

Ceramic Carbides: The Tough Guys of the Materials World

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Silicon carbide (SiC) and boron carbide (B₄C) are among the world's hardest known materials and are used in a variety of demanding industrial applications, from blasting-equipment nozzles to space-based mirrors. But there is more to these “tough guys” of the materials world than hardness alone—these two ceramic carbides have a profile of properties that are valued in a wide range of applications and are worthy of consideration for new research and product design projects.

Silicon Carbide

Use of this high-density, high-strength material has evolved from mainly high-temperature applications to a host of engineering applications. Silicon carbide is characterised by:

- High thermal conductivity
- Low thermal expansion coefficient
- Outstanding thermal shock resistance
- Extreme hardness
- Semiconductor properties
- A refractive index greater than diamond

Although many people are familiar with the general attributes of this advanced ceramic (see Figure 1), an important and frequently overlooked consideration is that the properties of silicon carbide can be altered by varying the final compaction method. These alterations can provide knowledgeable engineers with small adjustments in performance that can potentially make a significant difference in the functionality of a finished component.

For example, within the two categories of silicon carbide production—sintering and reaction bonding—different methods of compaction can result in various advantages and limitations of the finished material. In one such case, reaction-bonded silicon-infiltrated silicon carbide (SiSiC) is produced by impregnating a porous skeleton of silicon carbide and free carbon with molten silicon. This creates a bond matrix of silicon carbide and leaves some silicon in unbonded form. The material does not contract during densification, resulting in dimensional stability

FIGURE 1:
Typical properties of silicon carbide
(hot-pressed sheet)

Chemical Resistance	
Acids, concentrated	Good
Acids, dilute	Good
Alkalies	Good-Poor
Halogens	Good-Poor
Metals	Fair
Electrical Properties	
Dielectric constant	40
Volume resistivity at 25°C (Ohm-cm)	10 ³ -10 ⁵
Mechanical Properties	
Compressive strength (MPa)	1000-1700
Hardness, Vickers (kgf mm ⁻²)	2400-2800
Shear strength (MPa)	210-380
Tensile modulus (GPa)	200-500
Physical Properties	
Apparent porosity (%)	0
Density (g cm ⁻³)	3.15
Thermal Properties	
Coefficient of thermal expansion at 20-1000°C (x10 ⁻⁶ K ⁻¹)	4.5
Melting point (°C)	2650-2950
Specific heat at 25°C (J K ⁻¹ kg ⁻¹)	670-710
Thermal conductivity at 20°C (W m ⁻¹ K ⁻¹)	90-160
Upper continuous use temperature (°C)	1500-1650

that enables the production of large-scale components and complex shapes. On the down side, the free silicon limits the operation temperature to about 1380°C.

Other compaction methods produce silicon carbide sintered without pressure (SSiC), hot-pressed or hot isostatically pressed silicon carbide (HPSiC/HIPSiC), recrystallised silicon carbide (RSiC), and liquid-phase sintered silicon carbide (LPSiC). These methods variously alter porosity, strength, durability, corrosion resistance, thermal spalling resistance or fracture toughness.

SiC Applications

Applications for silicon carbide are wide-ranging but grounded in the remarkable toughness of the material. Some of the most common applications include:

- Automotive components and seal faces, requiring superior resistance to wear and thermal shock and the ability to last the lifetime of the vehicle
- Mechanical seals, requiring superior resistance to corrosion, abrasion and shock
- Blast and atomisation nozzles, requiring excellent wear resistance, light weight and long life (silicon carbide lasts 50% longer than tungsten carbide)
- Process industry valve applications, requiring outstanding corrosion resistance, particularly in acids
- Semiconductor production, requiring exceptional resistance to wear and corrosion, which in turn leads to reduced maintenance and component recycling

NASA's Glenn Research Center has been developing silicon carbide as a material for advanced semiconductor electronic devices that could have both functional and financial implications for the space program. Silicon carbide-based electronics and sensors can operate at temperatures of up to 600°C, compared to an upper limit of 350°C for conventional silicon-based electronics. This could be an advantage in launch vehicle and aircraft engines, which operate at extremely high temperatures.

At the much lower operational temperatures associated with spacecraft, silicon carbide-based electronics would lend themselves to a more compact spacecraft power system and would also not require as much cooling by a spacecraft's thermal radiators as conventional silicon-based electronics. These thermal radiators could, in turn, be made smaller and lighter, reducing overall weight and, potentially, cost. In addition, the use of high-temperature, radiation-hardened silicon carbide-based circuits would require less shielding in nuclear-powered spacecraft, further reducing weight.

Form Follows Function

Silicon carbide and boron carbide can be found in a range of forms to facilitate the development of new products and applications.

Fibre	Rod
Foam	Sheet
Granule	Sputtering target
Monofilament	Tile
Powder	Tube

Note: Not all forms are available for both silicon carbide and boron carbide.



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Image credit: NASA/Sandra Joseph and Kevin O'Connell

Boron Carbide

Boron carbide's hardness ranks behind only diamond, cubic boron nitride and boron oxide (see Figure 2). Difficult to sinter to full density, boron carbide is usually produced with the addition of sintering aids such as fine carbon or silicon carbide. Boron carbide is typically characterised by:

- Extreme hardness
- Low thermal conductivity
- High elastic modulus
- High compressive strength
- Good nuclear properties
- Low density

B₄C Applications

In addition to applications requiring excellent wear resistance and high strength, other applications can take advantage of the distinctive properties of boron carbide. The following are a few of this ceramic carbide's varied applications:

- Abrasives, requiring extreme hardness for use in polishing and lapping applications, dressing diamond tools, and water jet cutting
- Nozzles, requiring wear and abrasion resistance for slurry pumping, grit blasting, and water jet cutters
- Nuclear applications, since 20% of natural boron is the ¹⁰B isotope, boron carbide can be used as an absorbent for neutron radiation in nuclear power plants
- Body armour, requiring a critical balance of hardness, compressive strength, high elastic modulus and low specific density

The use of boron carbide for armour applications has increased dramatically in recent years, with the ceramic carbide rapidly becoming the material of choice for military and law enforcement personnel. This advanced ceramic, in the form of plates or "tiles" inserted into ballistic vests, provides an approximately 50% reduction in weight while offering equal or greater protection than previous forms of body armour. New processes to shape the material for an optimal fit have also improved performance and undoubtedly saved lives.

Looking Ahead

Given their unique properties and proven versatility, silicon carbide and boron carbide offer researchers and design engineers opportunities to investigate other exciting but currently unexplored uses for these remarkable advanced ceramics. The "tough guys" surely have a lot more to offer.

For more information regarding ceramic carbides, contact the authors at paul.everitt@goodfellow.com or ian.doggett@goodfellow.com.

FIGURE 2:
Typical properties of boron carbide (hot-pressed sheet).

Chemical Resistance	
Acids, concentrated	Fair
Acids, dilute	Good
Alkalis	Fair
Halogens	Fair
Metals	Fair
Electrical Properties	
Volume resistivity at 25°C (Ohm-cm)	0.1-10
Mechanical Properties	
Compressive strength (MPa)	1400-3400
Hardness, Knoop (kgf mm ⁻²)	2800-3500
Hardness, Vickers (kgf mm ⁻²)	3200
Shear strength (MPa)	210-380
Tensile modulus (GPa)	440-470
Physical Properties	
Apparent porosity (%)	< 3
Density (g cm ⁻³)	2.45-2.52
Thermal Properties	
Coefficient of thermal expansion at 20-1000°C (x 10 ⁻⁶ K ⁻¹)	5.6
Melting point (°C)	2450
Specific heat at 25°C (J K ⁻¹ kg ⁻¹)	950
Thermal conductivity at 20°C (W m ⁻¹ K ⁻¹)	30-90
Upper continuous use temperature (°C)	600-800



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