CHAPTER TWO

CERAMICS INDUSTRY

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An important goal of this study was to identify key needs in the Industries of the Future and to explore ways that ceramics might meet these needs. As shown in Fig. 2.1, key needs that crosscut the Industries of the Future and that match the favorable characteristics of ceramics include wear resistance, corrosion resistance, temperature resistance, controlled surface behavior, dimensional stability, engineered behavior, heat recovery, and filtration. In some cases, only ceramics can simultaneously meet combinations of these needs. In other cases, the favorable characteristics of ceramics are often offset by cost considerations or by concerns that ceramics are weak and have poor durability and toughness. However, broad progress has been accomplished in the past 15–20 years to alleviate these negatives through material improvement, new ceramic materials, and improved design methods. This new generation of ceramics and design methods has the potential to help the Industries of the Future reach their visions of increased efficiency, decreased maintenance, optimized recycling, and decreased pollution.

Important advances have occurred in four ceramic material categories: monolithic ceramics, composite ceramics, coatings, and refractories. Some of the progress, especially in monolithic and composite ceramics, is described in the following sections. The emphasis is on reviewing what is new and different about these new ceramic materials (compared to perceptions industry individuals may have acquired using prior ceramic materials) and identifying the types of applications that have been successful.

2.1 KEY MONOLITHIC CERAMICS

The term *monolithic* has been applied to ceramic materials which are entirely ceramic, typically have low porosity, and comprise a complete component or a lining. Examples include dense forms of aluminum oxide (Al_2O_3), silicon nitride (Si_3N_4), silicon carbide (SiC), zirconium oxide (ZrO_2), transformation-toughened zirconia (TTZ), transformation-toughened alumina (TTA), and aluminum nitride (AlN).

Major progress has been accomplished in the past 20 years to increase the capability of monolithic ceramics for thermal, wear, corrosion and structural applications. In particular, the

Fig. 2.1. Ceramic materials can meet crosscutting needs of Industries of the Future.

strength and toughness have been dramatically improved to the degree that ceramics are now available that can compete with metals in applications previously thought impossible for ceramics. Figure 2.2 illustrates the level of increases in the key structural characteristics of strength, toughness, and Weibull Modulus. Strength is a measurement of the resistance to formation of a crack or structural damage in the material when a load is applied. Toughness is a measurement of the resistance of the material to propagation of a crack or extension of damage to the point of failure. The Weibull Modulus is a measurement of the uniformity in strength. The lower the Weibull Modulus, the higher the likelihood that the material will fail at a stress substantially below the average strength. Thus, high Weibull Modulus means better material reliability and greater ease in designing with the material.

Most ceramics prior to 1970 had strength well below 345 MPa (50,000 psi). Now Al_20_3 and SiC are commercially available with strength over 345 MPa, and Si_3N_4 and toughened zirconia are available with strengths above 690 MPa (100,000 psi). Strength at elevated temperatures also has been improved, as shown in Fig. 2.3 for Si_3N_4 materials. SiC ceramics retain strength to even higher temperatures.

One of the most significant advances in ceramics during the past 20 years has been to increase fracture toughness. Increased fracture toughness is important to industry because it reduces risk of fracture during installation and service, which has always been a concern with glass and traditional ceramics. Figure 2.4 compares the toughness of some of the new ceramic materials with typical ceramics and other key engineering materials. Glass has fracture toughness of about 1 $MPa{\cdot}m^{1/2}$, and conventional ceramics range from about 2–3 $MPa{\cdot}m^{1/2}$. Steel is around 40 $MPa{\cdot}m^{1/2}$. Some Si_3N_4 materials approach 10 $MPa{\cdot}m^{1/2}$, which is higher than cast iron. Some transformation-toughened ZrO_2 materials have toughness around 15 $MPa{\cdot}m^{1/2}$, which is higher than that of tungsten carbide–cobalt (WC-Co) cermet. These new tougher ceramics have demonstrated dramatically better resistance to impact, contact stress and handling damage and are providing high reliability and durability that users are accustomed to receiving with metals and WC-Co. New continuous fiber ceramic composites (CFCCs) are under development that provide further improvements in fracture toughness. These are discussed under Sect.2.4.

Silicon Nitride

Silicon nitride refers to an alloy family of ceramics whose primary constituent is Si_3N_4. The ceramics in this family have a favorable combination of properties that includes high strength over a broad temperature range, high hardness, moderate thermal conductivity, low coefficient of thermal expansion, moderately high elastic modulus, and unusually high fracture toughness for a ceramic. This combination of properties leads to excellent thermal shock resistance, ability to withstand high structural loads to high temperature, and superior wear resistance.

Si_3N_4 has been continuously under development in the U.S. since the late 1960s. Since the early 1980s, much of the development of Si_3N_4 materials has been cofunded by the Department of Energy (DOE) and industry and has been directed especially towards gas turbine engines and other heat engines. These developments have resulted in improved properties, increased reliability, complex shape fabrication capability, and some cost reduction.

Si_3N_4 has been successfully demonstrated in a variety of applications. In general, the issue has not been technical performance, but cost. As the cost has come down, the number of production applications is accelerating. Table 2.1 lists some of the applications, the kind of conditions that the silicon nitride is exposed to in each application, and the benefit that is perceived by the customer. The objective of the table is to provide to the Industries of the Future a baseline for comparison with their specific materials needs. To further achieve this objective, subsequent paragraphs provide additional details of the conditions silicon nitride is surviving in existing applications.

Although the driver for Si_3N_4 development has been gas turbine engine components, the first major application was cutting tool inserts. Grinding, milling, and boring of metals is a major cost of manufacturing. A study in the early 1970s estimated that there were 2,692,000 metal-cutting machine tools in the United States with an annual operating cost of $64 billion. The life of the cutting tool insert and the speed of cutting were the key factors identified in the study regarding the number of machines required and the operation cost.

Cutting hard metals such as cast iron and high-temperature alloys results in high temperature at the tool–work piece interface. WC-Co, the

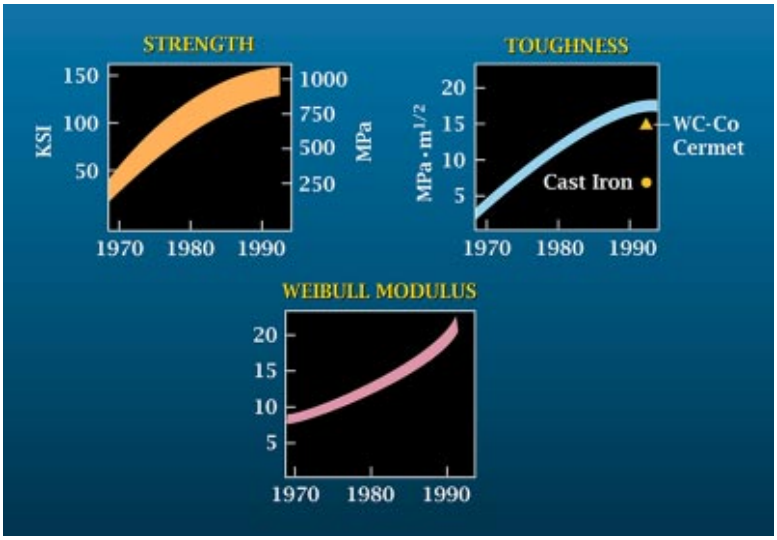
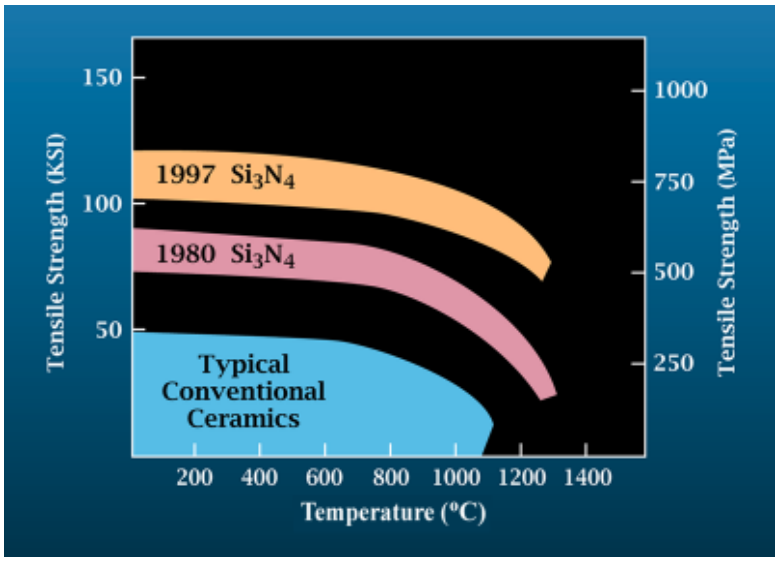


Fig. 2.2. Strength, toughness, and uniformity have been dramatically increased since 1960.

Fig. 2.3. Silicon nitride alloys have evolved from properties comparable to conventional ceramics to very high strength which is retained to high temperatures.



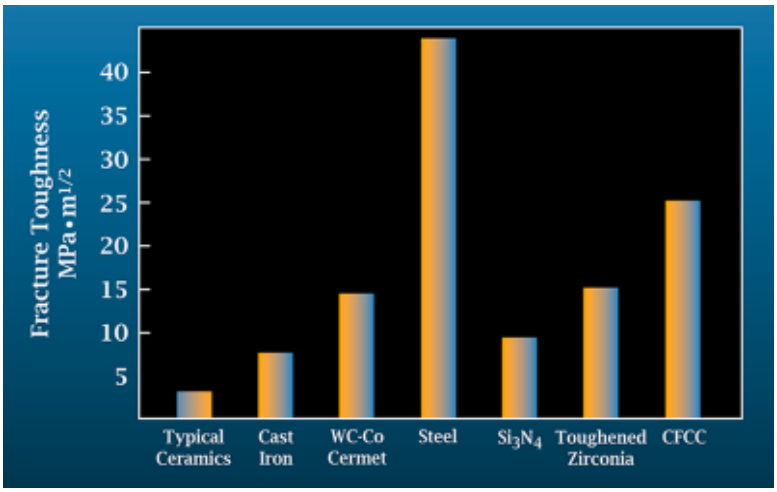


Fig. 2.4. Comparison of the fracture toughness of new ceramic materials with conventional ceramics and other key structural materials.

Table 2.1. Production applications of silicon nitride

Application	Conditions imposed on the silicon nitride	Benefits demonstrated or perceived by customers
Cutting tool inserts (introduced late 1970s)	High contact stress, severe physical and chemical erosion, temperatures to around 1100°C	75–90% reduction in machining time for cast iron, 5–10 times increase in the metal-removal rate, and increase in the number of parts machined per tool
Diesel cam follower rollers (introduced 1990s)	Highly concentrated rolling contact stress	Increased life at higher injection pressures, reduced frictional losses, improved engine performance
Bearings (introduced late 1980s)	High contact loads that can exceed 2 million psi (~13,800 MPa)	3–10 times life of best metal bearings, 80% lower friction, 80% higher speed, 60% lighter, higher operation temperature, ability to operate with lubrication starvation
Papermaking machine foils	Sliding contact, wet environment	Increased life, decreased maintenance
Wear parts for many applications	Depends on application, but typically abrasion, erosion, and some impact over a broad range of temperature	Dramatic increase in life and decrease in maintenance
Turbocharger rotors (introduced 1985)	Centrifugal and thermal stress at elevated temperature	Reduced inertia due to the low specific gravity of silicon nitride (about 40% that of turbo-charger rotor metals)
Manufacturing tooling (dies for aluminum can making, drawing dies, etc.)	Depends on application, but can include high stress, sliding erosion, and elevated temperature	Extended life, reduced maintenance, improved dimensional control of product
Aircraft engine seal (for man-rated gas turbine aircraft propulsion engine — introduced mid-1990s)	Sliding seal operating at engine shaft speed and elevated temperature	Much higher reliability and life than metals
Fuel injector link (for timing control— introduced 1989)	Sliding contact	>60% less wear
Diesel glow plug (tungsten heating element in a silicon nitride container — introduced 1981)	High temperature, thermal shock, combustion gas environment	Quicker starting, cleaner exhaust gases
Diesel prechamber (swirl chamber— introduced about 1983)	Elevated temperature, thermal shock	Improved power, reduced pollution
Check valve balls	Impact, abrasive particles erosion, adverse chemical environments, elevated temperature	Longer life, reduced maintenance
Slotted dewatering centrifuge liners for mining industry	Severe erosion, some impact	Longer life, decreased maintenance

traditional workhorse for metals machining, wears rapidly if the temperature gets too high, so the cutting speed must be limited to around 400 surface feet per minute (sfpm) (121.6 m / min.) and sometimes even down to around 80 sfpm. Because Si_3N_4 is much more resistant to temperature, cutting speeds as high as 5000 sfpm (1520 m / min.) have been demonstrated. At a depth of cut of 0.2 in. (5 mm) and feed rate of 0.015 in. (0.4 mm) per revolution, this speed represents a material removal rate each minute equivalent to a block of metal $3 \times 6 \times 10$ in. ($7.6 \times 15.2 \times 24.5$ cm). The Si_3N_4 is exposed to thermal shock, impact, contact stress, severe erosion, and temperatures around 1100° C. This gives an indication of the severe conditions that silicon nitride materials can survive.

The use of Si_3N_4 cutting tool inserts has had a dramatic effect on manufacturing output (see Fig. 2.5.) For example, face milling of gray cast iron gear-case housings with silicon nitride inserts doubled the cutting speed, increased tool life from one part to six parts per edge, and reduced the average cost of inserts by 50%. Outside grinding of diesel truck cylinder liners increased the number of parts machined per tool index from around 130 to 1200 and totally eliminated a prior problem with insert breakage. As a result, tool life was increased to achieve 9600 cylinders per cutter load of inserts compared to 450. Just the decreased downtime alone increased the output per shift 25%.

A more recent application for Si_3N_4 that is having revolutionary impact on many industries is bearings (see example in Fig. 2.6). Si_3N_4 was first demonstrated as a superior bearing in 1972 but did not reach production until nearly 1990 because of challenges associated with reducing the cost. Since 1990, the cost has been reduced substantially as production volume has increased. Although Si_3N_4 bearings are still 2–5 times more expensive than the best bearing steel, their superior performance and life are justifying rapid adoption. Around 15–20 million Si_3N_4 bearing balls were produced in the U.S. in 1996 for machine tools and many other applications. Growth is estimated at 40% per year, but could be even higher if ceramic bearings are selected for consumer applications such as in-line skates and computer disk drives.

Si_3N_4 balls similar to bearings are also in production for ball-and-seat check valves (see examples in Fig. 2.7). One severe application is for down-hole pumping of oil with a "sucker rod." Si_3N_4 is used for the ball and WC-Co for the seat. With each stroke of the sucker rod, oil-containing fluid at the bottom of the oil well is forced into the

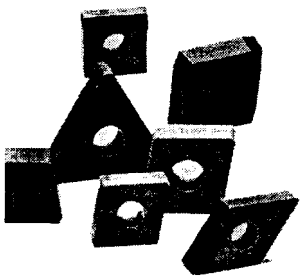


Fig. 2.5. Si_3N_4 can withstand the severe conditions of cutting metal and has resulted in dramatic improvements in the efficiency of machining cast iron. Photograph shows cutting tool inserts from Ceradyne, Inc., Costa Mesa, Calif.

Fig. 2.6. Si_3N_4 bearings, check valve balls and other high-strength, wear-resistant components from Saint-Gobain/Norton Advanced Ceramics, East Granby, Conn.

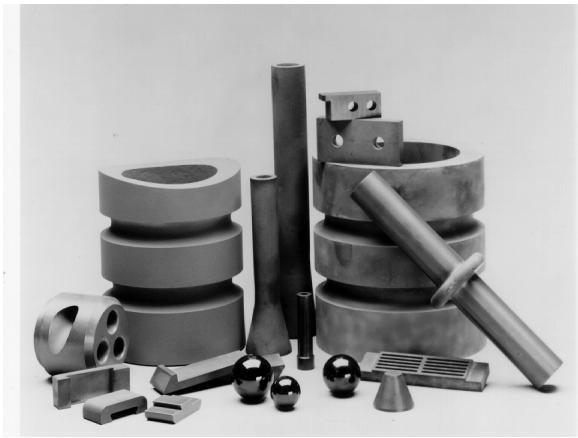


Fig. 2.7. Si_3N_4 components from Ceradyne, Inc., Costa Mesa, Calif. Includes grit-blast nozzle liners, wire-forming rolls and guides, papermaking dewatering foil segments, check valve balls, down-hole oil well parts, custom wear parts, a refractory ferrule, and a centrifugal dewatering screen and scraper blade for potash and coal dewatering.

rod and towards the surface of the well. At the end of the stroke, the ball drops back down to the seat to form a seal so the fluid does not flow back. This results in substantial impact on both the ball and seat under the weight of all the fluid in the well, which commonly is well over 2000 ft (608 m) deep. The fluid is a mixture of petroleum, water / steam, sand and other debris, hydrogen sulfide, and other chemicals—all at several hundred degrees temperature. The pump operates around 12 cycles / min, 24 h / day, 7 d / week.

The key message from the above examples is that the Si_3N_4 family is a new generation of ceramics that are much more durable and resistant to brittle fracture than traditional ceramics. In addition to the applications listed in Table 2.1, Si_3N_4 is being vigorously evaluated for diesel and auto engine valves, valve guides, stator vanes and rotors for turbines (Fig. 2.8), a variety of wear parts, tooling for aluminum processing (Fig. 2.9), and many other potential products. As additional production applications are achieved and current production levels increase, it is anticipated that the cost of silicon nitride will come down substantially, removing the primary barrier that has limited broad use of advanced silicon nitride materials. Within 10 years Si_3N_4 could be a commodity material similar to Al_2O_3.

Information on Si_3N_4 suppliers in the United States is included in the appendix to this report.

Aluminum Oxide

Al_2O_3 is the most mature high technology ceramic. It is the same composition as sapphire, which accounts for its high hardness and durability. Al_2O_3 ceramic is produced by compacting alumina powder into a shape and firing the powder at high temperature to allow it to densify into a solid, polycrystalline, nonporous part. About 5 million metric tons were produced in 1995 for wear, chemical, electrical, medical, and other applications. Table 2.2 lists some of the applications of Al_2O_3, the use conditions, and the advantages over alternate materials.

Al_2O_3 is used in these applications because of its high hardness and wear resistance, chemical resistance, and smooth surface (see examples in Fig. 2.10). Al_2O_3 also is used extensively for electrical applications due to its good electrical insulating characteristics. Examples are spark plug insulators, substrates for electronics modules (such as in automobiles), and packages for integrated circuits. Other applications of Al_2O_3 include radomes, medical components, orthodontic brackets, sodium vapor lamp arc tubes,

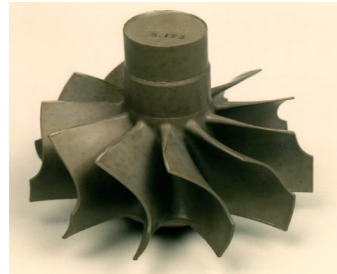


Fig. 2.8. Si_3N_4 gas turbine engine radial rotor from AlliedSignal Ceramic Components. *Source:* AlliedSignal Ceramic Components, Torrance, Calif.

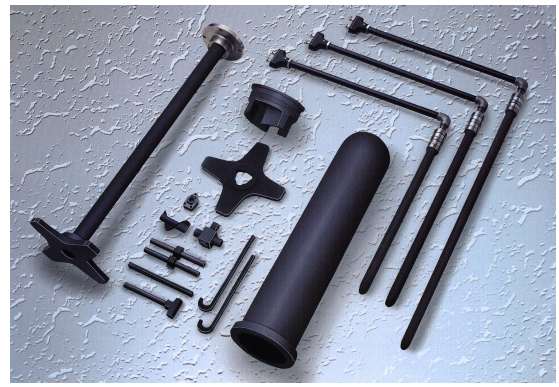


Fig. 2.9. Silicon nitride tooling designed for immersion in molten aluminum. *Source:* Kyocera Corporation, Kyoto, Japan.

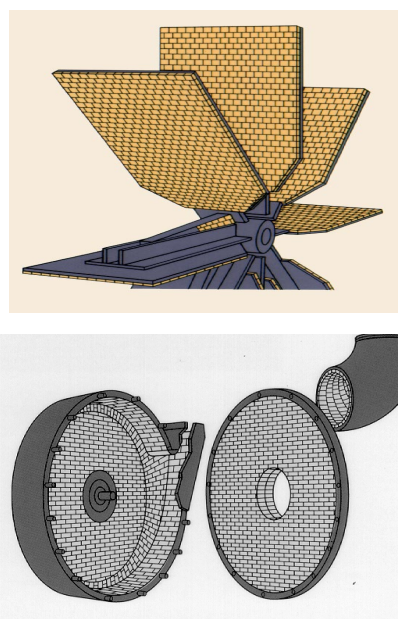


Fig. 2.10. Al_2O_3 tiles provide reliable wear-resistant surfaces on chutes, fans, housings, pipes, and cyclones in handling systems for pulverized coal, grain, ore, and other flowing abrasive materials. *Source:* Coors Wear Products, Inc. brochure, Coors Ceramics Company, Golden, Colo.

Table 2.2 Production applications of aluminum oxide ceramics

Application	Conditions imposed on the aluminum oxide	Benefits demonstrated or perceived by customer
Seal rings	Sliding contact, sometimes particulate erosion and corrosive fluids	Increased life, low maintenance
Rotary and gate valves	Same	Same
Pump parts and liners	Corrosive fluids, particles in suspension in a liquid, sometimes slurries with high solids content	Same
Papermaking foils, suction box covers, palm guides, cyclone liners	Sliding or fluid erosion, corrosive fluids	Same. Smooth surface also protects adjacent components.
Cyclone separator liners	Abrasive particles usually carried by a fluid.	Increased life, low maintenance
Liners in coal-handling systems	Erosion by pulverized coal	Same
Wire drawing tooling	Sliding contact	Same. Also prevents adhesion and provides a very smooth surface
Thread guides in the chemicals and textile industries	Same	Increased life, low maintenance, smooth surface to not damage or fray thread
Chute and conveyor liners	Gouging, erosion and sometimes impact by a wide range in size of materials carried by chute or conveyor	Increased life, low maintenance
Precision surfaces for metrology	Sliding contact	High smoothness and tolerances, low wear so retains smoothness and close tolerances
Wear pads for many applications	Sliding contact, sometimes elevated temperature or corrosive fluids	Increased life, low maintenance, low friction, no adhesive bonding
Chemical lab ware	Chemicals, wide temperature range	Inert to attack and noncontaminating
Molten metal filters	Molten metals such as aluminum	Substantial decrease in rejects caused by contaminants
Mill liners and media	Particulate abrasion	Low cost, reasonable life
Nozzles, pipe, and tubing liners	High velocity fluids and/or particles	Increased life compared to metals and polymers

thermocouple protection tubes, abrasives, heat exchanger balls, glass tank linings, abrasives and polishes, crucibles for metals melting, grinding wheels, and cutting tool inserts.

Al_2O_3 is presently the lowest-cost high-performance ceramic because of the large quantity produced. There is an enormous design and experience database at the Al_2O_3 suppliers, so they should be considered when seeking an alternate material for increased wear resistance, improved chemical resistance, dimensional stability, decreased friction and higher temperature use. Examples illustrating the uses of alumina are seen in Figs. 2.11 and 2.12. A listing of alumina suppliers is included in the appendix.

Silicon Carbide

Another ceramic that is well-established in the marketplace is SiC. Like Si_3N_4, SiC is a family of materials each with its special characteristics. Most of the SiC materials have very high hardness (harder than Al_2O_3 and Si_3N_4) and thus have superior wear resistance. Most have unusually high thermal conductivity for a ceramic, low thermal expansion compared to metals, and very high temperature capability. Hexoloy SA SiC from Saint-Gobain/Carborundum, for example, actually increases in strength with temperature, starting slightly above 60,000 psi flexural strength at room temperature and increasing to around 80,000 psi at 1600°C. Relatively pure silicon carbide also has excellent resistance to corrosion in the presence of hot acids and bases as illustrated in Table 2.3.

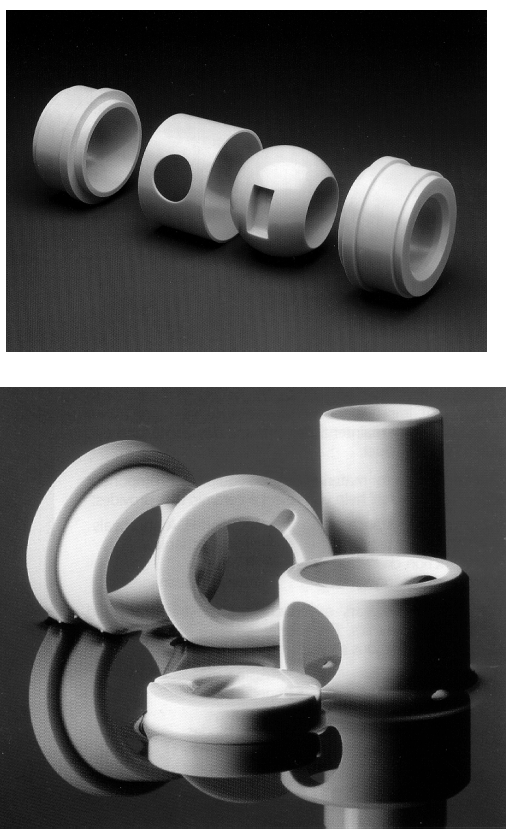


Fig. 2.11. Alumina is used extensively for face seals and various types of valve and pump components. *Source:* Coors Ceramics Company, Golden, Colo.

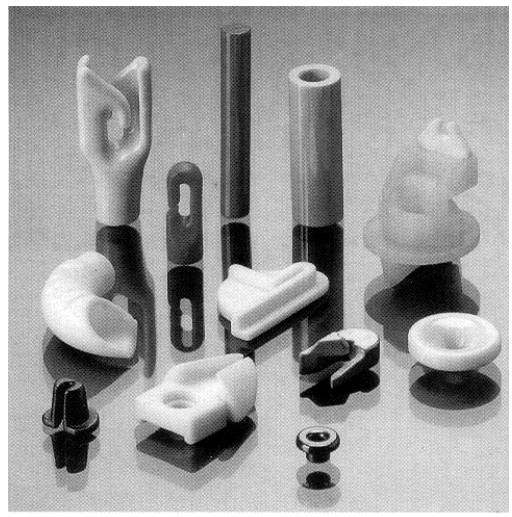


Fig 2.12. Thread guides of alumina and other ceramic materials. *Source:* Rauschert Technical Ceramics, Madisonville, Tenn.

The Hexoloy SP in Table 2.3 has another interesting characteristic. It contains a controlled dispersion of noninterconnected spherical pores that retain some of the working fluid and result in a thin low friction fluid layer between adjacent sliding surfaces. This provides additional wear resistance for some pump and seal applications (see examples in Figs 2.13 and 2.14).

SiC has many of the same applications as Al_2O_3 and Si_3N_4. It is more expensive than Al_2O_3 and lower toughness than Si_3N_4, so is not the optimum material for all wear applications. But where it can be used, it normally provides superior wear resistance and long life. Table 2.4 identifies some of the production applications of SiC.

SiC also is important for tooling in the semiconductor industry, for laser mirrors, as a substrate for wear-resistant diamond coatings, as an abrasive and grinding wheel, as heating elements and igniters, as an additive for reinforcement of metals, and for numerous

Table 2.3. Comparison of the corrosion in liquids of relatively pure SiC with other materials
Source: Saint Gobain/Carborundum Structural Ceramics, Niagara Falls, N.Y.

		Corrosive weight loss ($mg/cm^2/year$)[b]			
Test environment[a] conc. Reagent (wt %)	**Temp. (ºC)**	**Hexoloy SP (no free Si)**	**Reaction-bonded Sic (12% Si)**	**Tungsten carbide (6% Co)**	**Aluminum oxide (99%)**
98% H_2SO_4	100	1.8	55.0	>1000	65.0
50% NaOH	100	2.5	>1000	5.0	75.0
53% HF	25	<0.2	7.9	8.0	20.0
85% H_3PO_4	100	<0.2	8.8	55.0	>1000
70% HNO_3	100	<0.2	0.5	>1000	7.0
45% KOH	100	<0.2	>1000	3.0	60.0
25% HCL	70	<0.2	0.9	85.0	72.0
10% HF plus 57%	25	<0.2	>1000	>1000	16.0

[a]**Test time:** 125 to 300 h of submersive testing, continuously stirred.

[b]**Corrosion weight loss guide:**

>1000 $mg/cm^2/year$	Completely destroyed within days
100–999 $mg/cm^2/year$	Not recommended for service greater than a month
50–99 $mg/cm^2/year$	Not recommended for service greater than one year
10–49 $mg/cm^2/year$	Caution recommended, based on the specific application
0.3–9.9 $mg/cm^2/year$	Recommended for long-term service
<0.2 $mg/cm^2/year$	Recommended for long-term service; no corrosion, other than as a result of surface cleaning, was evidenced

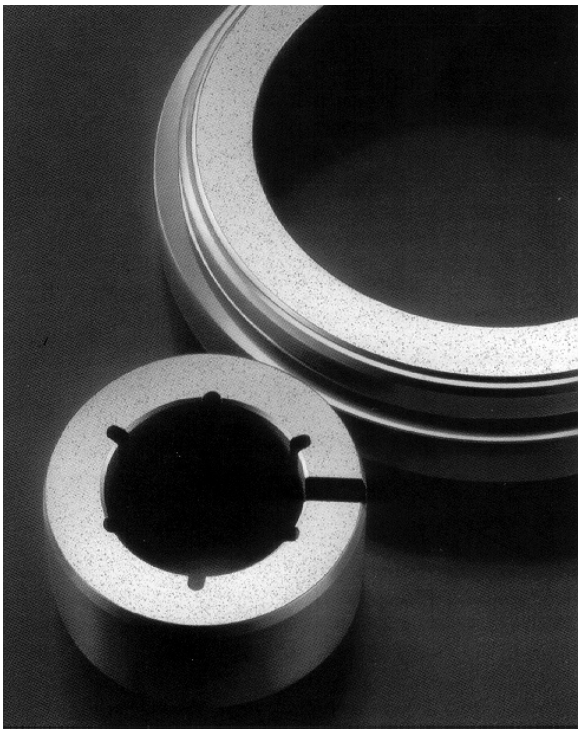


Fig. 2.13. Hexoloy SP SiC seal surfaces showing the dispersion of spherical pores which act as fluid reservoirs and reduce friction and wear. *Source:* Saint-Gobain / Carborundum Structural Ceramics, Niagara Falls, N.Y.

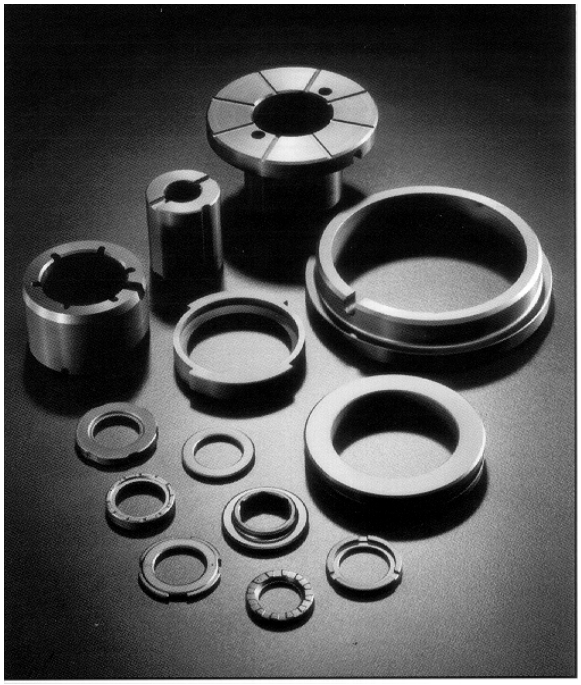


Fig. 2.14. SiC seal and pump parts. *Source:* Saint-Gobain / Carborundum Structural Ceramics, Niagara Falls, N.Y.

Table 2.4. Production applications of silicon carbide

Application	Conditions imposed on the silicon carbide	Benefits demonstrated or perceived by customer
Seals, thrust bearings, valves, pump parts, cyclone liners	Abrasion, erosion, and often corrosion, range of temperatures	Long life, low maintenance demonstrated in chemical processing, refining, mining, marine, waste water, pulp and paper, and nuclear applications
Radiant burners and heat exchanger tubes	High temperature, sometimes abrasion and/or harsh chemical environment, often severe thermal shock	Increased life, low maintenance
High temperature liners such as in waste incineration	High temperature, abrasion and mild impact, harsh chemical environment	Same
Thermocouple protection tubes	High temperature	Same
Links for high temperature belt furnace	High temperature, mechanical and thermal stress	Same
Bearings in magnetic drive seal-less pumps	Corrosion, wear, temperatures up to about 700°F	Safety, long life, low maintenance, doubles life of pump
Grit-blast nozzle liners	High-velocity particulate abrasion	Increased life

refractories applications. Figure 2.15 displays a variety of such applications. A listing of suppliers of SiC in the United States is included in the appendix.

Transformation-Toughened Zirconia

Transformation-toughened zirconium oxide (TTZ) is another important high-strength, high-toughness ceramic that has been developed during the past 20–25 years. Transformation toughening requires a bit of explanation.

It is one of those properties that involves control of composition and manipulation of microstructure. Zirconia is a material that undergoes a change in the way its atoms are stacked at different temperatures (polymorphic transformation). Zirconia has the monoclinic crystal structure between room temperature and about 950°C. Above 950°C zirconia converts to the tetragonal crystal structure. This transformation is accompanied by greater than one percent shrinkage during heating and equivalent expansion during cooling. At a much higher temperature, the zirconia changes from tetragonal to a cubic structure. With proper chemical additions and heat treatments, a microstructure can be achieved during cooling that consists of lens-shaped "precipitates" of tetragonal zirconia in cubic grains of zirconia, as shown in Fig. 2.16.

Normally, the tetragonal material would transform to the monoclinic form during cooling, but it must expand to do so. The high strength of the surrounding cubic zirconia prevents this expansion, so the tetragonal form is retained all the way down to room temperature. As a result, each tetragonal zirconia precipitate is under stress and full of energy that wants to be released, sort of like a balloon that has been stuffed into a box that is too small. As soon as the box is opened, the balloon is allowed to expand to its equilibrium condition and protrude from the box. The same thing happens for each tetragonal precipitate if a crack tries to form if someone tries to break the ceramic. The crack is analogous to opening the box. Tetragonal precipitates next to the crack are now able to expand and transform back to their stable monoclinic form. This expansion adjacent to the crack presses against the crack and stops it. This is the mechanism of transformation toughening. It is similar to the toughening mechanism in some forms of steel, so the TTZ has sometimes been called "ceramic steel."

TTZ has been developed in a couple of different forms. The one described above is typically called partially stabilized zirconia (PSZ). The second

Fig. 2.15. Variety of SiC parts for wear-resistance applications, thermal applications and semiconductor industry applications. *Source:* Saint-Gobain/Carborundum Structural Ceramics, Niagara Falls, N.Y.

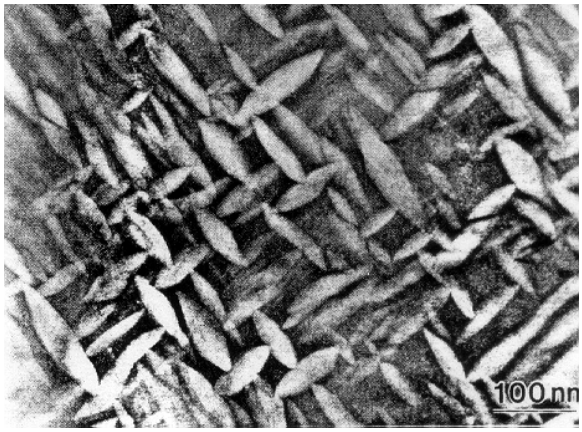


Fig. 2.16. Microstructure of one form of transformation-toughened zirconia. *Source*: David W. Richerson, *Modern Ceramic Engineering*, Marcel Dekker, New York, 1992.

form consists of nearly every crystallite or grain in the material being retained in the tetragonal form to room temperature so that each grain can transform instead of only the precipitates. This material is referred to as tetragonal zirconia polycrystal (TZP). Both types are mentioned because they have different properties, and one may be preferable for a specific application.

Transformation toughening was a breakthrough in achieving high-strength, high-toughness ceramic materials. For the first time in history a ceramic material was available with an internal mechanism for actually inhibiting crack propagation. A crack in a normal ceramic travels all the way through the ceramic with little inhibition, resulting in immediate brittle fracture. TTZ has fracture toughness (resistance to crack propagation) 3–6 times higher than normal zirconia and most other ceramics. It is tougher than cast iron and comparable in toughness to WC-Co cermet. TTZ is so tough that it can be struck with a hammer or even fabricated into a hammer for driving nails.

Table 2.5 lists some of the production applications for TTZ. Figure 2.17 displays examples of TTZ tooling for fabrication of aluminum cans.

For a part such as an extrusion die, TTZ typically costs around four times as much as steel and two times as much as WC-Co. The suppliers can provide information on life-cycle cost for existing applications and can probably estimate for similar applications. Some suppliers are listed in the appendix.

Table 2.5. Some production applications of transformation-toughened zirconia

Application	Conditions imposed on the TTZ	Benefits demonstrated or perceived by customers
Tooling for making aluminum cans	High stress, shearing contact with aluminum metal	High speed equipment operation, smooth surfaces and no tendency to bond to the aluminum, superior wear resistance, low maintenance
Wire-drawing capstans, pulleys, rolls, guides and some dies	Localized mechanical loading, wear, sometimes corrosion	7–10 times the life of WC-Co coatings
Metal extrusion dies	High stress, elevated temperature, gouging	Faster extrusion, less galling, tooling life typically at least 5 times that of WC-Co
Slitter for cutting paper in papermaking machine	Mechanical stress, abrasion	Maintains sharp edge and quality of cut, increased life, decreased maintenance
Knife and scissor blades	Mechanical stress	Same
Cutting tools	High contact loads, impact, high temperature	Increased cutting speed for some alloys
Hip replacements	High mechanical stress, attack by body	Long life, smooth surfaces, less interaction with body than metals
Golf cleats	High stress and wear	Long life, minimum damage to greens
Buttons	High mechanical stress during laundering	Much stronger and more durable than alternate materials

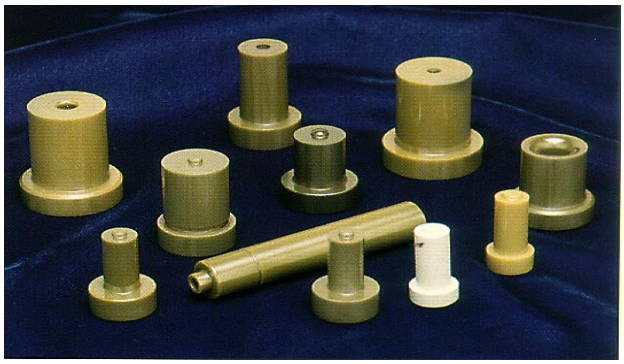


Fig. 2.17. Transformation-toughened zirconia tooling for fabrication of aluminum cans. *Source:* Saint-Gobain / Norton Advanced Ceramics, East Granby, Conn.

Toughened Aluminum Oxide

Transformation toughening can be achieved in other ceramic materials by additions of particles of PSZ. Toughening occurs if the particles are small, if the host ceramic is strong enough to prevent the particles from transforming during cooling, and if there is no chemical interaction between the materials. Alumina is the most important ceramic that is a suitable host for zirconia toughening. An addition of 15–25% zirconia to alumina results in toughness and strength nearly equivalent to that of pure TTZ, but the alumina is cheaper and much lighter in weight.

Other Monolithic Ceramic Material Options

Other ceramic compositions have been developed that have potential for specific applications, but have received limited evaluation and have not yet reached production status. For example, molybdenum disilicide has exhibited

favorable behavior in contact with molten glass, and titanium diboride is a candidate for electrodes in aluminum production by the Hall process. Other examples are aluminum nitride, mullite and low-thermal-expansion "NZP" compositions. NZP stands for sodium zirconium phosphate. Many useful compositions have been achieved by replacement of the sodium with calcium, barium, and magnesium. Some of the compositions have near-zero change in dimensions from roughly room temperature to 1000°C.

2.2 CERAMIC COATINGS

Coatings are another important ceramics option. In this case, a thin surface layer of ceramic deposited on metal imparts favorable ceramic characteristics such as corrosion resistance or wear resistance while retaining the durability and structural benefits of the metal. Many techniques have been developed and commercialized during the past 30 years for applying thicknesses of ceramic coatings ranging from less than 1 mm to greater than 1 µm. Some of these techniques include molten particle deposition, chemical vapor deposition, electron beam physical vapor deposition, and "coat and fire."

Many of the ceramic coatings in industry are the coat-and-fire type (see Fig. 2.18). Examples include porcelain and glass coatings for lining vessels exposed to corrosive fluids. Another widely used ceramic coating approach in industry is molten particle deposition. Ceramic particles are passed through a very high temperature torch (such as hydrogen-oxygen, oxyacetylene, or plasma). The particles melt in the torch and are sprayed molten onto the surface being coated. The most common applications are for wear resistance or as a thermal barrier (low-thermal-conductivity surface that decreases the temperature that the underlying material is exposed to).

Fig. 2.18. Cramic coating applied by a flame spray molten particle deposition method. *Source:* Sulzer Metco Holding A. G., Wohlen, Switzerland.

Thermal barrier coatings of ZrO_2 are currently in production to protect metals in the hot sections of military and commercial aircraft gas turbine engines. They are also under evaluation for increasing the life and temperature capability of hot section components in industrial- and utility-scale gas turbine engines, which would provide a crosscutting benefit to all the Industries of the Future that use gas turbine engines. The same coatings are being evaluated for drying rolls in the pulp and paper industry. The thermal barrier coatings are typically 0.5–1.0 µm thick.

Other ceramic coatings have demonstrated benefits of wear resistance and corrosion resistance at thicknesses of 5–100 µm. Examples include diamond coatings on a broad range of substrates and oxide and nitride coatings on carbide cutting tool inserts. The advantages of coatings are the following: (1) metals can still be used to carry structural loads, (2) ceramic coatings are typically much lower cost than monolithic ceramics, and (3) new design codes typically do not have to be established.

2.3 REFRACTORIES

A third category of ceramic materials is refractories. Substantial changes have occurred in refractories technology over the past 20 years that have had a crosscutting impact on several of the Industries of the Future. One change that has significantly reduced energy consumption in heat-treating furnaces has been to increase the use of fibrous insulation and high-strength porous setter plates. These greatly decrease the total mass of ceramic material that needs to be heated during each cycle, thus reducing energy consumption and allowing for much more rapid cycles.

Another major refractories change has occurred in the steel industry. Epoxy-bonded MgO-C-metal linings for the basic oxygen furnace have greatly extended the number of heats between relining. Furthermore, increase in the use of electric arc furnaces has reduced refractory use because the arc furnace uses water cooling to provide a protective slag lining inside metallic furnace walls.

Blast furnace life has also been increased through the use of SiC-based refractories.

2.4 CERAMIC MATRIX COMPOSITES

Ceramic matrix composites (CMCs) combine reinforcing ceramic phases with a ceramic matrix to create materials with new and superior properties. In ceramic matrix composites, the primary goal of the ceramic reinforcement is to provide toughness to an otherwise brittle ceramic matrix (Fig. 2.19). Fillers can also be added to the ceramic matrix during processing to enhance characteristics such as electrical conductivity, thermal conductivity, thermal expansion, and hardness. The desirable characteristics of CMCs include high-temperature stability, high thermal-shock resistance, high hardness, high corrosion resistance, light weight, nonmagnetic and nonconductive properties, and versatility in providing unique engineering solutions. The combination of these characteristics makes ceramic matrix composites attractive alternatives to traditional processing industrial materials such as high alloy steels and refractory metals. For the processing industry, related benefits of using ceramic composites include increased energy efficiency, increased productivity, and regulatory compliance. Key barriers to the broad application of ceramic matrix composites include the lack of specifications, databases, attachment concepts, in-service repair methodology, high cost, and scale-up.

Ceramic matrices can be categorized as either oxides or nonoxides and in some cases may contain residual metal after processing. Some of the more common oxide matrices include alumina, silica, mullite, barium aluminosilicate, lithium aluminosilicate and calcium aluminosilicate. Of these, alumina and mullite have been the most widely used because of their in-service thermal and chemical stability and their compatibility with common reinforcements.

Although oxide matrices are often considered more mature and environmentally stable, nonoxide ceramics—with superior structural properties, hardness, and, in some environments, corrosion resistance—are rapidly entering the marketplace. Some of the more common nonoxide ceramics include SiC, Si_3N_4, boron carbide, and AlN. Of these, SiC has been the most widely used, with AlN of increasing interest where high thermal conductivity is required and Si_3N_4, where high strength is desired.

Ceramic reinforcements are available in a variety of forms. Early ceramic composites used discontinuous reinforcements which, when combined with ceramic matrices, could be formed using conventional monolithic ceramic processes. Some of the more common discontinuous reinforcements include whiskers, platelets, and particulates having compositions of Si_3N_4, SiC, AlN, titanium diboride, boron carbide, and boron nitride. Of these, SiC has been the most widely used because of its stability with a broad range of ceramic oxide and nonoxide matrices. Discontinuous oxide ceramic reinforcements are less prevalent because of their incompatibility with many common ceramic matrices.

Modern day composites, which use the fiber in a continuous form to better optimize the structural properties, generally require more costly manufacturing processes. Continuous fiber is available in both monofilament and multifilament tow forms, with multifilament tow fiber being lower in cost on a per-pound basis and, in many cases, easier to process into complex shapes. Some of the more common continuous reinforcements include glass, mullite, alumina, carbon, and SiC. Of these, SiC fibers have been the most widely used because of their high strength, stiffness and thermal stability. Common trade names for silicon carbide fiber include Nicalon™, Hi-Nicalon™, SCS, Sylramic™, and Tyranno. For applications where temperature is lower (< 100°C) or exposure times limited, mullite fibers have been the most widely used because of their lower cost. Nextel is a common trade name for both mullite and alumina fiber. Continuous ceramic fibers are of increasing interest because of their ability to provide pseudo-ductile characteristics to otherwise brittle ceramic materials (Fig. 2.19).

Continuous ceramic fibers become especially important in large structures where the probability of processing- or in-service-induced flaws increases with part size and could result in catastrophic failure. Due to the limited commercial demand, certain grades of continuous ceramic fiber are currently available for $500–$5,000 / lb. As demand increases, continuous ceramic fiber cost is projected to approach $50–$100 / lb. When combined with a ceramic matrix, composite part cost could ultimately reach $200–$400 / lb, which then becomes cost competitive with high alloy steels on a life-cycle cost basis and with refractory metal alloys on both an acquisition and life-cycle cost basis. Today ceramic composite part costs exceed $1,000 / lb when using continuous fiber reinforcement. Discontinuous reinforced composite part cost is currently $7–$50 / lb.

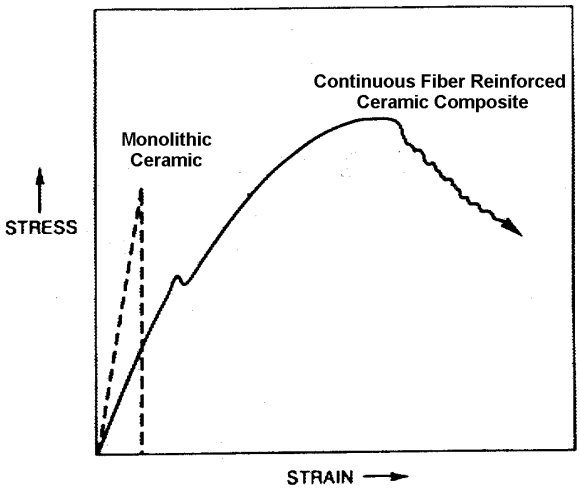


Fig. 2.19. Comparison of failure modes for monolithic ceramics and CFCCs.

Production of ceramic composites in the United States is dominated by a few large firms while small companies are involved in the manufacture of ceramic composites for niche markets. A representation of suppliers of discontinuous and continuous fiber–reinforced ceramic composites is shown in Table 2.6. In 1994, U.S. company shipments for ceramic composite materials totaled about $475 million, of which a majority was for discontinuous reinforced composites. Japanese companies are estimated to control 50% of the world market in advanced ceramics, which includes ceramic composites. Major markets for ceramic composites include cutting tools, aerospace and military, engines, wear and industrial, bioceramics, and energy related. Industrial processing applications currently make up a small fraction of the overall market but the market is growing rapidly as technology and economic barriers are overcome and user confidence builds.

The Department of Energy (DOE) has supported the development of ceramic composites from their inception because of the perceived benefits to energy efficiency, which have since been demonstrated. Early success by DOE occurred with the development and successful commercialization of whisker-reinforced ceramic composites for the cutting tool industry. In 1991, a comprehensive program was started by DOE Office of Industrial Technology to support the development of CFCCs with the goals of developing, in U.S. industry, the primary processing methods for the reliable and cost-effective fabrication of CFCCs for use in industrial applications. Specific goals include the following:

- Develop and demonstrate, at pilot scale, efficient and economic methods of processing CFCC components that are representative of the geometries and properties required to meet the performance requirements of potential end-use applications.
- Develop the necessary supporting technologies to design, analyze and test the materials processing methods and components.
- Provide representative components and relate technologies as inputs to end-user application development programs.

The remaining discussion focuses on ceramic composites considered important to the industrial processing community.

Table 2.6. Representative ceramic composite suppliers

Continuous fiber ceramic composites	Discontinuous reinforced ceramic composites
3M Company	Advanced Refractory Technologies, Inc.
Synterials, Inc.	ALANX Wear Solutions, Inc.
B. F. Goodrich	Cercom
Composite Optics, Inc.	DuPont Lanxide Composites, Inc.
Dow Corning Corporation	Greenleaf Corporation
DuPont Lanxide Composites, Inc.	
McDermott Technology, Inc.	
Techniweave, Inc.	
Textron Systems Corporation	

Discontinuous Reinforced Ceramic Composites

Discontinuous reinforced ceramic composites are produced using processes originally developed for monolithic ceramics. Processing methods commonly used include slip casting or injection molding followed by sintering to full density in a high-temperature-capable furnace. The shaping and sintering processes can also be combined using unidirectional hot pressing or hot isotatic pressing. Net or near-net shape processing can be achieved with final machining often limited to satisfying high-tolerance dimensions or surface finishes. An example of the material microstructure showing the matrix and uniformly distributed discontinuous reinforcement is shown in Fig. 2.20.

Silicon carbide whisker reinforced alumina (SiC_w / Al_2O_3) composite cutting tools have been commercialized by several vendors in the United States (Fig. 2.21). These tools have found an important niche in difficult-to-machine materials and where there is a desire for high machining rates for these materials. Examples can be found in the machining of nickel-based superalloys in the gas turbine industry. A four axis machine retrofit with SiC_w / Al_2O_3 cutting tools was used to reduce machining time of a specific operation from 3 h to 18 s. Factors that allow the increase in productivity include not only increases in cutting speeds by up to a factor of ten, but also lower wear rates and more predictable tool failure times. SiC_w / Al_2O_3 is also being used as the wear components in ceramic / metal hybrid tooling and dies in the canning industry. Key benefits include increased tool life, reduced down time, improved surface finish, lower maintenance cost, and increased production rates. SiC_w / Al_2O_3 is presently used in cupping, drawing, ironing and can necking tools.

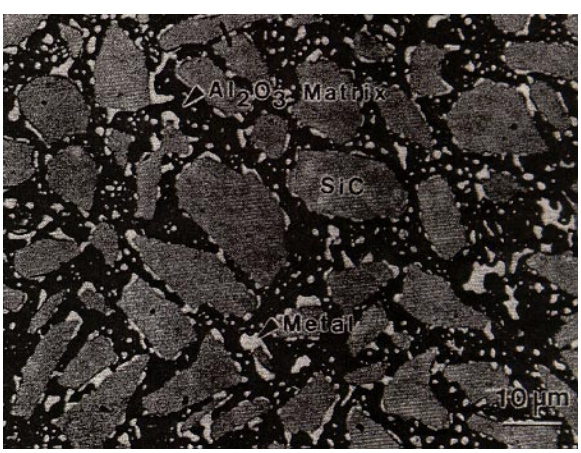


Fig. 2.20. Typical microstructure for a discontinuous reinforced ceramic composite (SiC/Al_2O_3-Al). ***S****ource:* Lanxide Corporation, Newark, Del.

Fig. 2.21. SiC_w/Al_2O_3 cutting tools. ***S****ource:* Greenleaf Corporation, Saegertown, Pa.

Discontinuous reinforced ceramics are being used in the mining and abrasives industry, where use of these ceramics has reduced downtime usually needed for replacing worn parts. The largest application has been chute liners. One product, consisting of 75% SiC + 15% Al_2O_3 + 10% Al, provides excellent resistance to dry erosion, slurry erosion, sliding abrasion, thermal shock, and chemical attack. Similar high-wear applications where discontinuous reinforced ceramics have shown improvements include liners for cyclones, pipes, and pump housings (Fig. 2.22).

Discontinued reinforced ceramics are also being considered for use in a high-pressure (1035-kPa) heat exchanger designed for use in steam reforming of methane. Advantages of ceramic composites for this application include higher temperature capability, reduced fouling, increased energy efficiency, reduced emissions and reduced reformer weight and size. Of the materials testes, a product composed of SiC + Al_2O_3 +Al proved the least vulnerable to steam attack at elevated temperatures.

Continuous Reinforced Ceramic Composites

Ceramic composites containing continuous fiber reinforcements must be processed by

Fig. 2.22. Examples of discontinuous reinforced industrial wear parts. *Source:* ALANX Wear Solutions, Inc., Newark, Del

methods that accommodate the continuous nature of the reinforcement. Typically, processing involves the formation of a fiber preform that contains an interface coating applied by chemical vapor deposition (CVD) or a particle-filled slurry process followed by impregnation with a second particle-filled slurry mix, preceramic polymer, precursor gases, molten metal, or other raw material that converts to a ceramic matrix when heated. The interface is a very thin layer (< 5 µm total thickness), can be multiple layers to achieve the desired result, and is applied to the individual ceramic filaments. The interface serves as protection for the fibers during matrix processing and as a source of debonding during crack propagation in the brittle ceramic matrix. A typical CFCC microstructure shown in Fig. 2.23 illustrates the matrix, fiber, and interface phases.

Fig. 2.23. Typical microstructure of a SiC/SiC CFCC. *Source*: AlliedSignal Composites, Inc., Newark, Del.

SiC Matrix CFCCs

SiC matrix CFCCs have been successfully demonstrated in a number of applications where a combination of high thermal conductivity, low thermal expansion, light weight, and good corrosion and wear resistance is desired. SiC matrix CFCCs—the most mature of the available CFCCs—can be fabricated using a variety of processes, fibers, and interface coatings. Fibers widely used for industrial applications where long life is desired include SiC or mullite. Processes available to fabricate SiC matrix CFCCs and the matrix composition formed include chemical vapor infiltration (SiC), polymer infiltration (SiCN, SiC), nitride bonding (Si–SiC-Si_3N_4), and melt infiltration (Si-SiC). The interface coating can be either carbon or boron nitride with a protective overcoat of SiC or Si_3N_4.

The material properties of SiC matrix CFCCs are ultimately determined by the combination of fiber, process and interface coating selected with typical values shown in Table 2.7

The CVD process is illustrated in Fig. 2.24. In this example a ceramic interface and the SiC matrix are both formed by deposition from a gas precursor at elevated temperature. Multiple cycles of the matrix-forming process are required to achieve the desired final density, with each cycle taking up to a week in many cases. The number of cycles varies from 2 to 5, depending on the part geometry and size.

The infiltration of a fiber preform with preceramic polymer or a particle slurry is illustrated in Fig. 2.25. In this example, the interface is applied onto the fiber, cloth, or preform by CVI or particle-filled slurry processes before coating with a matrix-forming second slurry or

Table 2.7. Typical material properties for a SiC matrix CFCC

Density	2.1 g/cm^3
Tensile strength	262 MPa
Tensile modulus	96 GPa
Strain to failure	0.4%
Compressive strength	450 MPa
Shear strength	34 MPa
Thermal expansion	2.7×10^{-6}/°C
Thermal conductivity	1.32 W/m°C

Source: Dow Corning Corporation

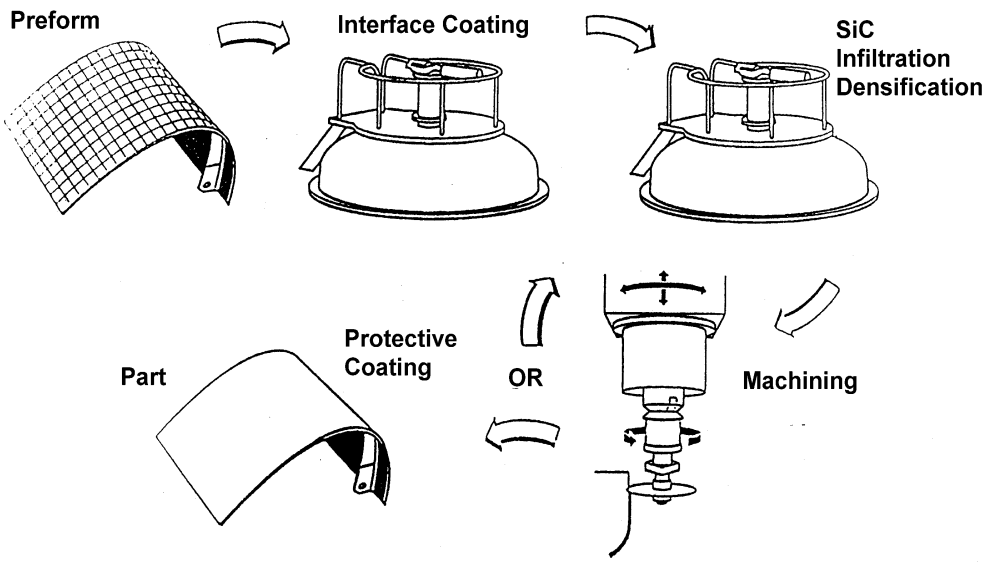


Fig. 2.24. Flowchart for the processing of CFCCs by chemical vapor deposition.

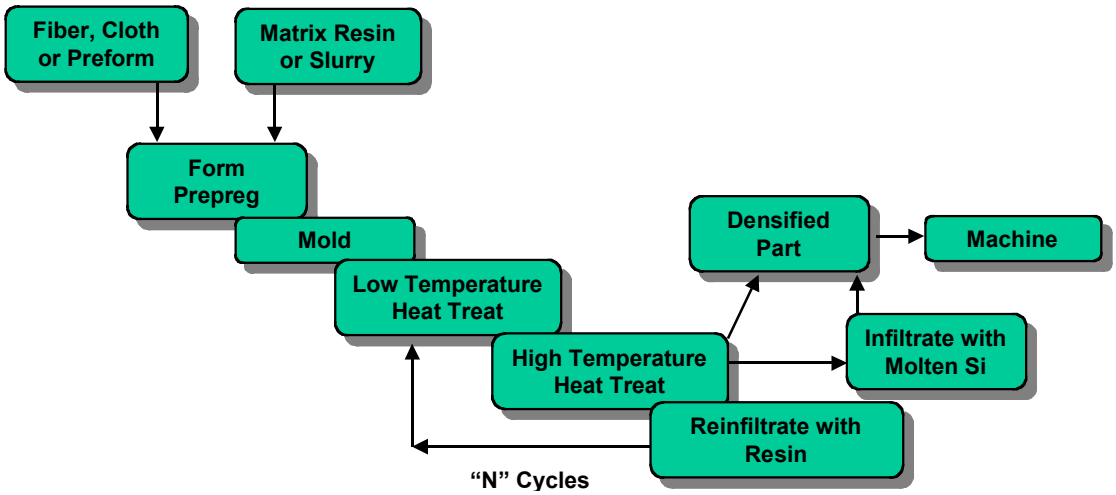


Fig. 2.25. Flowchart for the processing of SiC CFCCs by resin infiltration, melt infiltration, or nitridation.

preceramic polymer. Once coated with a polymer or slurry, the shape is formed and heat treated at low temperatures to rigidize the shape. The rigidized shape is then heat treated at elevated temperatures to convert the polymer to a ceramic matrix or bond particles in the ceramic-filled slurry. For preceramic polymers, multiple cycles are required to achieve the desired final density, with each cycle taking one to three days. The number of cycles used varies from 4 to 15 depending on the polymer and the desired final density. When using particle-filled slurries to form the matrix, porosity remaining after rigidizing the preform is either filled with molten silicon metal to form a matrix of Si-SiC or Si contained in the slurry reacts during high temperature heat treatment in nitrogen to form a matrix of Si–SiC-Si_3N_4. Variants of the melt infiltration process can also be used in which the molten silicon reacts with carbon present in the matrix to form additional silicon carbide.

Shaping to near-net dimensions occurs during preforming with final machining limited to high tolerance attachments to avoid surface fiber damage. Additional machining may be required for complex shapes and is generally performed early in the process when the composite is less dense and easier to machine. External coatings can be used to enhance environmental resistance with some of the more common environmental barrier coatings including mullite, SiC, and Si_3N_4.

Shape- and size-making capability can also be limited by the combination selected due to restrictions on available manufacturing facilities and limitations inherent in the fabrication processes themselves. Manufacturing facilities for CFCCs currently exist for parts as large as 1.5 m in diameter and 2.5 m long. Many of the technical barriers for producing SiC matrix CFCCs have been overcome, with the key remaining barrier being high cost. Applications for which SiC matrix CFCCs are being considered are summarized in Table 2.8 and are shown in Figs. 2.26–2.31. The applications are in various stages of development, with gas-fired radiant burner screens and gas turbine engine combustors well along in the product development cycle and the nearest to commercialization. SiC matrix CFCCs have operated in gas turbine engine combustor liners for 1,000 h and radiant burner screens for 10,000 thermal cycles without failure.

Oxide Matrix CFCCs

Alumina and mullite matrix CFCCs have been successfully demonstrated in applications where a high tolerance to salt corrosion, molten glass or oxidation is required in combination with the high toughness, light weight, and high-thermal-shock resistance characteristic of CFCCs. Fibers generally used for industrial applications requiring long life include SiC, mullite, or alumina and mullite matrix CFCCs. Processes available to fabricate alumina and mullite matrix CFCCs, and the matrix compositions formed, include sol-gel (Al_2O_3, Al_2O_3, SiO_2), directed metal oxidation (Al_2O_3 + Al), and chemical bonding ($AlPO_4$). The interface coating varies widely and in some cases is not required, resulting in improved thermal stability but reduced interlaminar properties.

Processes used to fabricate alumina and mullite matrix CFCCs are generally lower temperature, which results in simplified scale-up, virtually unlimited size- and shape-making capability, and reduced cost. The sol-gel and chemical bonding processes are similar to the preceramic polymer process previously described in Fig. 2.25. The directed metal oxidation processes is illustrated in Fig. 2.32. In this example, the interface is applied onto the fiber, cloth, or preform by CVI processes after forming to shape because the overall thickness of the interface makes further shaping difficult once applied. The rigidized shape containing the fiber and interface coating is next exposed to molten aluminum metal at elevated temperatures in a reactive atmosphere of oxygen to form a matrix of Al-Al_2O_3. Depending on the application, excess metal can be removed from the microstructure by a additional processing.

Material properties of alumina and mullite CFCCs are ultimately determined by the combination of fiber, process, and interface coating sizing selected, with typical values shown in Table2.9.

Applications for which alumina or mullite matrix CFCCs are being considered are summarized in Table2.10 and are shown in Figs.2.33–2.35. The applications ar e in various stages of development, with hot gas filtration being well along in the product development cycle and the nearest to commercialization.

Table 2.8. Applications being considered for SiC matrix CFCCs

Application	Conditions imposed on SiC matrix CFCC	Benefits demonstrated or perceived by the customer
Hot-gas recirculating fan	High mechanical stresses, high temperature	Increased life and temperature capability
Heat exchanger	High temperature, high thermal stresses, highly erosive and hot corrosion	Higher temperature capability and life
Gas-fired radiant burner screen	High temperature, high thermal stresses	Increased life and thermal output
Gas-fired radiant burner tubes	High temperature, high thermal stress	Increased life and temperature capability
Gas turbine engine combustion liners and tip shrouds	High temperature, hot corrosion	Reduced emissions and increased efficiency resulting from reduced cooling air, higher temperature capability
Hot-liquid filtration	Harsh chemical environment, high temperature	Increased life, higher temperature capability
Canned motor pump containment shell	Harsh chemical environment	Increased electrical efficiency through reduced eddy current drag
Gas-fired melting immersion burner tube	Harsh molten metal environment, high thermal shock	Reduced contamination, increased efficiency, improved heating uniformity
Furnace pipe hanger	High temperature, high mechanical stresses	Longer life, higher temperature capability, reduced supporting structure

Fig. 2.26. SiC matrix CFCC hot gas recirculating fan manufacturing using chemical vapor infiltration. *Source:* AlliedSignal Composites, Inc., Newark, Del.

Fig. 2.27. SiC matrix CFCC radiant burner screen manufactured using chemical vapor infiltration. *Source:* AlliedSignal Composites, Inc., Newark, Del.

Fig. 2.28. SiC matrix CFCC gas turbine engine combustor liners manufactured using chemical vapor infiltration and tip shroud manufactured using melt infiltration. ***S****ources:* AlliedSignal Composites, Inc., Newark, Del., and General Electric Power Systems, Schenectady, NY.

Fig. 2.29. SiC matrix CFCC filters manufactured using chemical vapor infiltration. ***S****ource:* AlliedSignal Composites, Inc., Newark, Del.

Fig. 2.30. SiC matrix CFCC immersion burner tubes manufactured using nitridation. ***S****ource:* Textron Systems Corporation, Lowell, Mass.

Fig. 2.31. SiC matrix CFCC furnace pipe hangers manufacured using preceramic polymer infiltration. ***S****ource:* Dow Corning Corporation, Midland, Mich.

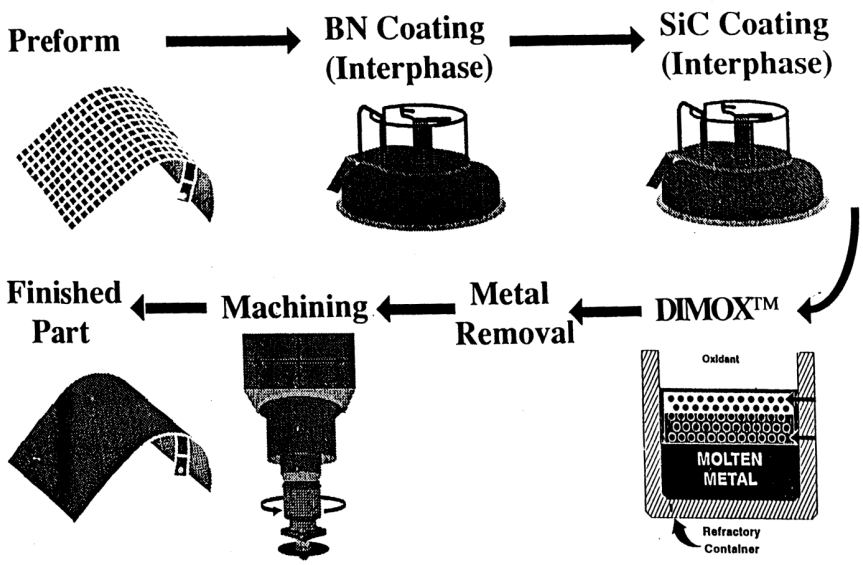


Fig. 2.32. Flowchart for the processing of Al_2O_3-Al Matrix CFCCs by direct metal oxidation.
Source: Textron Systems Corporation, Lowell, Mass.

Table 2.9. Typical material properties for an alumina matrix CFCC

Density	2.82 g/cm^3
Tensile Strength	365 MPa
Tensile Modulus	124 GPa
Strain to Failure	0.35%
Compressive Strength	270 MPa
Thermal Expansion	8.5×10^{-6}/°C
Shear Strength	15.2 MPa

Source: Composite Optics, McDermott Technology, Inc., Alliance, Ohio, and Lynchburg, Va.

Table 2.10. Applications being considered for alumina and mullite matrix CFCCs

Application	Conditions imposed on SiC matrix CFCC	Benefits demonstrated or perceived by the customer
Thermophotovoltaic burner/emittor	High thermal shock, high temperature, surface combustion	Increased efficiency, multifuel capability, maximum on/off response, increased life
Heat exchanger	High temperature, high thermal stresses, highly erosive and hot corrosion	Higher temperature capability and life
Hot-gas filtration	Harsh chemical environment, high temperature	Increased life, higher temperature capability
Gas turbine engine combustion liners and shrouds	High temperature, hot corrosion	Reduced emissions and increased efficiency resulting from reduced cooling air, higher temperature capability
Burner stabilizer	High corrosion	Longer life

Fig. 2.33. Alumina matrix CFCC burner stabilizer ring. ***S****ource:* McDermott Technology, Inc., Alliance, Ohio, and Lynchburg, Va.

Fig. 2.34. Alumina matrix CFCC heat exchanger headers. *Source:* AlliedSignal Composites, Inc., Newark, Del.

2.5 SUMMARY

In summary, advanced monolithic ceramics are being used throughout the industrial processing industry and have demonstrated superior performance to conventional materials at an affordable price. As user confidence continues to grow and as energy savings, increased productivity, and reduced maintenance are confirmed, the need has emerged for advanced ceramics with improved toughness (also known as ceramic composites). Discontinuous reinforced ceramic composites have partially filled this need, but their application is limited in both size and geometry, and their toughness is less than desired for a risk-adverse industry. Continuous fiber reinforced ceramic composites are viewed as the ultimate solution with many applications rapidly becoming commercially viable.

The following chapters discuss industrial processing applications where advanced ceramics are contributing today or could become contributors with additional product development. Industries considered are those identified by DOE's Office of Industrial Technologies as being the largest users of energy, and they include steel, aluminum, metal casting, glass, forest products, and chemical/petrochemical. Included in the discussion on potential opportunities for advanced ceramics is an overview of the character of each industry and the industrial processes currently used.

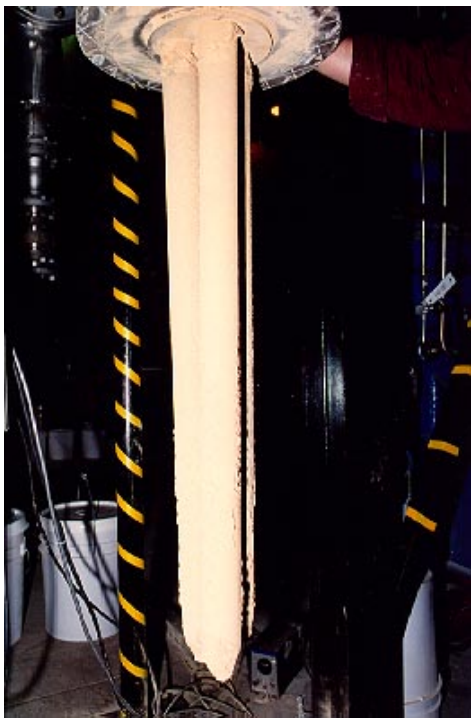


Fig. 2.35. Alumina matrix CFCC hot-gas filter. *Source:* McDermott Technology, Inc., Alliance, Ohio, and Lynchburg, Va.

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AlliedSignal Composites, Inc., Newark, Del.
Ceradyne, Inc., Costa Mesa, Calif.
Composite Optics, Inc., Emmaus, Pa., and San Diego, Calif.
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