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.

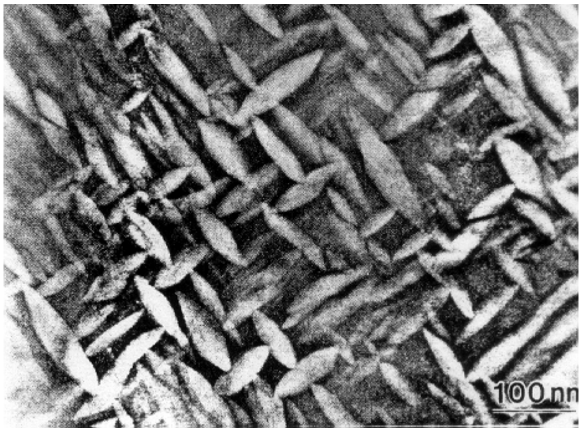

Fig. 2.16. Microstructure of one form of transformation-toughened zirconia. *Source*: David W. Richerson, *Modern Ceramic Engineering*, Marcel Dekker, New York, 1992.

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

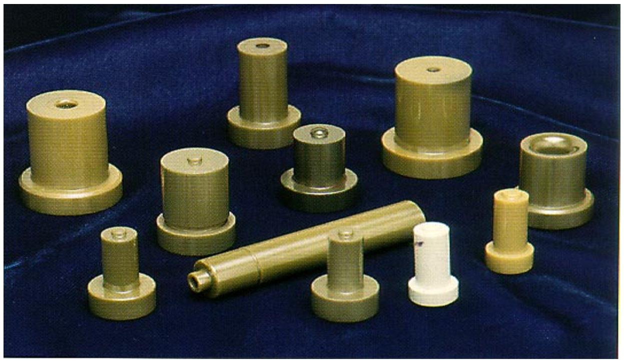

Fig. 2.17. Transformation-toughened zirconia tooling for fabrication of aluminum cans. *Source:* Saint-Gobain / Norton Advanced Ceramics, East Granby, Conn.

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.