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,

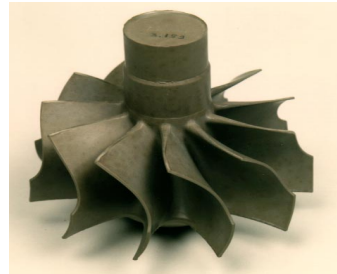

Fig. 2.8. Si_3N_4 gas turbine engine radial rotor from AlliedSignal Ceramic Components. *Source:* AlliedSignal Ceramic Components, Torrance, Calif.

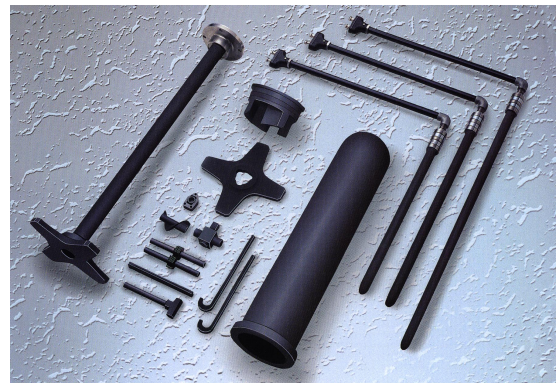

Fig. 2.9. Silicon nitride tooling designed for immersion in molten aluminum. *Source:* Kyocera Corporation, Kyoto, Japan.

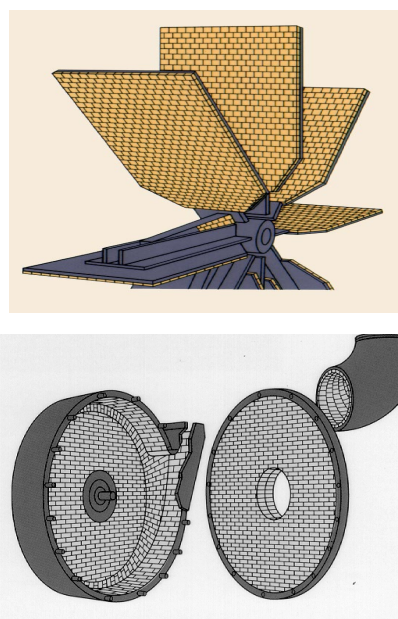

Fig. 2.10. Al_2O_3 tiles provide reliable wear-resistant surfaces on chutes, fans, housings, pipes, and cyclones in handling systems for pulverized coal, grain, ore, and other flowing abrasive materials. *Source:* Coors Wear Products, Inc. brochure, Coors Ceramics Company, Golden, Colo.

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.

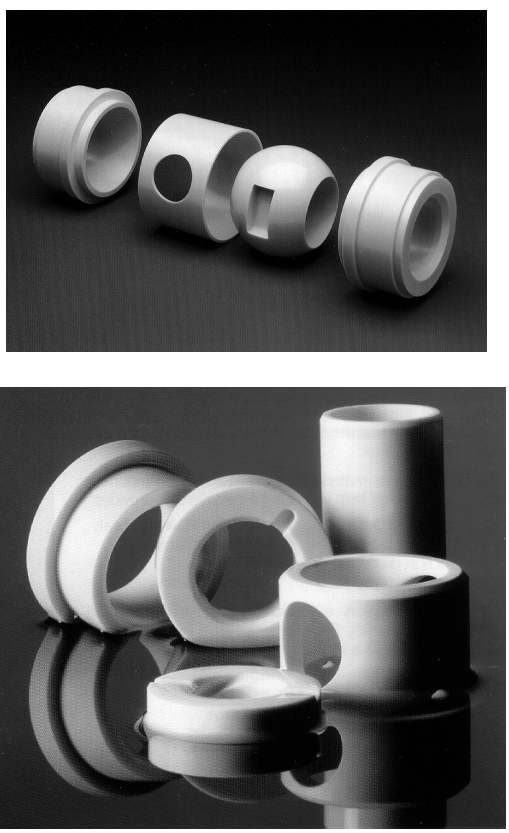

Fig. 2.11. Alumina is used extensively for face seals and various types of valve and pump components. *Source:* Coors Ceramics Company, Golden, Colo.

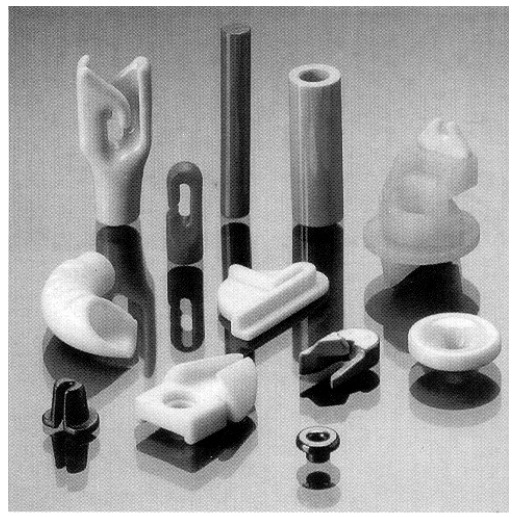

Fig 2.12. Thread guides of alumina and other ceramic materials. *Source:* Rauschert Technical Ceramics, Madisonville, Tenn.

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