Introduction to Ceramic Materials

Ceramics are compounds between metallic and nonmetallic elements; they are most frequently oxides, nitrides, and carbides. Eg. aluminum oxide (or alumina,Al_2O_3), silicon dioxide (or *silica,* SiO_2), silicon carbide (SiC), silicon nitride (Si_3N_4).

The term ceramics comes from the Greek word keramikos which means 'burnt stuff'.

A wide-ranging group of materials whose ingredients are clays, sand and felspar

With regard to mechanical behavior, ceramic materials are

- relatively stiff and strong—stiffnesses and strengths are comparable to metals
- very hard and extremely brittle (lack ductility)
- highly susceptible to fracture
- low electrical conductivities
- more resistant to high temperatures
- transparent, translucent, or opaque
- oxide ceramics (e.g., Fe_3O_4) exhibit magnetic behavior

Ceramics greatly differ in their basic composition. The properties of ceramic materials also vary greatly due to differences in bonding, and thus found a wide range of engineering applications.

Classification of ceramics based on their specific applications and composition are two most important ways among many.

Based on their composition, ceramics are classified as:

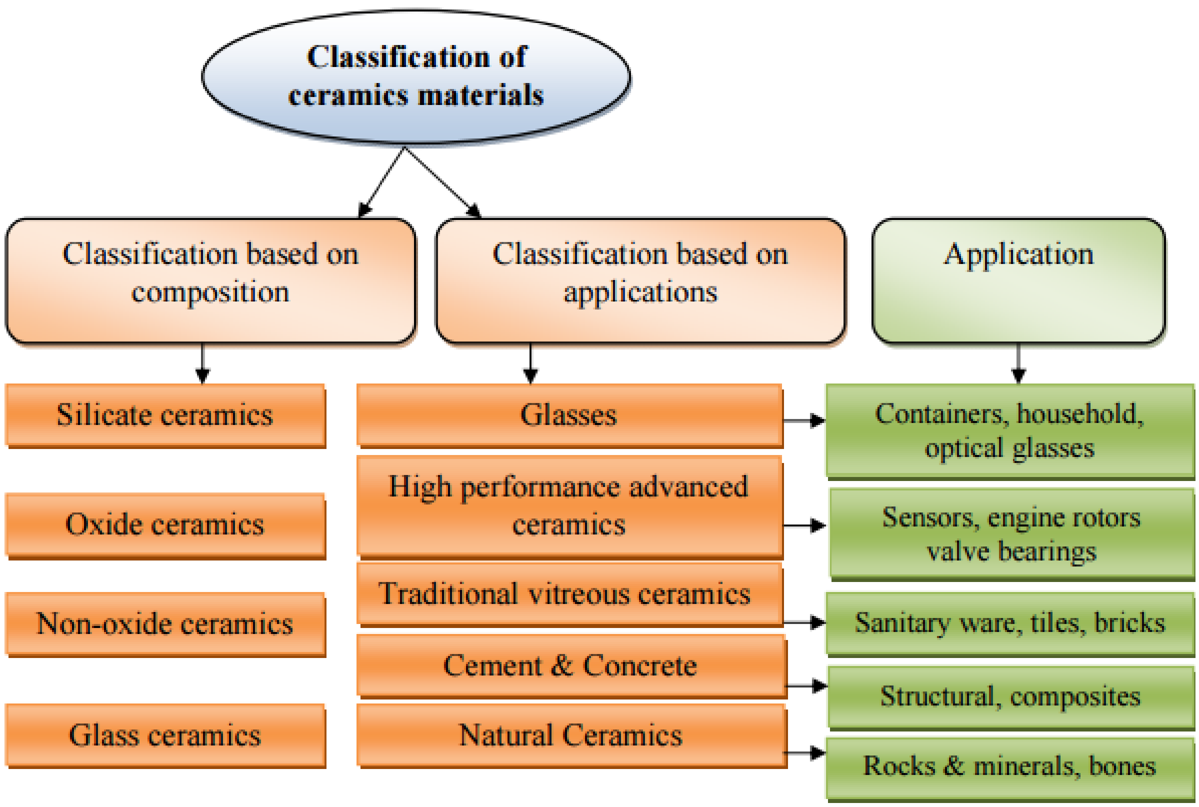
- Oxides, Carbides,
- Nitrides,
- Sulfides and Fluorides, etc.

The other important classification of ceramics is based on their application, such as:

- Glasses,
- Clay products,
- Refractories and Abrasives

- Ceramics once referred purely to pottery and to articles made by firing materials extracted from Earth. Today, the term has a much broader definition. Ceramics are generally thought of as inorganic and nonmetallic solids with a range of useful properties, including very high hardness and strength, extremely high melting points, and good electrical and thermal insulation.

- The best-known ceramics are pottery, glass, brick, porcelain, and cement. But the general definition of a ceramic—a nonmetallic and inorganic solid—is so broad that it covers a much wider range of materials. At one end of the scale, ceramics include simple materials such as graphite and diamond, made up from different crystalline arrangements of the element carbon. But at the other end of the scale, complex crystals of yttrium, barium, copper, and oxygen make up the advanced ceramics used in so-called high-temperature superconductors (materials with almost no electrical resistance). Most ceramics fall somewhere between these extremes.



Glasses:

Glasses are a familiar group of ceramics – containers, windows, mirrors, lenses, etc. They are non-crystalline silicates containing other oxides, usually CaO, Na2O, K2O and Al2O3 which influence the glass properties and its color. Typical property of glasses that is important in engineering applications is its response to heating. There is no definite temperature at which the liquid transforms to a solid as with crystalline materials. A specific temperature, known as glass transition temperature or fictive temperature is defined based on viscosity above which material is named as super cooled liquid or liquid, and below it is termed as glass.

Clay products:

Clay is the one of most widely used ceramic raw material. It is found in great abundance and popular because of ease with which products are made. Clay products are mainly two kinds – structural products (bricks, tiles, sewer pipes) and whitewares (porcelain, chinaware, pottery, etc.).

Refractories:

These are described by their capacity to withstand high temperatures without melting or decomposing; and their inertness in severe environments. Thermal insulation is also an important functionality of refractories.

Abrasive ceramics:

These are used to grind, wear, or cut away other material. Thus the prime requisite for this group of materials is hardness or wear resistance in addition to high toughness. As they may also exposed to high temperatures, they need to exhibit some refractoriness. Diamond, silicon carbide, tungsten carbide, silica sand, aluminium oxide / corundum are some typical examples of abrasive ceramic materials.

Cements:

Cement, plaster of paris and lime come under this group of ceramics. The characteristic property of these materials is that when they are mixed with water, they form slurry which sets subsequently and hardens finally. Thus it is possible to form virtually any shape. They are also used as bonding phase, for example between construction bricks.

General Classification

In general, ceramic materials used for engineering applications can be divided into two groups: traditional ceramics, and the engineering ceramics. Typically, traditional ceramics are made from three basic components: clay, silica (flint) and feldspar. For example bricks, tiles and porcelain articles. However, engineering ceramics consist of highly pure compounds of aluminium oxide (Al_2O_3), silicon carbide (SiC) and silicon nitride (Si_3N_4).

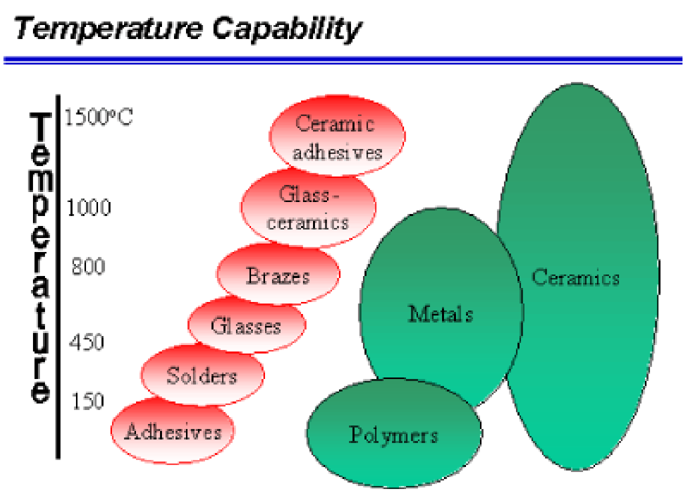
A ceramic material is an inorganic, non-metallic material and is often crystalline. Traditional ceramics are basically clays. The earliest application was in pottery. Most recently, different types of ceramics used are alumina, silicon carbide etc. Latest advancements are in the bio-ceramics with examples being dental implants and synthetic bones.

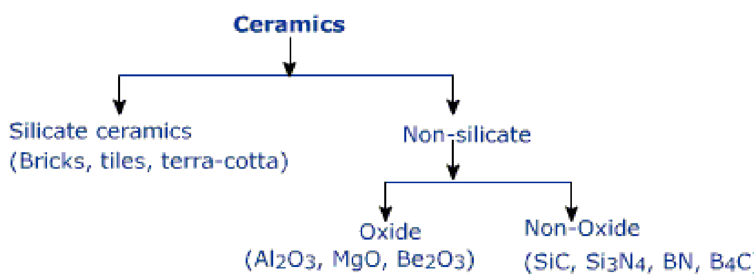
Applications

- Pottery products, sanitary ware, floor and roof tiles
- Crucibles, kiln linings, other refractories
- High end applications such as in ceramic matrix composites, tiles in space shuttle, bullet proof jackets, disk brakes, ball bearing applications, bio-ceramics

Classification of ceramics materials

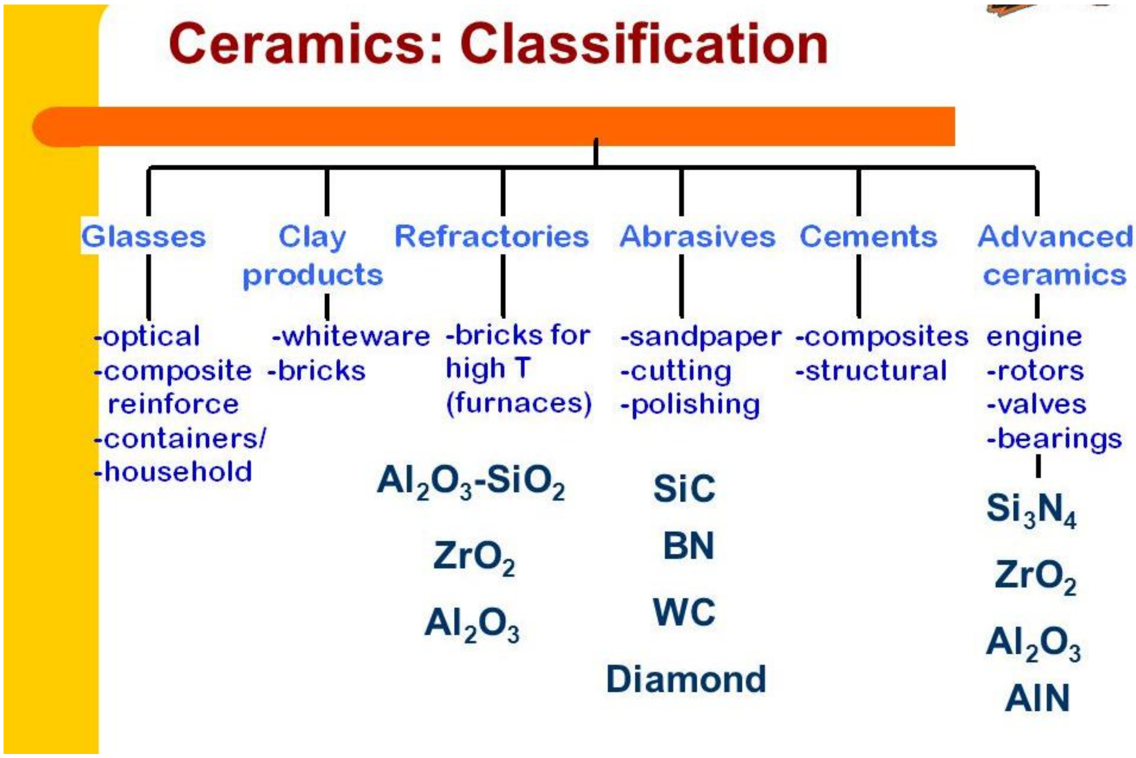
Ceramics can be classified in diverse ways i.e. there are number of ways to classify the ceramic materials. Most commonly, the ceramics can be classified on the following basis: - Classification based on composition - Classification based on applications





Ceramics are of the following types:
a) Silicate - Bricks, tiles, terracotta, dinnerware
b) Non-silicate - oxide and non-oxide ceramics
(i) Oxide ceramics - Al_2O_3, MgO, Be_2O_3 (beryllia)
(ii) Non-oxide ceramics - SiC, Si_3 N_4, BN, B_4C.

Classification based on composition



(i) Silicate ceramics

Silicates are materials generally having composition of silicon and oxygen (figure 2a). Four large oxygen (o) atoms surround each smaller silicon (Si) atom as shown in figure 2b. The main types of silicate ceramics are based either on alumosilicates or on magnesium silicates. Out of these two, the former include clay-based ceramics such as porcelain, earthenware, stoneware, bricks etc. while the latter consists of talc-based technical ceramics such as steatite, cordierite and forsterite ceramics. Silicate ceramics are traditionally categorized into coarse or fine and, according to water absorption, into dense (< 2 % for fine and < 6 % for coarse) or porous ceramics (> 2% and > 6 %, respectively).

	Composition (wt%)					
Ceramic	SiO_2	Al_2O_3	K_2O	Mg O	CaO	Othe r
Silica refractory	96					4
Fireclay refractory	50-70	45-25				5
Mullite refractory	28	72				-
Electrical porcelain	61	32	6			1
Steatite porcelain	64	5		30		1
Portland cement	25	9			64	2

Composition of some silicate ceramics

(ii) Oxide ceramics

Oxide ceramics include alumina, zirconia, silica, aluminium silicate, magnesia and other metal oxide based materials. These are non-metallic and inorganic compounds by nature that include oxygen, carbon, or nitrogen. Oxide ceramics possess the following properties: (a) High melting points (b) Low wear resistance (c) An extensive collection of electrical properties.

These types of ceramics are available with a variety of special features. For example, glazes and protective coatings seal porosity, improved water or chemical resistance, and enhanced joining to metals or other materials. Oxide ceramics are used in a wide range of applications, which include materials and chemical processing, radio frequency and microwave applications, electrical and high voltage power applications and foundry and metal processing. Aluminium oxide (Al2O3) is the most important technical oxide ceramic material. This synthetically manufactured material consists of aluminium oxide ranging from 80 % to more than 99 %.

Figure 3 (a) Aluminium oxide

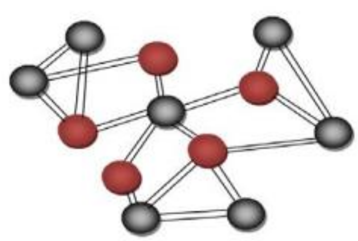


Figure 3 (b) Structure of aluminium oxide

(iii) Non-Oxide ceramics

The use of non-oxide ceramics has enabled extreme wear and corrosion problems to be overcome, even at high temperature and severe thermal shock conditions. These types of ceramics find its application in different spheres such as pharmaceuticals, oil and gas industry, valves, seals, rotating parts, wear plates, location pins for projection welding, cutting tool tips, abrasive powder blast nozzles, metal forming tooling etc.

- ✓ Aluminum nitride (AlN) is the only technical ceramic material that features an extremely interesting combination of very high thermal conductivity and excellent electrical insulation properties. This makes aluminum nitride predestined for use in power and microelectronics applications. For example, it is used as a circuit carrier (substrate) in semiconductors or as a heat-sink in LED lighting technology or high-power electronics.
- ✓ Silicon nitrides (Si3N4) feature an excellent combination of material properties. They are nearly as light as silicon carbide (SiC), but their microstructure gives them excellent thermal shock resistance and their high fracture toughness makes them resistant to impacts and shocks. The combination of good tribological properties and excellent fracture toughness makes silicon nitride ceramics predestined for applications as balls and rolling elements for light and extremely precise bearings, heavy-duty ceramic forming tools and automotive components subject to high stress. And the good thermal shock resistance and high temperature resistance is exploited in welding processes.
- ✓ Silicon carbide (SiC) behaves almost like a diamond. It is not only the lightest, but also the hardest ceramic material and has excellent thermal conductivity, low thermal expansion and is very resistant to acids and lyes. These material properties make silicon carbide predestined for use as a construction material. Silicon carbide masters corrosion, abrasion and erosion as skillfully as it stands up to frictional wear. Components are used in chemical plants, mills, expanders and extruders or as nozzles,

Traditional Ceramics

Segment	Products
Structural clay products	Brick, sewer pipe, roofing tile, clay floor and wall tile (i.e., quarry tile), flue linings
Whitewares	Dinnerware, floor and wall tile, sanitaryware (vitreous china plumbing fixtures), electrical porcelain, decorative ceramics
Refractories	Brick and monolithic products used in iron and steel, non-ferrous metals, glass, cements, ceramics, energy conversion, petroleum, and chemicals industries, kiln furniture used in various industries
Glasses	Flat glass (windows), container glass (bottles), pressed and blown glass (dinnerware), glass fibers (home insulation)
Abrasives	Natural (garnet, diamond, etc.) and synthetic (silicon carbide, diamond, fused alumina, etc.) abrasives are used for grinding
Cements	Concrete roads, bridges, buildings, dams, residential sidewalks, bricks/blocks

Advanced Ceramics

Segment	Products
Automotive	Diesel engine cam rollers, fuel pump rollers, brakes, clutches, spark plugs, sensors, filters, windows, thermal insulation, emissions control, heaters, igniters, glass fiber composites for door chassis and other components
Aerospace	Thermal insulation, space shuttle tiles, wear components, combustor liners, turbine blades/rotors, fire detection feedthrus, thermocouple housings, aircraft instrumentation and control systems, satellite positioning equipment, ignition systems, instrument displays and engine monitoring equipment, nose caps, nozzle jet vanes, engine flaps
Bio-materials	Alumina and zirconia based ceramics are used in dental applications, Hydroxyapatite

Chemical/ petrochemical	Thermocouple protection tubes, tube sheet boiler ferrules, catalysts, catalyst supports, pumping components, rotary seals
Coatings	Engine components, cutting tools, industrial wear parts, biomedical implants, anti-reflection, optical, self-cleaning coatings for building materials
Electrical/electronic	Capacitors, insulators, substrates, integrated circuit packages, piezoelectrics, transistor dielectrics, magnets, cathodes, superconductors, high voltage bushings, antennas, sensors, accelerator tubes for electronic microscopes, substrates for hard disk drives
Environmental	Solid oxide fuel cells, gas turbine components, measuring wheels/balls for check valves (oilfields), nuclear fuel storage, hot gas filters (coal plants), solar cells, heat exchangers, isolator flanges for nuclear fusion energy research, solar-hydrogen technology, glass fiber reinforcements for wind turbine blades
Homeland security/military	Particulate/gas filters, water purification membranes, catalysts, catalyst supports, sulfur removal/recovery, molecular sieves

1. GLASS–CERAMICS

Most inorganic glasses can be made to transform from a noncrystalline state to one that is crystalline by the proper high-temperature heat treatment. This process is called **crystallization,** and the product is a fine-grained polycrystalline material which is often called a **glass–ceramic.**

Glass ceramics These are basically polycrystalline material manufactured through the controlled crystallization of base glass. Glass-ceramic materials share many common characteristics with both glasses and ceramics. Glass-ceramics possess an amorphous phase and more than one crystalline phases. These are produced by a controlled crystallization procedure. Glass-ceramics holds the processing advantage of glass and has special characteristics of ceramics. Glass-ceramics yield an array of materials with interesting properties like zero porosity, fluorescence, high strength, toughness, low or even negative thermal expansion, opacity, pigmentation, high temperature stability, low dielectric constant, machinability, high chemical durability, biocompatibility, superconductivity, isolation capabilities and high resistivity. These properties can be altered by controlling composition and by controlled heat treatment of the base glass.

The formation of these small glass-ceramic grains is, in a sense, a phase transformation, which involves nucleation and growth stages.

- Main ingredient is Silica (SiO2)
- If cooled very slowly will form crystalline structure.
- If cooled more quickly will form amorphous structure consisting of disordered and linked chains of Silicon and Oxygen atoms.
- This accounts for its transparency as it is the crystal boundaries that scatter the light, causing reflection.
- Glass can be tempered to increase its toughness and resistance to cracking.

Three common types of glass:

- *Soda-lime glass* - 95% of all glass, windows containers etc.
- *Lead glass* - contains lead oxide to improve refractive index
- *Borosilicate* - contains Boron oxide, known as Pyrex

Properties of Glass–Ceramics

Glass-ceramic materials have been designed to have the following characteristics:

- relatively high mechanical strengths;
- low coefficients of thermal expansion (to avoid thermal shock);
- relatively high temperature capabilities;
- good dielectric properties (for electronic packaging applications);
- good biological compatibility.
- some may be made optically transparent; others are opaque.
- Easy fabrication
- conventional glass-forming techniques may be used conveniently in the mass production of nearly pore-free ware.

Composition	*Property - Glass Ceramics*	*Use*
MgO, Al_2O_3, SiO_2	Insulator with high mechanical strength at high temperatures	Spark plug insulators
$CaSiO_3$, $CaMgSi_2O_6$, $CaAl_2Si_2O_8$	Wear resistant	Building materials
$Li_2Si_2O_5$	Resistant to thermal shock	Nose cones on rockets, cookware

Applications

The most common uses for these materials are as ovenware, tableware, oven windows, and rangetops—primarily because of their strength and excellent resistance to thermal shock.

They also serve as electrical insulators and as substrates for printed circuit boards, are used for architectural cladding, and for heat exchangers and regenerators.

2. CLAY–CERAMICS

When mixed in the proper proportions, clay and water form a plastic mass that is very amenable to shaping. The formed piece is dried to remove some of the moisture, after which it is fired at an elevated temperature to improve its mechanical strength.

Most of the clay-based products fall within two broad classifications: the **structural clay products** and the **whitewares.**

Structural clay products include building bricks, tiles, and sewer pipes—applications in which structural integrity is important. The whiteware ceramics become white after the high-temperature **firing.** Included in this group are porcelain, pottery, tableware, china, and plumbing fixtures (sanitary ware). In addition to clay, many of these products also contain nonplastic ingredients, which influence the changes that take place during the drying and firing processes, and the characteristics of the finished piece.

3. REFRACTORY–CERAMICS

Another important class of ceramics that are utilized in large tonnages is the **refractory ceramics.** The salient properties of these materials include the capacity to withstand high temperatures without melting or decomposing, and the capacity to remain unreactive and inert when exposed to severe environments. In addition, the ability to provide thermal insulation is often an important consideration. Refractory materials are marketed in a variety of forms, but bricks are the most common. Typical applications include furnace linings for metal refining, glass manufacturing, metallurgical heat treatment, and power generation. Of course, the performance of a refractory ceramic, to a large degree, depends on its composition. On this basis, there are several classifications—namely, fireclay, silica, basic, and special refractories. For many commercial materials, the raw ingredients consist of both large (or grog) particles and fine particles, which may have different compositions. Upon firing, the fine particles normally are involved in the formation of a bonding phase, which is responsible for the increased strength of the brick; this phase may be predominantly either glassy or crystalline. The service temperature is normally below that at which the refractory piece was fired. Porosity is one microstructural variable that must be controlled to produce a suitable refractory brick. Strength, load-bearing capacity, and resistance to attack by corrosive materials all increase with porosity reduction. At the same time, thermal insulation characteristics and resistance to thermal shock are diminished. Of course, the optimum porosity depends on the conditions of service.

Firebricks for furnaces and ovens. Have high Silicon or Aluminium oxide content.

Brick products are used in the manufacturing plant for iron and steel, non-ferrous metals, glass, cements, ceramics, energy conversion, petroleum, and chemical industries.

- Used to provide thermal protection of other materials in very high temperature applications, such as steel making (T_m=1500°C), metal foundry operations, etc.
- They are usually composed of alumina (T_m=2050°C) and silica along with other oxides: MgO (T_m=2850°C), Fe_2O_3, TiO_2, etc., and have intrinsic porosity typically greater than 10% by volume.

- Specialized refractories, (those already mentioned) and BeO, ZrO_2, mullite, SiC, and graphite with low porosity are also used.

Ceramic fibre products due to their cost-effectiveness and excellent insulating properties. They are lightweight and have low thermal conductivities, excellent resistance to thermal shock, outstanding electrical resistivity, and good acoustical properties.

They are available in the following forms

- Blanket, Bulk
- Modules & Blok Products
- Board Products, Vacuum Formed
- Textiles, Cement & Mastic, Cement, Paper

Typical Applications

- ✓ Power generation especially HRSG duct insulation
- ✓ Chimney insulation, Process heater linings, Pipe wrap
- ✓ Annealing furnace linings
- ✓ Furnace & kiln back-up insulation
- ✓ Storage heater insulation, Domestic oven insulation

- ✓ Automotive exhaust heat shields, Aluminium transfer launder covers
- ✓ Welding stress relief

Advanced ceramics

Advanced ceramics are utilized in optical fiber communications systems, in microelectromechanical systems (MEMS), as ball bearings, and in applications that exploit the piezoelectric behavior of a number of ceramic materials.

- Advanced ceramic materials have been developed over the past half century
- Applied as thermal barrier coatings to protect metal structures, wearing surfaces, or as integral components by themselves.
- Engine applications are very common for this class of material which includes silicon nitride (Si_3N_4), silicon carbide (SiC), Zirconia (ZrO_2) and Alumina (Al_2O_3)
- Heat resistance and other desirable properties have lead to the development of methods to toughen the material by reinforcement with fibers and whiskers opening up more applications for ceramics
- *Structural:* Wear parts, bioceramics, cutting tools, engine components, armour.
- *Electrical:* Capacitors, insulators, integrated circuit packages, piezoelectrics, magnets and superconductors
- *Coatings:* Engine components, cutting tools, and industrial wear parts
- *Chemical and environmental:* Filters, membranes, catalysts, and catalyst supports

Few Advanced ceramics with examples

- These are newly developed and manufactured in limited range for specific applications. Usually their electrical, magnetic and optical properties and combination of properties are exploited. Typical applications: heat engines, ceramic armors, electronic packaging, etc.
- Some typical ceramics and respective applications are as follows:

i. Aluminium oxide / Alumina (Al2O3):

- It is one of most commonly used ceramic material. It is used in many applications such as to contain molten metal, where material is operated at very high temperatures under heavy loads, as insulators in spark plugs, and in some unique applications such as dental and medical use. Chromium doped alumina is used for making lasers.

ii. Aluminium nitride (AlN):

- Because of its typical properties such as good electrical insulation but high thermal conductivity, it is used in many electronic applications such as in electrical circuits operating at a high frequency. It is also suitable for integrated circuits. Other electronic ceramics include – barium titanate ($BaTiO_3$) and Cordierite ($2MgO$-$2Al_2O_3$-$5SiO_2$).

iii. Diamond (C):

It is the hardest material known to available in nature. It has many applications such as industrial abrasives, cutting tools, abrasion resistant coatings, etc. it is, of course, also used in jewelry. **Lead zirconium titanate (PZT):**

It is the most widely used piezoelectric material, and is used as gas igniters, ultrasound imaging, in underwater detectors.

iv. Silica (SiO_2):

It is an essential ingredient in many engineering ceramics, thus is the most widely used ceramic material. Silica-based materials are used in thermal insulation, abrasives, laboratory glassware, etc. it also found application in communications media as integral part of optical fibers. Fine particles of silica are used in tires, paints, etc.

v. Silicon carbide (SiC):

It is known as one of best ceramic material for very high temperature applications. It is used as coatings on other material for protection from extreme temperatures. It is also used as abrasive material. It is used as reinforcement in many metallic and ceramic based composites. It is a semiconductor and often used in high temperature electronics. Silicon nitride (Si_3N_4) has properties similar to those of SiC but is somewhat lower, and found applications in such as automotive and gas turbine engines.

vi. Titanium oxide (TiO_2):

It is mostly found as pigment in paints. It also forms part of certain glass ceramics. It is used to making other ceramics like $BaTiO_3$.

vii. Titanium boride (TiB_2):

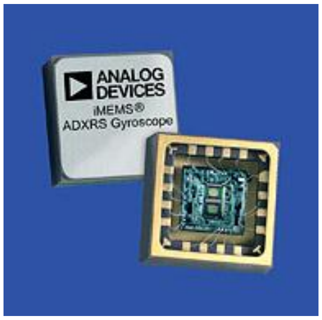
It exhibits great toughness properties and hence found applications in armor production. It is also a good conductor of both electricity and heat.

viii. Zirconia (ZrO_2):

It is also used in producing many other ceramic materials. It is also used in making oxygen gas sensors, as additive in many electronic ceramics. Its single crystals are part of jewelry.

1. **Microelectromechanical Systems (MEMS)**

Microelectromechanical systems (abbreviated *MEMS*) are miniature "smart" systems consisting of a multitude of mechanical devices that are integrated with large numbers of electrical elements on a substrate of silicon. The mechanical components are microsensors and microactuators. Microsensors collect environmental information by measuring mechanical, thermal, chemical, optical, and/or magnetic phenomena. The microelectronic components then process this sensory input, and subsequently render decisions that direct responses from the microactuator devices—devices that perform such responses as positioning, moving, pumping, regulating, and filtering.These actuating devices include beams, pits, gears, motors, and membranes, which are of microscopic dimensions, on the order of microns in size.



The processing of MEMS is virtually the same as that used for the production of silicon-based integrated circuits; this includes photolithographic, ion implantation, etching, and deposition technologies, which are well established. In addition, some mechanical components are fabricated using micromachining techniques. MEMS components are very sophisticated, reliable, and miniscule in size. Furthermore, since the above fabrication techniques involve batch operations, the MEMS technology is very economical and cost effective.

There are some limitations to the use of silicon in MEMS. Silicon has low fracture toughness a relatively low softening temperature 600^{o}C and is highly active to the presence of water and oxygen. Consequently, research is currently being conducted into using ceramic materials—which are tougher, more refractory, and more inert—for some MEMS components, especially high-speed devices and nanoturbines. Those ceramic materials being considered are amorphous
silicon carbonitrides (silicon carbide–silicon nitride alloys), which may be produced using metal organic precursors.

One example of a practical MEMS application is an accelerometer (accelerator/decelerator sensor) that is used in the deployment of air-bag systems in automobile crashes. For this application the important microelectronic component is a free-standing microbeam. Compared to conventional air-bag systems, the MEMS units are smaller, lighter, more reliable, and are produced at a considerable cost reduction.

Table 1: Comparison of Silicon MEMS, Quartz and Compensated LC Timing Components

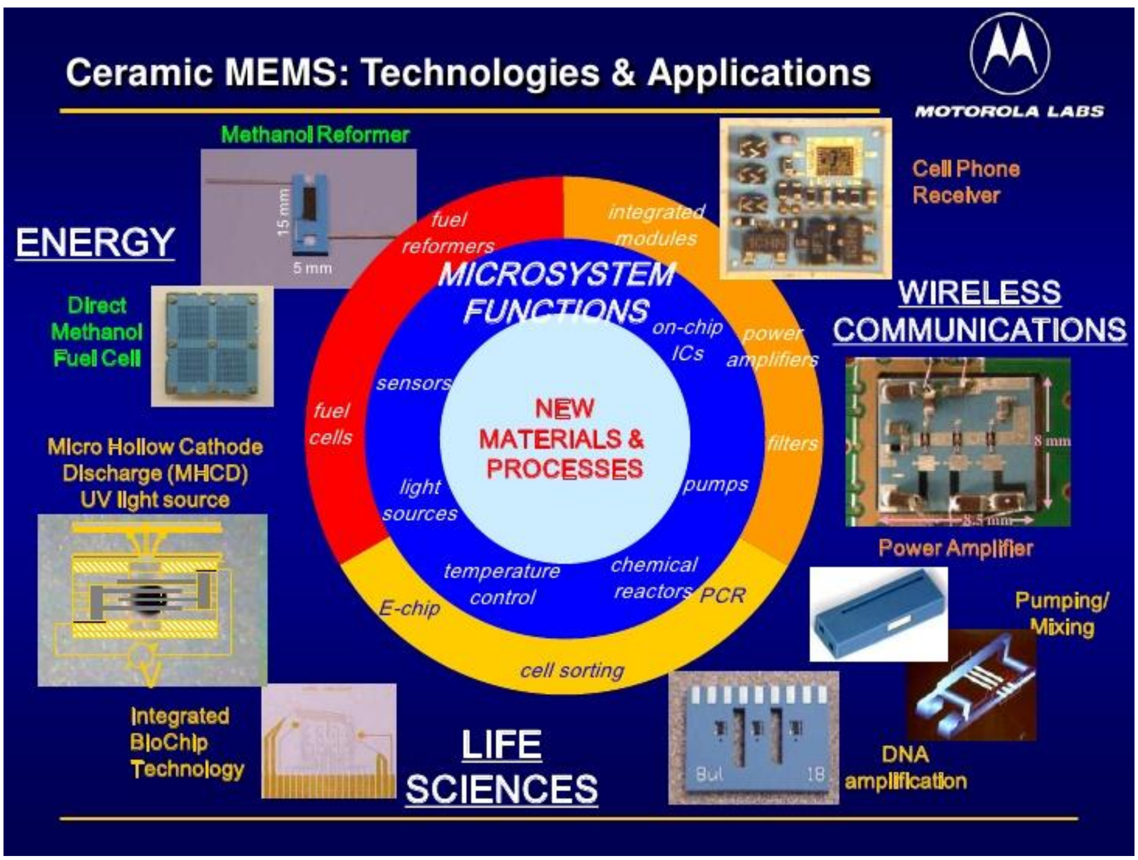
	Silicon MEMS	Quartz	Compensated LC
Best total frequency stability (XO) over –40° to 85°C	10 ppm	20 ppm	300 ppm (100 ppm for 0° to 70°C)
Best total frequency stability (TCXO) from 0° to 70°C	0.1 ppm	0.1 ppm	Not possible
Frequency range	up to 800 MHz Using self-developed PLL technology	up to 70 MHz in fundamental mode Up to 1 GHz using SAW, overtone, or PLL technologies	Up to 200 MHz Using temperature compensated LC oscillator with dividers
Supply current (LVCMOS, no load)	Low-to-medium (3 to 33 mA)	Low-to-medium (2 to 50 mA)	Low to medium (2 to 15 mA)
Phase noise at 10-kHz offset (10-MHz carrier)	-148 dBc/Hz	–150 dBc/Hz	–135 dBc/Hz
Rms period jitter driving 15-pF load	2 to 5 ps	2 to 5 ps	2 to 7 ps
Integrated rms phase jitter (12 kHz to 20 MHz)	< 1 ps	< 1 ps	1 to 10 ps
Aging (10 years)	3 ppm	3 ppm	10 to 30 ppm (expected)
Flexibility	Programmable, many features	Usually fixed, few features	Programmable, many features
Robustness to shock	50,000 G	5,000 G	Unknown
Robustness to vibration	70 G	10 G	Unknown
In-package integration	Cost effective	Expensive	Cost effective
Production lead time	2 to 4 weeks (all)	6 to 10 weeks (standard) 10 to 20 weeks (custom)	2 to 4 weeks (all)
Applications	Consumer, Computing, Networking, Telecom, Mobile, Storage, RF, Video, Defense	Consumer, Computing, Networking Telecom, Mobile, Storage, RF, Video, Defense	USB 2.0 Some microprocessor and memory applications

☐ Colored cells indicate best specifications in the row

Potential MEMS applications include electronic displays, data storage units, energy conversion devices, chemical detectors (for hazardous chemical and biological agents, and drug screening), and microsystems for DNA amplification and identification. There are undoubtedly many yet unforeseen uses of this MEMS technology, which will have a profound impact on our society in the future; these will probably overshadow the effects of microelectronic integrated circuits during the past three decades.

Applications

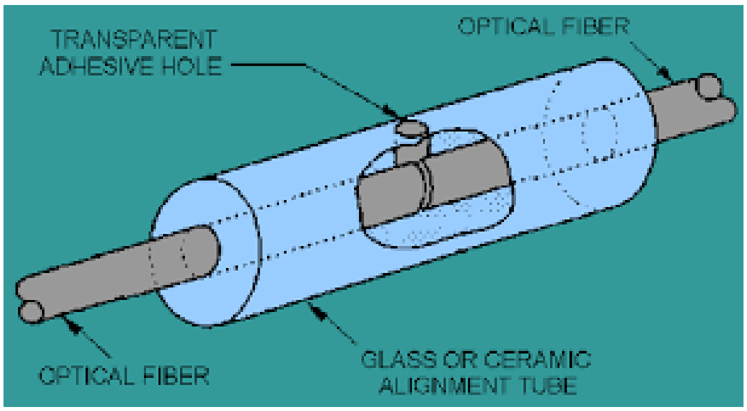
- Accelerometers
- Angular rate sensors (gyro sensors, yaw-rate sensors)
- Pressure sensors
- CMOS / CCD Image sensors

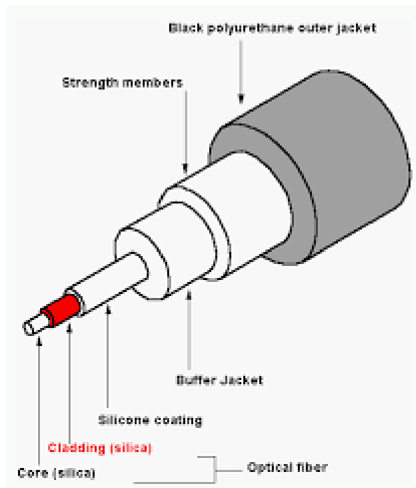


2. Optical Fibers

One new and advanced ceramic material that is a critical component in our modern optical communications systems is the **optical fiber.** The optical fiber is made of extremely high-purity silica, which must be free of even minute levels of contaminants and other defects that absorb, scatter, and attenuate a light beam. Very advanced and sophisticated processing techniques have been developed to produce fibers that meet the rigid restrictions required for this application.

- An optical fiber is essentially a waveguide for light
- It consists of a **core** and **cladding** that surrounds the core
- The **index of refraction** of the cladding is less than that of the core, causing rays of light leaving the core to be refracted back into the core
- A light-emitting diode (LED) or **laser diode** (LD) can be used for the source
- Advantages of optical fiber include:
  - Greater bandwidth than copper, Lower loss
  - Immunity to **crosstalk** , No electrical hazard





- Optical fiber is made from thin strands of either glass or plastic
- It has little mechanical strength, so it must be enclosed in a protective jacket
- Often, two or more fibers are enclosed in the same cable for increased bandwidth and redundancy in case one of the fibers breaks
- It is also easier to build a full-duplex system using two fibers, one for transmission in each direction
- The **angle of refraction** at the interface between two media is governed by Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

They are also used in medical imaging and mechanical engineering inspection.

Flexible Medical imaging

- in bronchoscopes, endoscopes, laparoscopes

Mechanical imaging - inspecting mechanical welds in pipes and engines (in airplanes, rockets, space shuttles, cars)

Plumbing - to inspect sewer lines

- Optical fiber are made from oxide glasses and most popular is silica (SiO_2) which has refractive index of 1.458 at 850 nm.
- To produce two similar materials with slightly different refraction indices for core and cladding, either fluorine or other oxides (dopants) are added to silica

Desired properties are

i. resistance to deformation at temperatures as high as 1000 C
ii. High resistance to breakage from thermal shock
iii. Good chemical durability
iv. High transparency in both visible and infrared regions of interest

3. Ceramic Ball bearings

Another new and interesting application of ceramic materials is in bearings. A bearing consists of balls and races that are in contact with and rub against one another when in use. In the past, both ball and race components traditionally have been made of bearing steels that are very hard, extremely corrosion resistant, and may be polished to a very smooth surface finish. Over the past decade or so silicon nitride (Si_3N_4) balls have begun replacing steel balls in a number of applications, since several properties of Si_3N_4 make it a more desirable material. In most instances races are still made of steel, because its tensile strength is superior to that of silicon nitride.

This combination of ceramic balls and steel races is termed a *hybrid bearing*. Since the density of Si_3N_4 is much less than steel (3.2 versus 7.8 g/cm3) hybrid bearings weigh less than conventional ones; thus, centrifugal loading is less in the hybrids, with the result that they may operate at higher speeds (20% to 40% higher). Furthermore, the modulus of elasticity of silicon nitride is higher than for bearing steels (320 GPa versus about 200 GPa). Thus, the Si_3N_4 balls are more rigid, and experience lower deformations while in use, which leads to reductions in noise and vibration levels.

Lifetimes for the hybrid bearings are greater than for steel bearings — normally three to five times greater. The longer life is a consequence of the higher hardness of Si3N4 (75 to 80 HRC as compared to 58 to 64 HRC for bearing steels) and silicon nitride's superior compressive strength (3000 MPa versus 900 MPa), which results in lower wear rates. In addition, less heat is generated usingthe hybrid bearings, because the coefficient of friction of Si3N4 is approximately 30% that of steel; this leads to an increase in grease life. In addition, lower lubrication levels are required than for the all-steel bearings. Ceramic materials are inherently more corrosion resistant than metal alloys; thus, the silicon nitride balls may be used in more corrosive environments and at higher operating temperatures. Finally, because Si3N4 is an electrical insulator (bearing steels are much more electrically conductive), the ceramic bearings are immune to arcing damage. Some of the applications that employ these hybrid bearings include inline skates, bicycles, electric motors, machine tool spindles, precision medical hand tools (e.g., high-speed dental drills and surgical saws), and textile, food processing, and chemical equipment.

It should also be mentioned that all-ceramic bearings (having both ceramic races and balls) are now being utilized on a limited basis in applications where a high degree of corrosion resistance is required. A significant research effort has gone into the development of this silicon nitride bearing material. Some of the challenges that were encountered are as follows: processing/fabrication techniques to yield a pore-free material, fabrication of spherical pieces that require a minimum of machining, and a polishing/lapping technique to produce a smoother surface finish than steel balls

Ceramic ball bearings

There are a variety of different ceramic materials each with their own different capabilities, advantages and disadvantages; their use in bearing and rolling element applications was pioneered by many of the space agencies and continues to be at the forefront of engineering technology.

A Ceramic Hybrid Ball Bearing made of ceramic elements such as silicon nitride, Zirconia bearings, silicon carbide etc.,

i. **Silicon Nitride Bearings**

Silicon nitride has better high temperature capabilities than most metals combining retention of high strength and creep resistance with oxidation resistance. In addition, its low thermal expansion coefficient gives good thermal shock resistance compared with most ceramic materials.

Silicon nitride is the material of choice for vacuum and high speed applications. 58% lighter than traditional steel silicon nitride provide a weight saving benefit and due to the reduction in weight there is a reduction in the centripetal force generated by the rolling elements therefore for similar application when compared to bearing steel silicon nitride offer a significantly increased fatigue life time. Unlike other ceramic materials silicon nitride has the ability to carry similar loads to that of bearing steel however, due to the hardness of the material any application with shock loading is unsuitable for use of silicon nitride or any other ceramic materials for races.

ii. **Zirconia Bearings**

Zirconia (ZrO2) was developed in the 1960s and ’70s and was used to produce the external tiles which created a thermal barrier on the space shuttle that allowed it to re-enter the earth’s atmosphere therefore, zirconia is the material of choice for high temperature applications. The thermal expansion and density of zirconia is close to steel than that of any other ceramic material so it does not have the same weight saving and thermal shock resistance that are found in other ceramic materials.

Best used under low loads, zirconia bearings are used in high temperature and highly corrosive applications.

iii. **Silicon Carbide Bearings**

Less frequently used than other ceramic materials due to its raw materials cost and difficulty to machine, silicon carbide offers the best heat and corrosion resistance of all the ceramic materials.

Silicon Carbide is best used under low loads and in highly corrosive environments. Silicon nitride is a highly processed silica and ceramic material.

The use of Ceramics for bearing components results in a far superior product.

iv. Beryllium Copper Bearings

Beryllium copper is high strength alloy comparable to steel with non magnetic properties which can be heat treated for use in bearings.

The use of this material in bearings offers many advantages in extreme environments, excellent heat dissipation with a thermal conductivity between that of steel and aluminium, the material structure
makes it suitable for situations of occasional overload, impact, high temperature, low temperature and marginal lubrication.

The material properties make beryllium copper suitable for use in cryogenic, ultra high vacuum, magnetically sensitive environments as well as certain corrosive applications.

Features of ceramic ball bearings

- Non-conductive.
- 50% higher modulus of elasticity.
- Low Density
- Less maintenance.
- Coefficient of Friction.
- Corrosion Resistance
- High Hardness

Characteristics of Ceramic ball bearing during Micro weld

- Micro Weld occurs when microscopic surface"peaks" on the ball and race make contact andactually weld together.
- This occurs even with light loading and adequate lubrication.
- This results in higher temperatures, higher friction and decreased life.
- The ceramic hybrid bearing cannot micro-weld to steel, thus eliminating the problem entirely.

Advantages

- Lower Maintenance Cost, Extended Service Life
- Prevents Electrical Arcing, Extended Grease Life
- Reduced Wear From Vibration
- Lower Operating Temperature
- Reduced Wear From Contamination

Applications

- Motor Racing.
- Machine tool applications, Aircraft accessories/aerospace.
- Industrial Machinery, Medical equipment.
- Ceramic ball is tremendously harder than steel(Rockwell 78c versus Rockwell 60c for steel balls).
- Ceramic ball is 60% lighter than a steel ball.
- Ceramic ball is much less prone to "skid".
- Ceramic ball is significantly rounder and has a finerfinish than conventional steel balls.
- Operating temperature for ceramic is 2000 degrees F.versus 600 F. degrees for steel.
- Vibration levels of ceramic hybrid bearings averagetwo to seven times lower than that of steel.
- Service life is two to five times longer thanconventional steel ball bearings.
- 25% of all electrical energy produced is used to power some type of electric motor. Imagine the savings in resources if all motors were to run withceramic hybrid ball bearings!

__**Modern ceramics have many other advantages over metals.**__

1) Ceramics are usually lighter than metals, sometimes weighing only about 40 % as much. This is important in aircraft, missile and spacecraft applications, where reduced weight conserves fuel. In a gas turbine engine, a lightweight ceramic rotor accelerates more rapidly than a heavier metallic rotor because it has less inertia.
2) They are highly resistant to oxidation and other chemical glue, as well as to corrosion.
3) Because of their high temperature resistance, ceramics may obviate the need for cooling equipment, especially in diesel engines.
4) Some ceramics are exceptionally hard. The hardest substances known, such as diamond, boron carbide, cubic boron nitride and silicon carbide are ceramics. They can be excellent cutting agents.

5) Because of their low coefficient of friction, high compressive strength and wear resistance, some ceramics can be used in bearings and other mechanical parts without requiring lubrication.
6) Some modern ceramics can withstand temperatures as high as 1600°C, whereas even the best super-alloys can seldom be used above about 1100 °C.
7) Modern ceramics are potentially less expensive than super-alloys. In the years ahead, these ceramics are expected to be much cheaper than super-alloys.
8) Unlike super-alloys ceramics do not require the increasingly expensive strategic metals (viz, cobalt, chromium, nickel and tungsten) for high temperature use.