotions, deodorants, and soaps. Talc is produced from soapstone, which occurs in the form of large subsurface boulders. One concern is that some of the finest powder is obtained from soapstone that is the result of illegal mining in India's Jamwa Ramgarh Wildlife Sanctuary and the neighboring Sariska Tiger Reserve 250 km southwest of Delhi. These sites are considered essential to the revival of the Indian tiger. The current population of Indian tigers is about 3,000, but they are threatened with extinction because of the loss of habitat and prey caused by the mining activities. The other concern is that some studies indicate that talc particles cause tumors in the ovaries and lungs of cancer victims; however, talc often contains asbestos, so all is not clear.

RARE-EARTH ELEMENTS

The REEs are the 15 lanthanides plus scandium and yttrium. They play a major role in the development of a number of advanced materials, including those with applications related to clean energy technology.

38.6.2 Vermiculite

Vermiculate is a mica-like mineral used as housing insulation and in gardening or even animal feed! Up to 80% of the world's supply

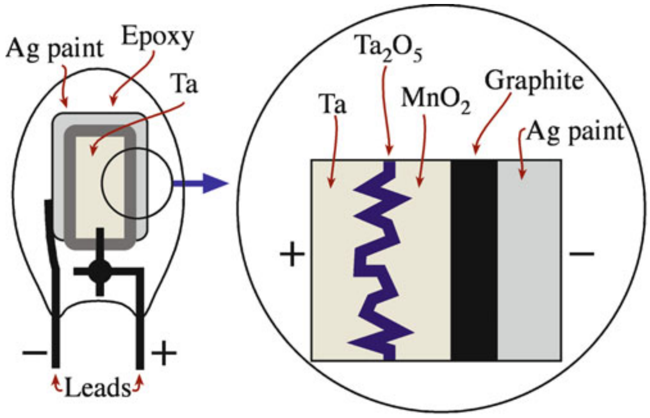

FIGURE 38.8. Structure of a solid electrolyte Ta capacitor.

came from Zonolite Mountain in Montana. Workers have a 50% chance of developing health problems relating to lung cancer.

38.6.3 Tantalite

The dielectric in tantalum electrolytic capacitors is tantalum pentoxide (Ta_2O_5), which forms a thin layer on tantalum, as illustrated in Figure 38.8. The benefits of using tantalum capacitors are that they are small, have a wide operating temperature range (−55°C to +125°C), and are very reliable.

Ta IN CAPACITORS

The major use for Ta is in electrolytic capacitors; it accounts for about 60% of this market. The value of Ta consumed in the U.S. in 2010 was ~$170 M.

Controversy has arisen recently concerning the source of tantalum: the mineral tantalite, which is found in association with niobium as the ore columbite-tantalite (col-tan). A major supply of col-tan is found in the Kahuzi-Biéga Park in the Democratic Republic of Congo. The park is home to the eastern lowland gorilla, one of the most rare animals in the world. As a result of col-tan mining, the gorilla population is being decimated, and the billion-dollar export has funded the Congo's civil war.

38.6.4 Dysprosium Oxide

Dysprosium is one of the rare-earth elements (REEs) and, according to the U.S. Department of Energy, may be the single most critical element for emerging clean-energy technologies. The spot price (August 2011) for 1 kg of dysprosium oxide (Dy_2O_3) was ~$1,500—a more than fourfold increase in less than 8 months. The price has increased from only $300 kg^{-1} in 2010. China is the only country with significant known deposits of dysprosium and mines over 90% of the supply of REEs. The most important dysprosium-containing minerals are xenotime, which is mined in Guangdong, and rare-earth laterite, which is mined in Longnan in Jiangxi Province. China imposed an export quota of 30,258 t of REEs in 2010 in response to a demand from the rest of the world for 48,000 t. The mining of dysprosium (and other REEs) creates two separate environmental problems. First, the REEs often occur together with radioactive elements (e.g., thorium, uranium), which pose significant health risks for miners. Second, the refining process uses toxic acids.

38.6.5 Lithium Carbonate

When you think batteries, you think Li and you would be correct. Lithium-ion battery production represents about 75% of the total portable rechargeable battery market worldwide. Around the world, lithium batteries power most cell phones and laptops (including iPods and iPads), as well as many heavy-duty power tools. In 2009, the United States consumed 1,399 t of Li. That is about 45% below 2007 and 2008 values: use is determined by the economy. Lithium is mined as an ore or brine. Fortunately, lithium ore is found worldwide. Australia is currently the leading producer of lithium mineral concentrates; the spodumene was mainly exported to China to produce lithium carbonate. Major sources of Li are in Bolivia and Chile where mining is having a critical impact on local politics. Comibol (Corporación Minera de Bolivia) expects to produce 30,000 t/year at the Salar de Uyuni salt flat, which is the world's largest.

Afghanistan may become the largest supplier of lithium, with deposits valued at $1 trillion in 2010. The mineral deposits are scattered throughout the country, including in the southern and eastern regions along the border with Pakistan, which have seen some of the most intense combat in recent years.

38.7 RECYCLING

There are three basic reasons given for recycling.

1. Preserve finite resources
2. Protect the environment
3. Save energy

The raw materials used for glass production are abundant and, unlike many metal ores, are not in any imminent danger of being depleted. Producing glass does involve consumption of large amounts of energy, as shown in Table 38.7. (Glass is the lowest on this list because high-purity sources of SiO_2 are readily available). Table 38.8 shows the total energy involved in producing a 12-oz beverage bottle, including factors such as mining, transportation, etc. The energy savings by recycling and reusing glass containers are also shown in Table 38.8.

TABLE 38.7 Energy Consumption to Extract 1 t of Raw Material from Its Ore or Source

Material	*Energy (GJ)*
Aluminum	238
Plastics	100
Zinc	70
Steel	50
Glass	20

TABLE 38.8 Energy Consumption per Use for a 12-oz Beverage Container

Container	*Energy (MJ)*
Aluminum can used once	7.4
Glass bottle used once	3.9
Recycled aluminum can	2.7
Recycled glass bottle	2.7
Refillable glass bottle used 10 times	0.6

BOTTLE BANKS

First appeared in the UK in August 1977. There are now over 22,000 bottle bank sites and more than 570,000 t of glass are recycled annually.

GLASS RECYCLING: FACTS AND FIGURES

More than 40 billion glass containers are produced each year in the US.
All glass food and beverage containers can be recycled.
Recycling a glass jar saves enough energy to light a 100-W light bulb for 4 h.
Glass constitutes about 6% of US municipal solid waste.
Approximately 12 million tons of waste glass food and beverage containers are generated each year in the US.
About 25% of all glass food and beverage containers are recycled in the US.
The average glass bottle contains over 25% recycled glass.

Glass recycling has been going on for thousands of years; broken glass was reused in antiquity to make new glass objects. This ancient recycling system makes it difficult for archeologists to determine the provenance of a glass object from its chemical composition alone. A structured recycling program for domestic glass waste started in 1975, initiated by the glassmaking companies.

In Chapter 26 we described the glass-forming process. The initial step is that the batch, which consists primarily of sand, is melted. The temperature required varies with the composition of the batch but is typically in the range 1,300–1,600°C. Adding crushed recycled glass, called cullet, to the melt promotes melting of the sand, permitting the use of reduced furnace temperatures with considerable savings in both raw materials and energy. For example, if a glass batch for beverage-container glass contains 25% cullet, it requires 5% less energy to melt. Although cullet has been used in ratios ranging from 0% to 100% of the glass, 30–60% cullet is the most effective range. For colored bottles, cullet comprises about 50% of the batch.

One difficulty associated with using recycled glass, particularly from consumer recycling, is the necessity to sort the discarded bottles according to color. In the United States, over 65% of container glass is clear, 25% is brown or "amber," and 10% comes in different shades of green and occasionally blue and other colors. These percentages do not correspond exactly with the glass contents in domestic waste because of the consumption of imported beverages that come in mostly brown and green bottles. In France, 80% of the glass containers are green. Wine is usually packed in green bottles because it provides better UV protection, but the original reason is that when the wine bottle was invented in England during the seventeenth century it was made of green glass.

Clear glass is the most valuable glass for recycling. Both clear and brown glasses are very sensitive to impurities, so they cannot be mixed with each other or with other types of glass. Green glass, on the other hand, can accept other glass types without noticeable influence on the color. However, green glass is often the most difficult for the glass manufacturers to use simply because the supply of recycled green glass often exceeds the demand. One application for recycled green glass that is not influenced by color is fiberglass insulation.

It is important that container glass is not mixed with other types of glass product, such as windows, light bulbs, mirrors, and tableware. These glasses have different compositions, as we showed in Chapter 26. Because of problems associated with contamination of recycled glass, the use of returnable/refillable glass bottles and containers is increasing. Switching to refillable containers can save up to 56% of the energy consumed, reduce water consumption by up to 82%, and decrease materials consumption over 10 times for 35 refills.

Currently, the cost of recycling far outweighs the value of the recyclables. It may take up to five times the amount of money a recyclable product is worth to collect, process, and transport it to a buyer. As a result, the recycling industry is currently driven by consumer demand, not by profit. Many environmental economists point out that in a "sustainable" economic system (one based on the real costs to the environment resulting from the transportation and production of goods and materials) recycling is financially cost-effective. In such a system, the prices of products made from virgin materials would be prohibitive, encouraging manufacturers to use recycled materials instead. However, under such a system, the concept of curbside recycling would become even less cost-effective than it is now due to increasing transportation and energy costs.

Some of the issues that drive the need for recycling in Europe are quite different from those in the United States. One significant difference is population density. Recycling in The Netherlands, which recycles more than 80% of its glass waste, is much more important than in the United States. The population densities are about 372 inhabitants/km^2 and 27 inhabitants/km^2, respectively. As the population density increases, the landfilling of wastes, particularly industrial wastes, becomes more difficult and unacceptable for the nearby population. Landfill space has to compete with the land requirements for expanding suburban developments and, in many cases, agricultural land as well.

One recycling issue that is important throughout the developed world is what to do with the approximately 300 million (old fashioned!) TVs and computer monitors that are thrown out each year. The European Union Waste Electrical and Electronic Equipment Directive banned them from being dumped in landfills because the screens contain PbO (added to shield against the X-ray radiation released by the high anode voltage).

CATALYTIC CONVERTERS

Have reduced automobile pollution by more than 1.5 billion tons since 1974

TABLE 38.9 Some Typical Chemical Compositions of CRT Glasses (wt.%)

Oxide	*Color TV panel*	*Color PC panel*	*Color TV funnel*	*PC funnel*
Na_2O	8.0–8.6	6.6	6.3–6.8	5.45
K_2O	7.0–7.5	7.3	7.8–9.7	8.05
MgO	0.2–1.3	0.33	1.0–1.8	1.5
CaO	0.5–2.5	1.15	1.4–3.8	3.5
SrO	1.5–8.5	8.65	0.15–0.5	0.5
BaO	10–12	1.15	1.0–1.95	3.5
Al_2O_3	2.2–3.2	2.05	3.0–4.0	3.6
ZrO_2	0.2–1.5	0.95	0.08	0.1
PbO	0–0.1	0.05	14.7–22.7	20.25
SiO_2	60–62	59	52–59	53
CeO_2	0.25	—	—	—
TiO_2	0.4	0.6	0.05	0.07
Sb_2O_3	0.25	0.5	0.05	—
As_2O_3	0.02	0.02	0.01	—
Fe_2O_3	0.07	0.12	0.06	—
ZnO	—	0.6	—	0.06

CRT cathode ray tube, *TV* television, *PC* personal computer.

Table 38.9 shows typical compositions of cathode ray tube (CRT) glasses.

To prevent a growing mountain of TVs, one of the plans is to melt down the tubes in a sealed furnace under conditions that would reduce the PbO to Pb. The heavy molten metal would run out of fissures at the base of the furnace, but the molten glass would be retained. The purified glass could then be used for other applications, such as bottles.

The use of recycled glass as an ingredient in concrete is being explored in several locations worldwide.

38.8 AS GREEN MATERIALS

38.8.1 Catalytic Converters

Catalytic converters are used in the exhaust system of automobiles and can reduce emissions of carbon monoxide and hydrocarbons by up to 90%. Carbon monoxide can be transformed into carbon dioxide, and unburned hydrocarbons from the fuel get burned on the metal surfaces. Nitric oxide, one of the main contributors to urban smog, reacts with carbon monoxide to form carbon dioxide and nitrogen gas. These processes are conducted in catalytic converters.

The first catalytic converters used mainly platinum, but now palladium is the predominant catalyst metal. Sixty percent of the palladium manufactured worldwide is used in catalytic converters. Other uses are as the electrodes in MLCCs and other electronic components, and a small amount is used in jewelry (e.g., as an alloying element in white gold).

The metal is dispersed as tiny particles on a supporting framework of a porous ceramic. Because of the requirement of thermal shock resistance, a ceramic with a near-zero coefficient of thermal expansion is required. One such material is cordierite. Figure 38.9 shows an example of a ceramic honeycomb substrate for a catalytic converter. Substrates have been produced with up to 900 cells per square inch and walls with a thickness of 50 μm. These complex shapes are produced by extrusion, a process we described in Chapter 23. The ceramic powder is mixed with a hydraulic-setting polyurethane resin. The mix is extruded into a water bath at a rate of about 2 mm/s. The extrusion rate matches the rate at which the resin cures.

Other requirements for the catalyst substrate are:

- Low cost
- Thermal-mechanical durability
- Lightweight

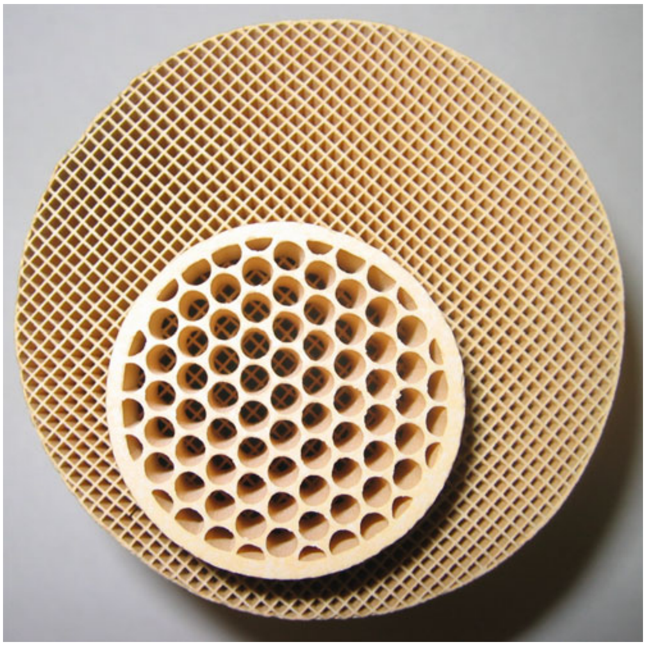

FIGURE 38.9. Looking through two ceramic extruded cordierite honeycomb substrates for catalytic converters.

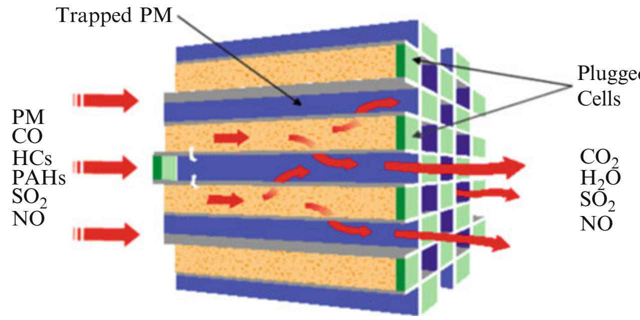

FIGURE 38.10. Cordierite or silicon carbide diesel particulate filter. Notice how the gas flow is required to go through the walls of the ceramic.

38.8.2 Diesel-Particulate Filters

Diesel-particulate filters (DPFs) are devices used to remove soot (small carbon particles often down to nanometer sizes) from the exhaust gas of a diesel engine. Cordierite is the most common DPF and looks much like the one shown in Figure 38.9. The difference is that alternate channels are blocked, which means the exhaust gas is forced through the porous walls where the carbon particles collect, as shown in Figure 38.10. Silicon carbide (SiC) is also used as a DPF material. It benefits from a higher melting point than cordierite and is primarily used for stationary diesel applications.

A recent addition to the DPF market is the Dow™ Aerify™, which consists of mullite whiskers grown on the inside of the channels of a cordierite DRF monolith, as shown in Figure 38.11. The DPF is designed for use in both on-road and off-road diesel applications and has the benefit of a low back-pressure, which improves engine performance and fuel efficiency. Mass production of Aerify™ was to begin in 2011.

38.8.3 Carbon Dioxide Utilization

Carbon dioxide (CO_2) is a product of the combustion of fossil fuels such as coal and is also produced by a number of industrial processes, such as the production of iron and steel. Currently, over 30 billion tons of CO_2 is emitted each year from the burning of fossil fuels, and this number is projected to reach 43 billion tons by 2030. Carbon capture and sequestration (CCS) of industrial CO_2 emissions has been proposed as an approach to mitigate its release into the atmosphere. However, CCS remains unproven, costly, and is not likely to be commercially available for decades. Perhaps a better approach is to consider converting CO_2 into useful fuels and chemicals (i.e., thinking of CO_2 as a resource and recycling it). Using a photocatalyst, such

PHOTOCATALYTIC REDUCTION OF CO_2

Several steps in the photocatalytic conversion of CO_2 have been proposed:

1. Absorption of light (usually UV) by the photocatalyst generating an exciton (electron–hole pair):

$$\text{Catalyst} + h\nu \rightarrow \text{catalyst}^* \ (e^- + h^+) \tag{38.1}$$

2. Oxidation ("splitting") of water:

$$H_2O + 2h^+ \rightarrow 1/2O_2 + 2H^+ \tag{38.2}$$

3. Reduction of carbon dioxide

$$CO_2(aq) + 2H^+ + 2e^- \rightarrow HCOOH \tag{38.3}$$

$$HCOOH + 2H^+ + 2e^- \rightarrow HCHO + H_2O \tag{38.4}$$

$$HCHO + 2H^+ + 2e^- \rightarrow CH_3OH \tag{38.5}$$

$$CH_3OH + 2H^+ + 2e^- \rightarrow CH_4 + H_2O \tag{38.6}$$

The possibility of "tuning" the reaction to favor certain products is particularly exciting about this approach.

as TiO_2 suspended in water, CO_2 has successfully been converted to C1 compounds, such as methanol (CH_3OH) and formaldehyde (HCHO), at room temperature. When the initial work was done back in 1979, the connection between anthropogenic CO_2 and global climate change had not been proposed; but now several groups are looking at photocatalytic conversion as an approach toward mitigating CO_2 emissions into the atmosphere. At the present time, the processes are not economical, and the development of improved catalysts is needed.

An alternative approach to utilizing CO_2 is to convert it into calcium carbonate ($CaCO_3$) or limestone, which can be used in cement production. The basic idea behind this technology was inspired by nature: CO_2 is naturally absorbed into the oceans and converted into stable mineral deposits. Whereas nature can take its time, the process is commercially viable only if it can be sped up. Also, it makes sense as a CO_2 utilization technology only if the energy associated with increasing the kinetics does not generate additional large amounts of CO_2.

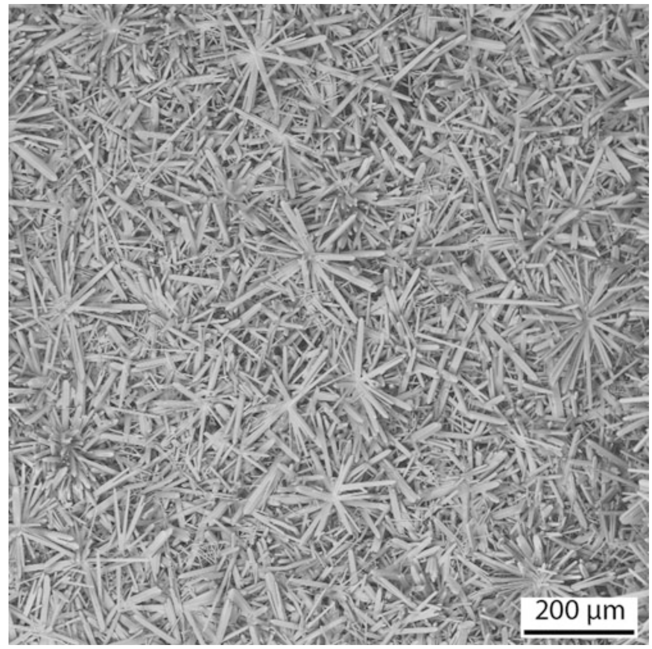

FIGURE 38.11. Scanning electron microscopy image of acicular mullite crystals used to trap carbon "soot" particles from diesel exhausts.

CHAPTER SUMMARY

In this chapter, we described some of the industrial aspects of ceramics. Ceramics make money. Unfortunately, obtaining the raw materials can have some undesirable environmental and societal impacts. The environmental impact of nanomaterials is an issue that has not significantly concerned the ceramics industry yet because no one knows exactly what that impact is. However, as the market for ceramic nanopowders and other nanostructures (e.g., wires and tubes) increases, the environmental concerns will have to be addressed. Many of the "grand challenges" we face as a society—such as producing energy, protecting the environment, and providing health care—require innovative technological solutions. Ceramics can play an important role in these areas. Three key examples that affect us all are nuclear waste immobilization, catalytic conversion, and viral nanosensors. Many ceramic materials are not thought of as ceramics, so the field seems smaller than it really is. For example, molecular sieves are zeolite-based or zeolite-like materials that are used as filters, absorbents, catalysts and catalyst supports. They are among the new ceramic materials, but they are often just left to the chemists. It is important to realize that industry is constantly in a state of flux, so numbers reported here can change from year to year. Indeed, several have changed since the first edition—some up and some down! Also, this chapter reflects a snapshot of an industry at the beginning of the twenty-first century. In a decade, the relative importance of some of the topics we described may have increased, decreased, or disappeared altogether.

PEOPLE AND HISTORY

Cronstedt, Axel Frederik (1722–1765) was the Swedish mineralogist who named zeolites because they are the stones that boil: the water they contain can be removed and replaced without changing the crystal structure.

Darby, Abraham I. (1678–1717) was born in Staffordshire. He patented sand casting in 1708 and invented coke smelting in 1709.

Feynman, Richard (1918–1988) gave his visionary talk in 1959 titled "There's Plenty of Room at the Bottom." Since then, nanotechnology has captured the minds and imaginations of many scientists and engineers. A transcript of his nanotechnology talk can be found at http://www.zyvex.com/nanotech/feynman.html. Feynman shared the 1965 Nobel Prize in Physics for work on quantum electrodynamics (physics of elementary particles). You can debate which topic was more important—it won't take long!

Wollaston, William Hyde (1766–1828). He was an English scientist who discovered Pd in 1803 and named it after the asteroid Pallas, found in 1802. The mineral wollastonite is named after him.

EXERCISES

38.1 In addition to oxygen, what other impurities might you expect in Si_3N_4 powder?

38.2 Why is the extent of Nd substitution in YAG so small?

38.3 What companies make the Pd-Ag metallization used for multilayer chip capacitors (MLCCs)?

38.4 Do TiO_2 and ZnO play different roles in sunscreen? Which is the best material?

38.5 Describe one process that can be used to make CeO_2 nanoparticles.

38.6 In the form of a table, compare the cost of conventional (micrometer-sized) ceramic powders with their nano-sized equivalents.

38.7 How much glass is recycled in your community (or state)?

38.8 Compare the costs of recycling to landfilling for various materials.

38.9 Why is the bismuth strontium calcium copper oxide (BSCCO) superconductor the material of choice for superconducting wires?

38.10 Find today's price for Pd. Is it higher than when this book was written?

38.11 What factors affect the price of Pd?

38.12 What is the current price for dysprosium oxide? How has the price changed since the value cited in this book?

38.13 Does China still impose export restrictions on rare-earth elements? If so, what are the current restrictions?

38.14 List three applications for dysprosium. Do any of these applications use dysprosium as a ceramic, or is it always used as part of a metal alloy?

38.15 List all the lanthanide elements. Several of these elements, when they are in the form of oxides, are used as glaze colorants. Praseodymium oxide produces transparent green glazes. What glaze colors are produced by neodymium oxide and erbium oxide?

38.16 What are the current catalog prices for neodymium oxide and erbium oxide? What purities are available?

38.17 Xenotime is a major mineral source of dysprosium. What is the crystal structure of xenotime?

38.18 In addition to China, where are other major reserves of xenotime?

38.19 Ce-doped YAG and Nd-doped YAG single crystals are used for a number of applications. We mentioned in Section 38.4 that these crystals are grown by the Czochralski process. Are any other processes used in industry to make Ce-YAG and Nd-YAG? If so, how do they differ from the Czochralski process. If not, why not?

38.20 Both cordierite and silicon carbide are used to make diesel particulate filters. In a table, compare the properties of these two ceramics that are relevant to this application.

GENERAL REFERENCES

Murday JS, Siegel RW, Stein J, Wright JF (2011) Translational nanomedicine: status assessment and opportunities. Nanomedicine: Nanotechnol Biol Med 5(2009):251–273, This review will make you think about nanomaterials!

Rödel J, Kounga ABN, Weissenberger-Eibl M, Koch D, Bierwisch A, Rossner W, Hoffman MJ, Danzer R, Schneider G (2009) Development of a roadmap for advanced ceramics: 2010–2025. J Eur Ceram Soc 29:1549, This roadmap was developed based on questionnaires and a workshop that included people from industry and academia

Tames R (1984) Josiah Wedgwood, an illustrated life of Josiah Wedgwood 1730–1795. Shire Publications, Aylesbury, A brief biography of man described by British Prime Minister (1868–1874) William Gladstone as "the greatest man who ever, in any age or country, applied himself to the important work of uniting art with industry"

SPECIFIC REFERENCES

Eakins DE, Held M, Norton MG, Bahr DF (2003) A study of fracture and defects in single crystal YAG. J Cryst Growth 267:502, This research was funded by a U.S. crystal growth company to help solve a processing problem

Inoue T, Fujishima A, Konishi S, Honda K (1979) Photoelectrocatalytic reduction of carbon dioxide in aqueous suspensions of semiconductor powders. Nature 277:637, Of all the photocatalysts they tried SiC worked best

Roy SC, Varghese OK, Paulose M, Grimes CA (2010) Toward solar fuels: photocatalytic conversion of carbon dioxide to hydrocarbons. ACS Nano 4:1259, Provides an overview of conversion methods with a focus on photoconversion using TiO_2 nanotubes

Rzigalinski BA, Cohen C, Singh N (2009) Cerium oxide nanoparticles for treatment and prevention of Alzheimer's disease, Parkinson's disease, and disorders associated with free radical production and/or mitochondrial dysfunction. Publication No. WO2009052295. This is an international patent application filed under the patent cooperation treaty (PCT). The full details of this patent and all PCTs can be found at www.wipo.int (The World Intellectual Property Organization.) The inventors are with the Virginia College of Osteopathic Medicine, VA, USA

Schrag DP (2007) Preparing to capture carbon. Science 315:812, An optimistic viewpoint on CCS: "Scientific and economic challenges still exist, but none are serious enough to suggest that carbon capture and storage will not work at the scale required to offset trillions of tones of carbon dioxide emissions over the next century"

Yanagida T, Kamada K, Fujimoto Y, Yokota Y, Yoshikawa A, Yagi H, Yanagitani T (2011) Scintillation properties of transparent ceramic and single crystalline Nd:YAG scintillators. Nucl Instrum Methods A 631:54, A comparison of polycrystalline and single crystal YAG scintillators

WWW

www.kitco.com/. Precious metal prices and historical trends

www.nulifeglass.com/. NuLife Glass of Wilmslow in Cheshire—a company that plans to recycle the glass used in TV and computer screens

www.kemet.com/. KEMET Corporation, in Greenville, SC (USA), is the largest manufacturer of solid tantalum capacitors and the fourth largest manufacturer of multilayer chip capacitors in the world

www.conectus.org/. The *con*sortium of *E*uropean *c*ompanies determined *t*o *u*se *s*uperconductivity

www.oxonica.com/. Oxonica developed the CeO_2 diesel fuel additive. In 2009, the company was sold to Energetics Pte Limited, www.energetics.org/

www.detectors.saint-gobain.com/. Saint-Gobain Crystals is a manufacturer of different scintillators including Ce-doped YAG

www.dow.com/. Among many products, Dow makes the Aerify diesel particulate filter

http://gonano-technologies.com/. University spin-off company that has demonstrated high-efficiency conversion of CO_2 using TiO_2 photocatalyst supported on silica nanosprings

www.calera.com/. Calera Corporation was founded in 2007 and is developing technologies to convert CO_2 into minerals and other materials that can be used by the building industry

www.lithiumsite.com/. Think of batteries

http://minerals.usgs.gov/minerals/pubs/commodity/lithium/. Just one of many topics