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.

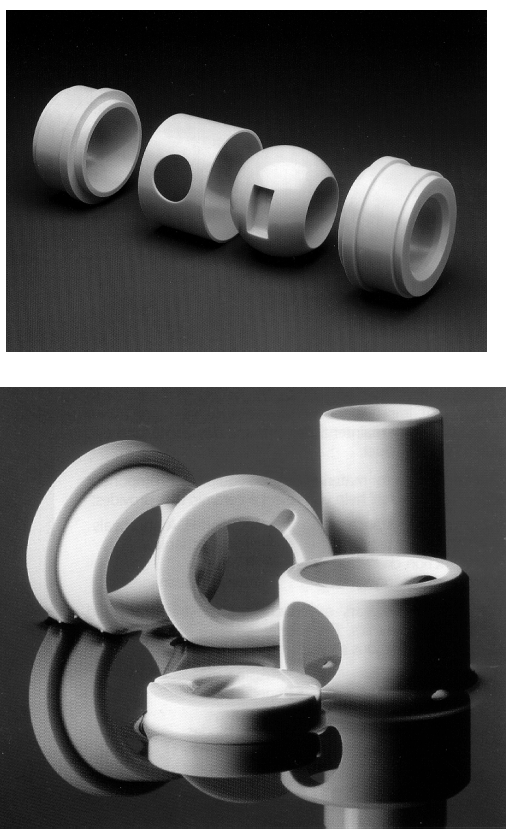

Fig. 2.11. Alumina is used extensively for face seals and various types of valve and pump components. *Source:* Coors Ceramics Company, Golden, Colo.

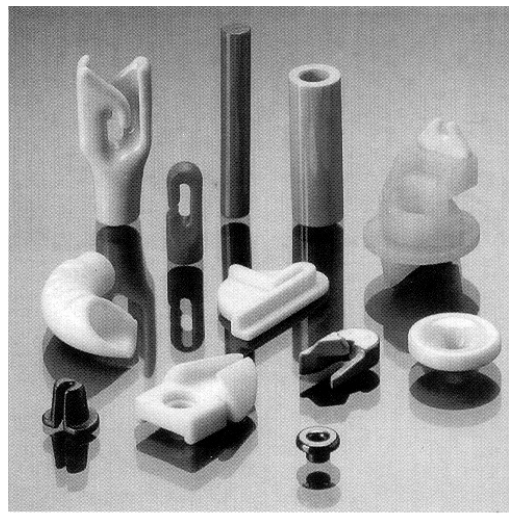

Fig 2.12. Thread guides of alumina and other ceramic materials. *Source:* Rauschert Technical Ceramics, Madisonville, Tenn.

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

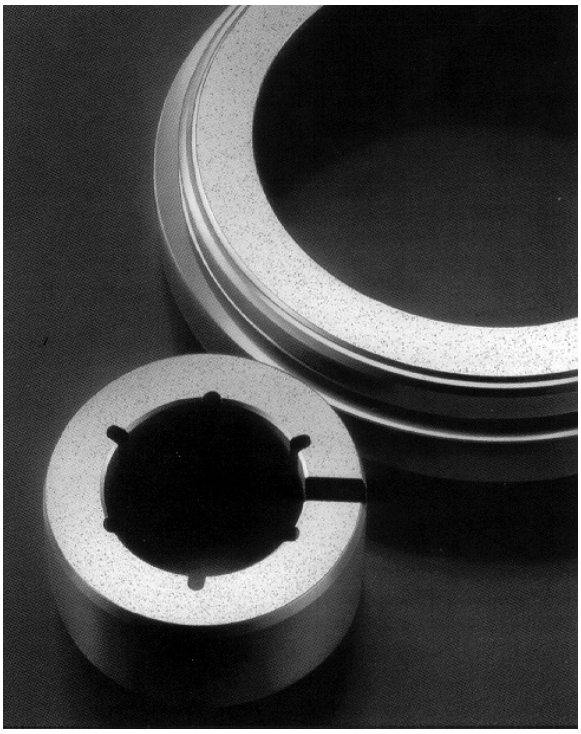

Fig. 2.13. Hexoloy SP SiC seal surfaces showing the dispersion of spherical pores which act as fluid reservoirs and reduce friction and wear. *Source:* Saint-Gobain / Carborundum Structural Ceramics, Niagara Falls, N.Y.

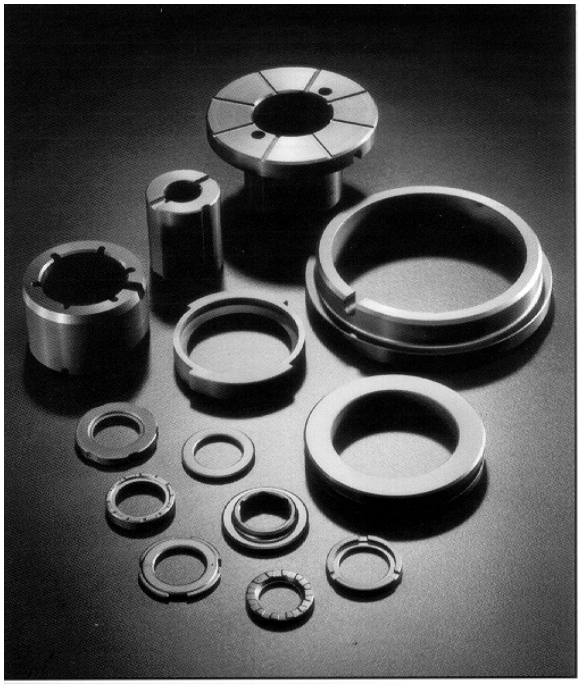

Fig. 2.14. SiC seal and pump parts. *Source:* Saint-Gobain / Carborundum Structural Ceramics, Niagara Falls, N.Y.

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