Material Properties Charts

Important Information

On the following pages, we have collected a number of charts detailing applications and properties for some of the most commonly used ceramic materials. While the data in these charts is, in most cases, *typical* of what you will find from ceramic component suppliers, it is only intended to be a general point of reference and should not be used for material selection or specification. The manufacture of ceramic components involves many different variables—from the starting material and additives used, to the forming method, sintering process/ temperature and final finishing techniques, as well as the size and shape of the part itself—all of which affect the component's final property values. In many cases, manufacturers can tailor properties to specific applications through partnerships with design engineers during the initial phases of a design concept.

It is also important to note that some of these charts originate from different sources. While we did our best to ensure that the data was comparable, different analysis techniques and units of measurement will affect the property values provided. As you review these charts, be sure to note the source (indicated at the bottom of each chart) and any differences in the type of information provided before using the data for comparison purposes.

Ceramic materials offer a number of benefits in a variety of applications. They provide high wear, heat and corrosion resistance, as well as high tensile strength, volume resistivity, dielectric strength and modulus of elasticity. These materials also offer lower thermal expansion than metals or plastics, and a longer part life at original design dimensions and tolerances. We hope that the information on the following pages will help guide your decision toward ceramic components as a viable design option, but these charts should only be used as a general starting point. Please contact the suppliers listed in the Address Index (pp. 63-75), Component Listings (pp. 28-57) or Professional Services (pp. 58-62) sections of this directory for specific ceramic component design information.

Contents

7 . . . .Key Features/Benefits of Some Advanced Technical Ceramics
8 . . . .Typical Alumina 99.5% Properties
9 . . . .Typical Aluminum Nitride Properties
10 . . .Typical Boron Carbide Properties
11 . . .Typical Boron Nitride Properties
12 . . .Typical Cordierite Properties
13 . . .Typical Graphite Properties
14 . . .Typical Mullite Properties
15 . . .Typical Sapphire Properties
16 . . .Typical Silicon Carbide Properties
17 . . .Terminology Commonly Associated with Silicon Carbide Processing
18 . . .Typical Silicon Nitride Properties
19 . . .Terminology Commonly Associated with Silicon Nitride Processing
20 . . .Typical Steatite L-5 Properties
21 . . .Typical Titanium Diboride Properties
22 . . .Typical Tungsten Carbide Properties
23 . . .Typical Zirconia Properties

Compressive Strength Comparison

Material	**Test**	**Compressive Yield Strength (psi)**
Ceramic		
99.9% Al_2O_3	ASTM C773	392,000
Plastic		
Polycarbonate Resin	ASTM D695	12,500
Metal		
316 Stainless Steel	Typical Value	30,000

Source: CoorsTek, Inc., Golden, Colo., www.coorstek.com.

Note: Although we have no reason to doubt the accuracy of the data presented, this information is offered for comparison only. CoorsTek and *Ceramic Industry* disclaim any and all liability from error, omissions or inaccuracies in the above chart.

Key Features/Benefits of Some Advanced Technical Ceramics

Aluminum Oxide (Al_2O_3). Aluminum oxide (alumina) is the workhorse of advanced technical ceramics. It has good mechanical and electrical properties, wear resistance and corrosion resistance. It has relatively poor thermal shock resistance. It is used as an electrical insulator for a number of electrical and electronic applications, including spark plug insulators and electronic substrates. It is also used in chemical, medical and wear applications.

Zirconium Oxide (ZrO_2). Zirconium oxide has the highest fracture toughness of any advanced technical ceramic. Its toughness, mechanical properties and corrosion resistance make it ideal for medical and selected wear applications. Its thermal expansion coefficient is very close to steel, making it an ideal plunger for use in a steel bore. Its properties are derived from a very precise phase composition. Some environmental conditions can make the material unstable, causing it to lose its mechanical properties. Its relatively low hardness and high weight also limit its broad use in wear applications.

Fused Silica (SiO_2). Fused silica is an excellent thermal insulator and has essentially zero thermal expansion. It has good chemical resistance to molten metals but is limited by its very low strength. It is used for a number of refractory and glass applications, as well as radomes for missiles.

Titanium Diboride (TiB_2). Titanium diboride is an electrically conducting ceramic and can be machined using electron discharge machining (EDM) techniques. It is a very hard material; however, its mechanical properties are poor. Its major use is in metallurgical applications involving molten aluminum. It is also used for some limited wear applications, such as ballistic armor to stop large-diameter (>14.5 mm) projectiles.

Boron Carbide (B_4C). Boron carbide is the hardest material after diamond, giving it outstanding wear resistance. Its mechanical properties, especially its fracture toughness, are low, limiting its application. However, it is used extensively for ballistic armor and blast nozzles. Boron carbide is also a neutron absorber, making it a primary choice for control rods and other nuclear applications.

Silicon Carbide (SiC). Silicon carbide has outstanding wear and thermal shock resistance. It has good mechanical properties, especially at high temperatures. It is a semiconductor material with electrical resistivities in the 10^5 ohm-cm range. It can be processed to a very high purity. Silicon carbide is used extensively for mechanical seals because of its chemical and wear resistance.

Tungsten Carbide (WC). Tungsten carbide is generally made with high percentages of either cobalt or nickel as a second, metallic phase. These ceramic metals, or "cermets," have wide use as cutting tools and other metal-forming tools. Pure tungsten carbide can be made as an advanced technical ceramic using a high-temperature hot isostatic pressing process. This material has very high hardness and wear resistance and is used for abrasive water jet nozzles; however, its weight limits its use in many applications.

Aluminum Nitride (AlN). Aluminum nitride has a very high thermal conductivity while being an electrical insulator. This makes it an ideal material for use in electrical and thermal management situations.

Boron Nitride (BN). Hexagonal boron nitride is a chalky white material and is often called "white graphite." It has generally poor mechanical properties. It has outstanding high-temperature resistance (>2500ºC) in inert atmospheres but cannot be used above 500ºC in an air atmosphere. It is used as a high-temperature insulator and in combination with TiB_2 in many ferrous and aluminum metallurgical applications.

Silicon Nitride (Si_3N_4). Silicon nitride has the best combination of mechanical, thermal and electrical properties of any advanced technical ceramic material. Its high strength and toughness make it the material of choice for automotive and bearing applications.

Source: Ceradyne Inc., Costa Mesa, Calif., www.ceradyne.com.

Note: Although we have no reason to doubt the accuracy of the data presented, this information is offered for comparison only. Exact properties will vary depending on the manufacturing method and part configuration, and can sometimes be tailored to meet specific requirements. Contact your component supplier for more detailed information. Ceradyne and *Ceramic Industry* disclaim any and all liability from error, omissions or inaccuracies in the above chart.

Typical Alumina (Al_2O_3) 99.5% Properties

Alumina represents the most commonly used ceramic material in industry. It provides superior abrasion, high temperature and chemical resistance, and is also electrically insulating. This material has an excellent cost-to-part life performance record. Purity levels are available from 85% through 99.9%. Applications include wear- and heat-resistant liners, mechanical and pump seals, nozzles, semiconductor equipment components, insulators, etc.

Properties	Units	Test	Value
Physical			
Chemical Formula			Al_2O_3
Density, ρ	g/cm^3	ASTM C20	3.7-3.97
Color			ivory/white
Crystal Structure			hexagonal
Water Absorption	% @ room temperature (R.T.)	ASTM C373	0.0
Hardness	Mohs		9
Hardness	Knoop (kg/mm^2)	Knoop 100 g	2000
Mechanical			
Compressive Strength	MPa @ R.T.	ASTM C773	2070-2620
Tensile Strength	MPa @ R.T.	ACMA Test #4	260-300
Modulus of Elasticity (Young's Modulus)	GPa	ASTM C848	393
Flexural Strength (MOR)	MPa @ R.T.	ASTM F417	310-379
Poisson's Ratio, υ		ASTM C818	0.27
Fracture Toughness, K_{Ic}	MPa x $m^{1/2}$	Notched Beam Test	4.5
Thermal			
Max. Use Temperature (in air)	ºC	No load cond.	1750
Thermal Shock Resistance	ΔT (ºC)	Quenching	200
Thermal Conductivity	W/m-K @ R.T.	ASTM C408	35
Coefficient of Linear Thermal Expansion, α_l	µm/m-ºC (~25ºC through ±1000ºC)	ASTM C372	8.4
Specific Heat, c_p	cal/g-ºC @ R.T.	ASTM C351	0.21
Electrical			
Dielectric Constant	1 MHz @ R.T.	ASTM D150	9.6
Dielectric Strength	kV/mm	ASTM D116	15
Electrical Resistivity	Ωcm @ R.T.	ASTM D1829	$>10^{14}$

Source: Ferro-Ceramic Grinding, Inc., Wakefield, Mass., www.ferroceramic.com.

Note: Although we have no reason to doubt the accuracy of the data presented, this information is offered for comparison only. Exact properties will vary depending on the manufacturing method and part configuration, and can sometimes be tailored to meet specific requirements. Contact your component supplier for more detailed information. Ferro-Ceramic Grinding and *Ceramic Industry* disclaim any and all liability from error, omissions or inaccuracies in the above chart.

Typical Aluminum Nitride (AlN) Properties

While AIN is not a new material, manufacturability developments over the past 15 years have made it an exciting and viable ceramic design option. One of the most useful applications AIN has found is in replacing beryllium oxide (BeO) in the semiconductor industry due to BeO's toxicity. The thermal expansion coefficient of AIN is lower than BeO or alumina, and closely matches that of the silicon wafers used in electronics. While this was once a limitation for AIN's use in electronic applications, there are now processes to metallize AIN. Electronic and structural grades of this material exist, classified as such by the thermal conductivity, which is controlled by the purity of the AIN. Pristine material is white, high-purity is tan, and a gray color indicates contaminants.

Properties	Units	Test	Value
Physical			
Chemical Formula			AlN
Density, ρ	g/cm^3	ASTM C20	3.25
Color			white/tan/gray
Crystal Structure			hexagonal
Water Absorption	% @ room temperature (R.T.)	ASTM C373	0.0
Hardness	Mohs		5
Hardness	Knoop (kg/mm^2)	Knoop 100 g	1170
Mechanical			
Compressive Strength	MPa @ R.T.	ASTM C773	2068
Tensile Strength	MPa @ R.T.	ACMA Test #4	—
Modulus of Elasticity (Young's Modulus)	GPa	ASTM C848	308
Flexural Strength (MOR)	MPa @ R.T.	ASTM F417	428
Poisson's Ratio, υ		ASTM C818	0.25
Fracture Toughness, K_{Ic}	MPa x $m^{1/2}$	Notched Beam Test	3.5
Thermal			
Max. Use Temperature (in air)	ºC	No load cond.	1600
Thermal Shock Resistance	ΔT (ºC)	Quenching	400
Thermal Conductivity	W/m-K @ R.T.	ASTM C408	82.3-170
Coefficient of Linear Thermal Expansion, α_l	µm/m-ºC (~25ºC through ±1000ºC)	ASTM C372	4.6-5.7
Specific Heat, c_p	cal/g-ºC @ R.T.	ASTM C351	0.25
Electrical			
Dielectric Constant	1 MHz @ R.T.	ASTM D150	8.0-9.1
Dielectric Strength	kV/mm	ASTM D116	15
Electrical Resistivity	Ωcm @ R.T.	ASTM D1829	$>10^{14}$

Source: Ferro-Ceramic Grinding, Inc., Wakefield, Mass., www.ferroceramic.com.

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Typical Boron Carbide (B_4C) Properties

Boron carbide is the hardest material after diamond, giving it outstanding wear resistance. Its mechanical properties, especially its fracture toughness, are low, limiting its application. However, it is used extensively for ballistic armor and blast nozzles. Boron carbide is also a neutron absorber, making it a primary choice for control rods and other nuclear applications.*

Properties	Units	Value
Physical		
Chemical Formula		B_4C
Density, ρ	g/cm^3	2.51
Color		black or dark gray*
Crystal Structure		hexagonal
Water Absorption	% @ room temperature (R.T.)	ng
Hardness	Vickers @ R.T. (GPa)	36
Hardness	Knoop (kg/mm^2)	ng
Mechanical		
Compressive Strength	GPa @ R.T.	2.9
Tensile Strength	MPa @ 980ÞC	155
Modulus of Elasticity	GPa @ R.T.	445
Flexural Strength (MOR)	MPa @ R.T.	375
Poisson's Ratio, υ	@ R.T.	0.19
Fracture Toughness, K_{Ic}	MPa x m$^{1/2}$	ng
Thermal		
Max. Use Temperature (melting point temperature)	ºC	2450
Thermal Shock Resistance	ΔT (ºC)	ng
Thermal Conductivity	W/m-K @ R.T.	28
Coefficient of Linear Thermal Expansion, α_l	10^{-6} K^{-1} (~25ºC through ±1000ºC)	5.54
Specific Heat, c_p	J kg^{-1} K^{-1} @ R.T.	945
Electrical		
Dielectric Constant	1 MHz @ R.T.	ng
Dielectric Strength	kV/mm	ng
Electrical Resistivity	Ωcm @ R.T.	ng

Source: NIST, www.ceramics.nist.gov/srd/scd/Z00093.htm#M1P1.

Note: Typical values usually are representative of trends of values commonly found for a general class of B_4C materials and are not necessarily the best or most appropriate values for any particular material. Exact properties will vary depending on the manufacturing method and part configuration, and can sometimes be tailored to meet specific requirements. Contact your component supplier for more detailed information. *Ceramic Industry* disclaims any and all liability from error, omissions or inaccuracies in the above chart.

* = information added by the editors; ng = not given in the original source

Typical Boron Nitride (BN) Properties

BN is made using a hot pressing process and comes as a lubricious white solid. It can be machined using standard carbide drills. Due to its crystal structure, BN is anisotropic electrically and mechanically. It exhibits a high electrical resistance, low dielectric constant and loss tangent, low thermal expansion, chemical inertness, and good thermal shock resistance. There are several different purity levels for this material. All offer very high thermal conductivity and stability in inert and reducing atmospheres up to 2800°C, and up to 850°C in oxidizing environments. Typical uses include vacuum components, low-friction seals, various electronic parts, nuclear applications and plasma arc insulators.

Properties	Units	Test	Value
Physical			
Chemical Formula			BN
Density, ρ	g/cm^3	ASTM C20	2.28
Color			white
Crystal Structure			hexagonal
Water Absorption	% @ room temperature (R.T.)	ASTM C373	0.0-1.0
Hardness	Mohs		2
Hardness	Knoop (kg/mm^2)	Knoop 100 g	25-205
Mechanical			
Compressive Strength	MPa @ R.T.	ASTM C773	23.5
Tensile Strength	MPa @ R.T.	ACMA Test #4	2.41 (1000ºC)
Modulus of Elasticity (Young's Modulus)	GPa	ASTM C848	675
Flexural Strength (MOR)	MPa @ R.T.	ASTM F417	51.8
Poisson's Ratio, υ		ASTM C818	0.05
Fracture Toughness, K_{Ic}	MPa x $m^{1/2}$	Notched Beam Test	2.6
Thermal			
Max. Use Temperature (in air)	ºC	No load cond.	985
Thermal Shock Resistance	ΔT (ºC)	Quenching	>1500
Thermal Conductivity	W/m-K @ R.T.	ASTM C408	20
Coefficient of Linear Thermal Expansion, α_l	μm/m-ºC (~25ºC through ±1000ºC)	ASTM C372	1.0-2.0
Specific Heat, c_p	cal/g-ºC @ R.T.	ASTM C351	0.19
Electrical			
Dielectric Constant	1 MHz @ R.T.	ASTM D150	4.08
Dielectric Strength	kV/mm	ASTM D116	374
Electrical Resistivity	Ωcm @ R.T.	ASTM D1829	10^{13}

Source: Ferro-Ceramic Grinding, Inc., Wakefield, Mass., www.ferroceramic.com.

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Typical Cordierite Properties

Cordierite is mainly a structural ceramic and is often used for kiln furniture due to its extremely good thermal shock resistance. Like other structural ceramic materials, cordierite also has good thermal and electrical insulating capabilities.

Properties	Units	Test	Value
Physical			
Chemical Formula			$2MgO\text{-}2Al_2O_3\text{-}5SiO_2$
Density, ρ	g/cm^3	ASTM C20	2.60
Color			tan
Crystal Structure			orthorhombic
Water Absorption	% @ room temperature (R.T.)	ASTM C373	0.02-3.2
Hardness	Mohs		7
Hardness	Knoop (kg/mm^2)	Knoop 100 g	—
Mechanical			
Compressive Strength	MPa @ R.T.	ASTM C773	350
Tensile Strength	MPa @ R.T.	ACMA Test #4	25.5
Modulus of Elasticity (Young's Modulus)	GPa	ASTM C848	70
Flexural Strength (MOR)	MPa @ R.T.	ASTM F417	117
Poisson's Ratio, υ		ASTM C818	0.21
Fracture Toughness, K_{Ic}	MPa x $m^{1/2}$	Notched Beam Test	—
Thermal			
Max. Use Temperature (in air)	ºC	No load cond.	1371
Thermal Shock Resistance	ΔT (ºC)	Quenching	500
Thermal Conductivity	W/m-K @ R.T.	ASTM C408	3.0
Coefficient of Linear Thermal Expansion, α_l	μm/m-ºC (~25ºC through ±1000ºC)	ASTM C372	1.7
Specific Heat, c_p	cal/g-ºC @ R.T.	ASTM C351	0.35
Electrical			
Dielectric Constant	1 MHz @ R.T.	ASTM D150	4.7
Dielectric Strength	kV/mm	ASTM D116	5.11
Electrical Resistivity	Ωcm @ R.T.	ASTM D1829	10^{14}

Source: Ferro-Ceramic Grinding, Inc., Wakefield, Mass., www.ferroceramic.com.

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Typical Graphite (C) Properties

Graphite oxidizes under (heated) use in an air (oxidizing) environment and therefore finds its use in inert and vacuum applications such as furnace insulation packages and semiconductors. This material has the same lubricious properties as boron nitride, thanks to the same crystal structure. In inert atmospheres, use temperatures can be upwards of 3500°C.

Properties	Units	Test	Value
Physical			
Chemical Formula			C
Density, ρ	g/cm^3	ASTM C20	2.28
Color			black
Crystal Structure			hexagonal
Water Absorption	% @ room temperature (R.T.)	ASTM C373	0.5-3.0
Hardness	Mohs		0.1-1.5
Hardness	Knoop (kg/mm^2)	Knoop 100 g	—
Mechanical			
Compressive Strength	MPa @ R.T.	ASTM C773	96
Tensile Strength	MPa @ R.T.	ACMA Test #4	4.8
Modulus of Elasticity (Young's Modulus)	GPa	ASTM C848	4.8
Flexural Strength (MOR)	MPa @ R.T.	ASTM F417	50
Poisson's Ratio, υ		ASTM C818	—
Fracture Toughness, K_{Ic}	MPa x m$^{1/2}$	Notched Beam Test	—
Thermal			
Max. Use Temperature (in air)	ºC	No load cond.	3650
Thermal Shock Resistance	ΔT (ºC)	Quenching	200-250
Thermal Conductivity	W/m-K @ R.T.	ASTM C408	24
Coefficient of Linear Thermal Expansion, α_l	μm/m-ºC (~25ºC through ±1000ºC)	ASTM C372	8.39
Specific Heat, c_p	cal/g-ºC @ R.T.	ASTM C351	0.16
Electrical			
Dielectric Constant	1 MHz @ R.T.	ASTM D150	—
Dielectric Strength	kV/mm	ASTM D116	—
Electrical Resistivity	Ωcm @ R.T.	ASTM D1829	7 x 10^{-3}

Source: Ferro-Ceramic Grinding, Inc., Wakefield, Mass., www.ferroceramic.com.

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Typical Mullite Properties

Mullite is an excellent structural material due to its high temperature stability, strength and creep resistance. It has a low dielectric constant and high electrical insulation capabilities. Typical applications include kiln furniture, furnace center tubes, heat exchange parts, heat insulation parts and rollers.

Properties	Units	Test	Value
Physical			
Chemical Formula			$3Al_2O_3$-SiO_2
Density, ρ	g/cm^3	ASTM C20	2.80
Color			tan
Crystal Structure			orthorhombic
Water Absorption	% @ room temperature (R.T.)	ASTM C373	0.0
Hardness	Mohs		8
Hardness	Knoop (kg/mm^2)	Knoop 100 g	1450
Mechanical			
Compressive Strength	MPa @ R.T.	ASTM C773	551
Tensile Strength	MPa @ R.T.	ACMA Test #4	103.5
Modulus of Elasticity (Young's Modulus)	GPa	ASTM C848	150
Flexural Strength (MOR)	MPa @ R.T.	ASTM F417	170
Poisson's Ratio, υ		ASTM C818	0.25
Fracture Toughness, K_{Ic}	MPa x $m^{1/2}$	Notched Beam Test	2.0
Thermal			
Max. Use Temperature (in air)	ºC	No load cond.	1700
Thermal Shock Resistance	ΔT (ºC)	Quenching	300
Thermal Conductivity	W/m-K @ R.T.	ASTM C408	3.5
Coefficient of Linear Thermal Expansion, α_l	µm/m-ºC (~25ºC through ±1000ºC)	ASTM C372	5.3
Specific Heat, c_p	cal/g-ºC @ R.T.	ASTM C351	0.23
Electrical			
Dielectric Constant	1 MHz @ R.T.	ASTM D150	6.0
Dielectric Strength	kV/mm	ASTM D116	9.8
Electrical Resistivity	Ωcm @ R.T.	ASTM D1829	10^{13}

Source: Ferro-Ceramic Grinding, Inc., Wakefield, Mass., www.ferroceramic.com.

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Typical Sapphire Properties

The advantages of sapphire as a design material are numerous. Extremely high use temperature, hardness, optical clarity, flexural strength and chemical resistance make it an increasingly popular choice. Applications include grocery store scanner windows, watch glasses, and countless semiconductor and aerospace/military applications.

Properties	Units	Test	Value
Physical			
Chemical Formula			α-Al_2O_3
Density, ρ	g/cm^3	ASTM C20	3.97
Color			white/transparent
Crystal Structure			trigonal
Water Absorption	% @ room temperature (R.T.)	ASTM C373	0.0
Hardness	Mohs		9
Hardness	Knoop (kg/mm^2)	Knoop 100 g	2200
Mechanical			
Compressive Strength	MPa @ R.T.	ASTM C773	2000
Tensile Strength	MPa @ R.T.	ACMA Test #4	250-400
Modulus of Elasticity (Young's Modulus)	GPa	ASTM C848	250-400
Flexural Strength (MOR)	MPa @ R.T.	ASTM F417	760-1035
Poisson's Ratio, υ		ASTM C818	0.29
Fracture Toughness, K_{Ic}	MPa x $m^{1/2}$	Notched Beam Test	1.89
Thermal			
Max. Use Temperature (in air)	ºC	No load cond.	~2000
Thermal Shock Resistance	ΔT (ºC)	Quenching	200
Thermal Conductivity	W/m-K @ R.T.	ASTM C408	40
Coefficient of Linear Thermal Expansion, α_l	µm/m-ºC (~25ºC through ±1000ºC)	ASTM C372	7.9-8.8
Specific Heat, c_p	cal/g-ºC @ R.T.	ASTM C351	0.18
Electrical			
Dielectric Constant	1 MHz @ R.T.	ASTM D150	9.3-11.4
Dielectric Strength	kV/mm	ASTM D116	15-50
Electrical Resistivity	Ωcm @ R.T.	ASTM D1829	10^{17}

Source: Ferro-Ceramic Grinding, Inc., Wakefield, Mass., www.ferroceramic.com.

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Typical Silicon Carbide (SiC) Properties

SiC is an artificial (man-made) mineral known for its very high hardness and abrasion resistance. Common applications include pump seals, valve components, and wear-intensive applications such as rollers and paper industry retainers.

Properties	Units	Test	Value
Physical			
Chemical Formula			α-SiC
Density, ρ	g/cm^3	ASTM C20	3.21
Color			dark gray
Crystal Structure			hexagonal
Water Absorption	% @ room temperature (R.T.)	ASTM C373	0.0
Hardness	Mohs		9-10
Hardness	Knoop (kg/mm^2)	Knoop 100 g	2800
Mechanical			
Compressive Strength	MPa @ R.T.	ASTM C773	1725-2500
Tensile Strength	MPa @ R.T.	ACMA Test #4	310
Modulus of Elasticity (Young's Modulus)	GPa	ASTM C848	476
Flexural Strength (MOR)	MPa @ R.T.	ASTM F417	324
Poisson's Ratio, υ		ASTM C818	0.19
Fracture Toughness, K_{Ic}	MPa x $m^{1/2}$	Notched Beam Test	4.0
Thermal			
Max. Use Temperature (in air)	ºC	No load cond.	1400
Thermal Shock Resistance	ΔT (ºC)	Quenching	350-500
Thermal Conductivity	W/m-K @ R.T.	ASTM C408	41
Coefficient of Linear Thermal Expansion, α_l	µm/m-ºC (~25ºC through ±1000ºC)	ASTM C372	5.12
Specific Heat, c_p	cal/g-ºC @ R.T.	ASTM C351	0.15
Electrical			
Dielectric Constant	1 MHz @ R.T.	ASTM D150	10.2
Dielectric Strength	kV/mm	ASTM D116	—
Electrical Resistivity	Ωcm @ R.T.	ASTM D1829	10^8

Source: Ferro-Ceramic Grinding, Inc., Wakefield, Mass., www.ferroceramic.com.

Note: Although we have no reason to doubt the accuracy of the data presented, this information is offered for comparison only. Exact properties will vary depending on the manufacturing method and part configuration, and can sometimes be tailored to meet specific requirements. Contact your component supplier for more detailed information. Ferro-Ceramic Grinding and *Ceramic Industry* disclaim any and all liability from error, omissions or inaccuracies in the above chart.

Terminology Commonly Associated with Silicon Carbide Processing

Recrystallized Silicon Carbide (RXSIC, ReSIC, RSIC, R-SIC). The starting raw material is silicon carbide. No densification aids are used. The green compacts are heated to over 2200ºC for final consolidation. The resulting material has about 25% porosity, which limits its mechanical properties; however, the material can be very pure. The process is very economical.

Reaction Bonded Silicon Carbide (RBSIC). The starting raw materials are silicon carbide plus carbon. The green component is then infiltrated with molten silicon above 1450ºC with the reaction: SiC + C + Si -> SiC. The microstructure generally has some amount of excess silicon, which limits its high-temperature properties and corrosion resistance. Little dimensional change occurs during the process; however, a layer of silicon is often present on the surface of the final part.

Nitride Bonded Silicon Carbide (NBSIC, NSIC). The starting raw materials are silicon carbide plus silicon powder. The green compact is fired in a nitrogen atmosphere where the reaction $SiC + 3Si + 2N_2$ -> $SiC + Si_3N_4$ occurs. The final material exhibits little dimensional change during processing. The material exhibits some level of porosity (typically about 20%).

Direct Sintered Silicon Carbide (SSIC). Silicon carbide is the starting raw material. Densification aids are boron plus carbon, and densification occurs by a solid-state reaction process above 2200ºC. Its high-temperature properties and corrosion resistance are superior because of the lack of a glassy second phase at the grain boundaries.

Liquid Phase Sintered Silicon Carbide (LSSIC). Silicon carbide is the starting raw material. Densification aids are yttrium oxide plus aluminum oxide. Densification occurs above 2100ºC by a liquid-phase reaction and results in a glassy second phase. The mechanical properties are generally superior to SSIC, but the high-temperature properties and the corrosion resistance are not as good.

Hot Pressed Silicon Carbide (HPSIC). Silicon carbide powder is used as the starting raw material. Densification aids are generally boron plus carbon or yttrium oxide plus aluminum oxide. Densification occurs by a simultaneous application of mechanical pressure and temperature inside a graphite die cavity. The shapes are simple plates. Low amounts of sintering aids can be used. Mechanical properties of hot pressed materials are used as the baseline against which other processes are compared. Electrical properties can be altered by changes in the densification aids.

CVD Silicon Carbide (CVDSIC). This material is formed by a chemical vapor deposition (CVD) process involving the reaction: CH_3SiCl_3 -> $SiC + 3HCl$. The reaction is carried out under a H_2 atmosphere with the SiC being deposited onto a graphite substrate. The process results in a very high-purity material; however, only simple plates can be made. The process is very expensive because of the slow reaction times.

Chemical Vapor Composite Silicon Carbide (CVCSiC). This process starts with a proprietary graphite precursor that is machined into near-net shapes in the graphite state. The conversion process subjects the graphite part to an *in situ* vapor solid-state reaction to produce a polycrystalline, stoichiometrically correct SiC. This tightly controlled process allows complicated designs to be produced in a completely converted SiC part that has tight tolerance features and high purity. The conversion process shortens the normal production time and reduces costs over other methods.*

Source (except where noted): Ceradyne Inc., Costa Mesa, Calif., www.ceradyne.com.

*Source: Poco Graphite, Inc., Decatur, Texas, www.poco.com.

Note: The above information is for general reference only and is not intended to represent the processes used by all SiC suppliers. Consult your supplier for specific SiC processing information. Ceradyne, Poco Graphite and *Ceramic Industry* disclaim any and all liability from error, omissions or inaccuracies in the above chart.

Typical Silicon Nitride (Si_3N_4) Properties

Si_3N_4 has the strongest covalent bond properties next to silicon carbide. It is used as a high-temperature structural ceramic due to its superior heat resistance, strength and hardness. It also offers excellent wear and corrosion resistance. Various types are available (sintered, CVD, HP), and they are used for different purposes. Main applications include heat exchangers, rotors, nozzles, bearings, valves, chemical plant parts, engine components and armor.

Properties	Units	Test	Value
Physical			
Chemical Formula			Si_3N_4
Density, ρ	g/cm^3	ASTM C20	3.31
Color			dark gray
Crystal Structure			hexagonal (alpha & beta)
Water Absorption	% @ room temperature (R.T.)	ASTM C373	0.0
Hardness	Mohs		9
Hardness	Knoop (kg/mm^2)	Knoop 100 g	2200
Mechanical			
Compressive Strength	MPa @ R.T.	ASTM C773	689-2760
Tensile Strength	MPa @ R.T.	ACMA Test #4	360-434
Modulus of Elasticity (Young's Modulus)	GPa	ASTM C848	317
Flexural Strength (MOR)	MPa @ R.T.	ASTM F417	679-896
Poisson's Ratio, υ		ASTM C818	0.23
Fracture Toughness, K_{Ic}	MPa x $m^{1/2}$	Notched Beam Test	5.0-8.0
Thermal			
Max. Use Temperature (in air)	ºC	No load cond.	1500
Thermal Shock Resistance	ΔT (ºC)	Quenching	750
Thermal Conductivity	W/m-K @ R.T.	ASTM C408	27
Coefficient of Linear Thermal Expansion, α_l	µm/m-ºC (~25ºC through ±1000ºC)	ASTM C372	3.4
Specific Heat, c_p	cal/g-ºC @ R.T.	ASTM C351	0.17
Electrical			
Dielectric Constant	1 MHz @ R.T.	ASTM D150	7.0
Dielectric Strength	kV/mm	ASTM D116	17.7
Electrical Resistivity	Ωcm @ R.T.	ASTM D1829	10^{13}

Source: Ferro-Ceramic Grinding, Inc., Wakefield, Mass., www.ferroceramic.com.

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Terminology Commonly Associated with Silicon Nitride Processing

Reaction Bonded Silicon Nitride (RBSN). Starting raw material is silicon. Formed by the reaction: $3Si+2N_2$ -> Si_3N_4 at 1400ºC. No sintering additives are used, and no volume change occurs during the reaction. The resulting material is generally 99% pure with about 25% porosity.

Sintered Silicon Nitride (SSN). Starting raw material is silicon nitride powder. Sintering additives such as yttrium oxide and aluminum oxide are used. Sintering takes place at about 1800ºC, depending on the amount of additives employed and 1 atmosphere of pressure. Densities are generally in the 98% range with strengths in the 600-700 MPa range.

Sintered Reaction Bonded Silicon Nitride (SRBSN). The starting raw material is silicon. Sintering additives such as yttrium oxide and aluminum oxide are used. The firing process is done in two stages. First is the reaction bonding process: $3Si+2N_2$ -> Si_3N_4 at 1400ºC, and then sintering at >1800ºC at 1 atmosphere. Properties are similar to SSN. The advantages are low-cost raw materials and lower sintering shrinkages that help in dimensional control.

Gas Pressure Sintered Silicon Nitride (GPS-SIN). Similar to SSN, except the sintering is performed at 20 to 100 atmospheres. The densities are generally over 99%, and the mechanical properties are superior. Lower amounts of sintering additives can be used.

Gas Pressure Sintered Reaction Bonded Silicon Nitride (GPS-SRBSN). A combination of SRBSN and GPS-SIN. This fabrication process offers the best combination of mechanical properties and low-cost processing.

Hot Pressed Silicon Nitride (HPSN). Silicon nitride powder is used as the starting raw material. Densification aids are generally magnesium or yttrium oxide plus aluminum oxide. Densification occurs by a simultaneous application of mechanical pressure and temperature inside a graphite die cavity. The shapes are simple plates, and low amounts of sintering aids can be used. Mechanical properties of hot pressed materials are used as the baseline against which other processes are compared.

Hot Isostatic Pressed Silicon Nitride (HIPSN). Similar to GPS-SIN, except that the pressures are higher—1000 to 2000 atmospheres. The sintering aids are similar to HPSN. Ultimate mechanical properties are achieved. This is the highest-cost near-net-shape processing route.

Source: Ceradyne Inc., Costa Mesa, Calif., www.ceradyne.com.

Note: The above information is for general reference only and is not intended to represent the processes used by all Si_3N_4 suppliers. Consult your supplier for specific Si_3N_4 processing information. Ceradyne and *Ceramic Industry* disclaim any and all liability from error, omissions or inaccuracies in the above chart.

Typical Steatite L-5* Properties

This material has applications where insulating and temperature resistance are a concern. Many insulators and other standoffs are made of steatite. The cost of this material is relatively low when compared with other ceramic materials.

Properties	Units	Test	Value
Physical			
Chemical Formula			$H_2Mg_3(SiO_3)4$
Density, ρ	g/cm^3	ASTM C20	2.71
Color			buff
Crystal Structure			hexagonal
Water Absorption	% @ room temperature (R.T.)	ASTM C373	0.0-0.2
Hardness	Mohs		7.5
Hardness	Knoop (kg/mm^2)	Knoop 100 g	—
Mechanical			
Compressive Strength	MPa @ R.T.	ASTM C773	621
Tensile Strength	MPa @ R.T.	ACMA Test #4	62
Modulus of Elasticity (Young's Modulus)	GPa	ASTM C848	138
Flexural Strength (MOR)	MPa @ R.T.	ASTM F417	140
Poisson's Ratio, υ		ASTM C818	—
Fracture Toughness, K_{Ic}	MPa x $m^{1/2}$	Notched Beam Test	—
Thermal			
Max. Use Temperature (in air)	ºC	No load cond.	1425
Thermal Shock Resistance	ΔT (ºC)	Quenching	190
Thermal Conductivity	W/m-K @ R.T.	ASTM C408	2.9
Coefficient of Linear Thermal Expansion, α_l	μm/m-ºC (~25ºC through ±1000ºC)	ASTM C372	7.0
Specific Heat, c_p	cal/g-ºC @ R.T.	ASTM C351	0.22
Electrical			
Dielectric Constant	1 MHz @ R.T.	ASTM D150	6.3
Dielectric Strength	kV/mm	ASTM D116	9.3
Electrical Resistivity	Ωcm @ R.T.	ASTM D1829	10^4

Source: Ferro-Ceramic Grinding, Inc., Wakefield, Mass., www.ferroceramic.com.

*Two common steatite grades are L-3, used for general applications, and L-5, typically used for applications in which low electrical loss is critical. A third grade, L-4, can also be obtained from some suppliers. For specific material properties, contact your steatite supplier.

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Typical Titanium Diboride (TiB_2) Properties

The values presented here are trend values derived for polycrystalline TiB_2 specimens with a purity (mass fraction of TiB_2) of at least 98%, a density of (4.5±0.1) g/cm³, and a mean grain size of (9±1) µm. Estimated combined relative standard uncertainties of the property values are listed in the last column. For example, a value of 3.0 with u_r = 5% is equivalent to 3.0±0.15. A question mark (?) for u_r means the uncertainty could not be determined with the available data.

Property [unit]	20°C	500°C	1000°C	1200°C	1500°C	2000°C	u_r [%][a]
Bulk Modulus [GPa]	240	234	228				24
Compressive Strength [GPa]	1.8						?
Creep Rate[b] [10^{-9} s^{-1}]					0.005	3.1	20
Density[c] [g/cm³]	4.500	4.449	4.389	4.363	4.322	4.248	0.07
Elastic Modulus [GPa]	565	550	534				5
Flexural Strength [MPa]	400	429	459	471	489		25
Fracture Toughness [MPa $m^{1/2}$]	6.2						15
Friction Coefficient[d]	0.9	0.9	0.6				15
Hardness[e] [GPa]	25	11	4.6				12
Lattice Parameter[f] a [Å]	3.029	3.039	3.052	3.057	3.066	3.082	0.03
Lattice Parameter[f] c [Å]	3.229	3.244	3.262	3.269	3.281	3.303	0.04
Poisson's Ratio	0.108	0.108	0.108				70
Shear Modulus [GPa]	255	248	241				5
Sound Velocity, longitudinal [km/s]	11.4	11.3	11.2				5
Sound Velocity, shear [km/s]	7.53	7.47	7.40				3
Specific Heat [J/kg·K]	617	1073	1186	1228	1291	1396	1.5
Thermal Conductivity [W/m·K]	96	81	78.1	77.8			6
Thermal Diffusivity [cm²/s]	0.30	0.17	0.149	0.147			6
Thermal Expansion[g], a axis [$10^{-6}K^{-1}$]	6.4	7.0	7.7	7.9	8.3	8.9	7
Thermal Expansion[g], c axis [$10^{-6}K^{-1}$]	9.2	9.8	10.4	10.6	11.0	11.6	5
Thermal Expansion[h], average [$10^{-6}K^{-1}$]	7.4	7.9	8.6	8.8	9.2	9.8	6
Wear Coefficient[d] [10^{-3}]	1.7						24
Weibull Modulus	11[i]						?

a) Estimated combined relative standard uncertainty expressed as a percentage; b) Flexure creep rate at 100 MPa for density = 4.29 g/cm³, grain size = 18 µm; c) Single crystal density; d) Density = 4.32 g/cm³, grain size = 2 µm, v_{slide}/P_{load} = 0.2 m s^{-1} MPa^{-1}; e) Vickers indentation, load = 5 N; f) Single crystal, hexagonal unit cell; g) Single crystal, for cumulative expansion from 293 K (20ºC), CTE = $(1/x_{293})(x-x_{293})/(T/K - 293)$, x = a or c; h) Bulk average, for cumulative expansion from 20ºC; i) Three values have been reported in the literature: 8, 11 and 29.

Source: NIST, www.ceramics.nist.gov/srd/summary/scdtib2.htm.

Note: The data presented here were derived from reported values for a narrowly defined material specification. Using trend analysis, property relations, and interpolation methods, the self-consistent trend values for the properties of polycrystalline TiB_2 were determined for a mass fraction of TiB_2 of at least 98%, a density of (4.5±0.1) g/cm³, and a mean grain size of (9±1) µm. *Ceramic Industry* disclaims any and all liability from error, omissions or inaccuracies in the above chart.

Typical Tungsten Carbide (WC) Properties

Tungsten carbide is generally made with high percentages of either cobalt or nickel as a second, metallic phase. These ceramic metals, or "cermets," have wide use as cutting tools and other metals-forming tools. Pure tungsten carbide can be made as an advanced technical ceramic using a high-temperature hot isostatic pressing process. This material has very high hardness and wear resistance, and is used for abrasive water jet nozzles; however, its weight limits its use in many applications.*

Properties	Units	Value
Physical		
Chemical Formula		WC
Density, ρ	g/cm^3	13.0-15.3
Color		metallic gray*
Crystal Structure		ng
Water Absorption	% @ room temperature (R.T.)	ng
Hardness	Vickers @ R.T. (GPa)	ng
Hardness	Knoop (kg/mm^2)	1307-2105*
Mechanical		
Compressive Strength	GPa @ R.T.	3.10-5.86
Tensile Strength	MPa @ 980ÞC	ng
Modulus of Elasticity	GPa @ R.T.	483-641
Flexural Strength (MOR)	MPa @ R.T.	ng
Poisson's Ratio, υ	@ R.T.	ng
Fracture Toughness, K_{Ic}	MPa x $m^{1/2}$	ng
Thermal		
Max. Use Temperature (melting point temperature)	ºC	ng
Thermal Shock Resistance	ΔT (ºC)	ng
Thermal Conductivity	W/m-K @ R.T.	71-121
Coefficient of Linear Thermal Expansion, α_l	10^{-6} K^{-1} (~25ºC through ±1000ºC)	5.9
Specific Heat, c_p	J kg^{-1} K^{-1} @ R.T.	945
Electrical		
Dielectric Constant	1 MHz @ R.T.	ng
Dielectric Strength	kV/mm	ng
Electrical Resistivity	Ωcm @ R.T.	ng

Source: NIST, www.ceramics.nist.gov/srd/scd/Z00093.htm#M3P1.

Note: Typical values usually are representative of trends of values commonly found for a general class of WC materials and are not necessarily the best or most appropriate values for any particular material. Exact properties will vary depending on the manufacturing method and part configuration, and can sometimes be tailored to meet specific requirements. Contact your component supplier for more detailed information. *Ceramic Industry* disclaims any and all liability from error, omissions or inaccuracies in the above chart.

* = information added by the editors; ng = not given in the original source

Typical Zirconia (ZrO_2) Properties

Zirconia ceramics have a martensite-type transformation mechanism of stress induction, which provides the ability to absorb great amounts of stress relative to other ceramic materials. It exhibits the highest mechanical strength and toughness at room temperature. Zirconia has excellent wear, chemical and corrosion resistance, and low thermal conductivity. Common applications include extrusion dies, wire and pipe extension, guide and other wear rollers, pressure valves, and bearing materials.

Properties	Units	Test	Value
Physical			
Chemical Formula			ZrO_2
Density, ρ	g/cm^3	ASTM C20	6.04
Color			white
Crystal Structure			tetragonal
Water Absorption	% @ room temperature (R.T.)	ASTM C373	0.0
Hardness	Mohs		6.5
Hardness	Knoop (kg/mm^2)	Knoop 100 g	1600
Mechanical			
Compressive Strength	MPa @ R.T.	ASTM C773	2500
Tensile Strength	MPa @ R.T.	ACMA Test #4	248
Modulus of Elasticity (Young's Modulus)	GPa	ASTM C848	207
Flexural Strength (MOR)	MPa @ R.T.	ASTM F417	900
Poisson's Ratio, υ		ASTM C818	0.32
Fracture Toughness, K_{Ic}	MPa x $m^{1/2}$	Notched Beam Test	13.0
Thermal			
Max. Use Temperature (in air)	ºC	No load cond.	500
Thermal Shock Resistance	ΔT (ºC)	Quenching	280-360
Thermal Conductivity	W/m-K @ R.T.	ASTM C408	2.7
Coefficient of Linear Thermal Expansion, α_l	µm/m-ºC (~25ºC through ±1000ºC)	ASTM C372	11.0
Specific Heat, c_p	cal/g-ºC @ R.T.	ASTM C351	0.10
Electrical			
Dielectric Constant	1 MHz @ R.T.	ASTM D150	26 @ 100kHz
Dielectric Strength	kV/mm	ASTM D116	9.0
Electrical Resistivity	Ωcm @ R.T.	ASTM D1829	$>10^4$

Source: Ferro-Ceramic Grinding, Inc., Wakefield, Mass., www.ferroceramic.com.

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