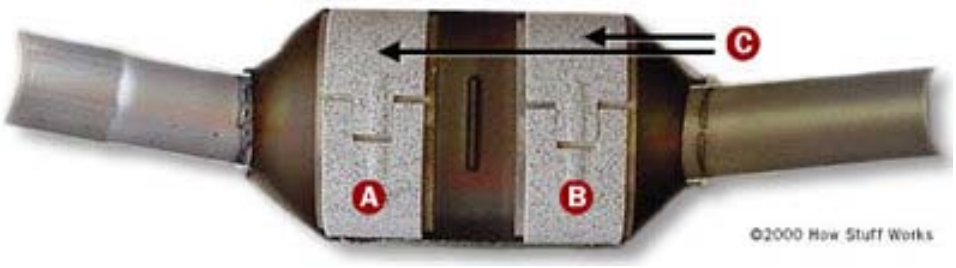
Ceramics: General Properties and Application

Session Objectives

At the end of this session the delegate should be able to analyze

- Different types of ceramics
- Properties of ceramics
- Application of ceramics

Catalytic Converter



- **A** Reduction catalyst
- **B** Oxidation catalyst
- **C** Honeycomb

Why Ceramics?

- A small bearing that is light, rigid, hard and resists high temperatures
- An electrical insulator to be used at high temperatures
- A transparent baking dish
- Surface of space shuttle orbiter (made of aluminum) which is exposed to 1450 ºC

Introduction

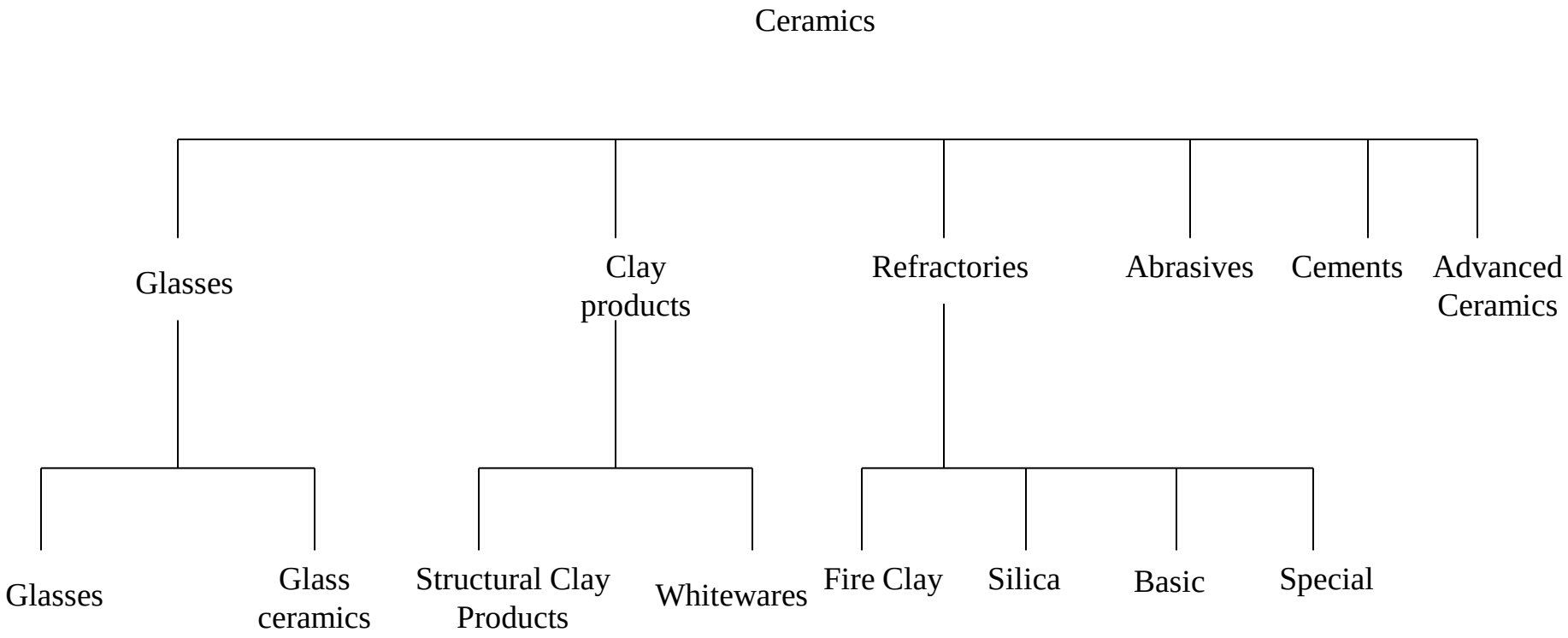
- Keramikos – ‘burnt stuff –Clay Products’
- Ceramics are inorganic compounds of metallic and non-metallic elements.
- Generally known as ‘*Clay products*’
- Ordinary glass: 74% SiO_2, 16% Na_2O, 5% CaO, 1% Al_2O_3 and 4% MgO.

E.g. Metal and nonmetal: *MgO*; NMES and nonmetal: SiO_2; Metal and NMES: *TiC*, ZrB_2, $MoSi_2$;

Two NMES : *SiC*, Si_3N_4;

Other non-binary ceramics: $BaTiO_3$, $YBa_2Cu_3O_7$, $PbZrO_3$;

Classification of Ceramics Based on their Applications



Characteristics of Ceramics

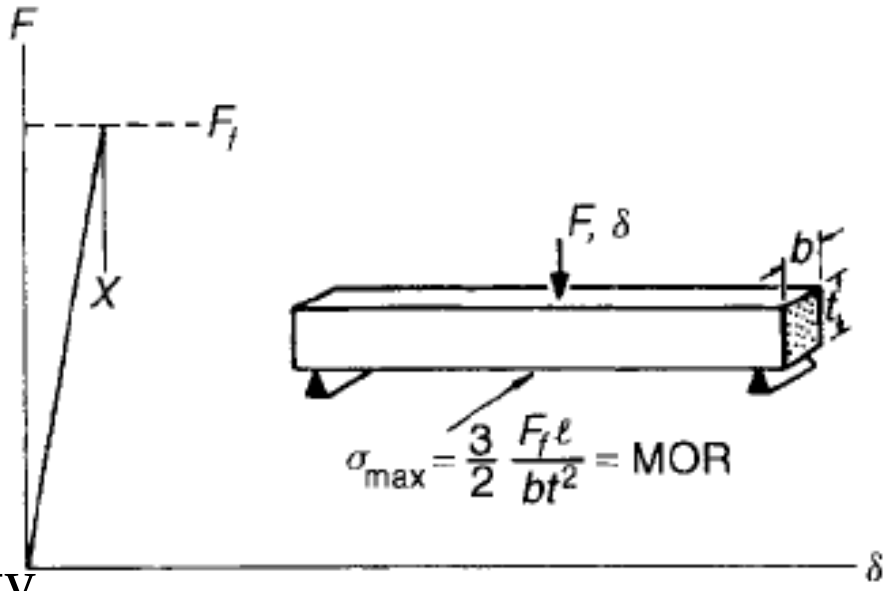
- Low density compared to metals
- High melting point or decomposition temperature
- High hardness and very brittle
- High elastic modulus and moderate strength
- Low toughness
- High electrical resistivity
- Low thermal conductivity
- High temperature wear resistance
- Thermal Shock resistance
- High corrosion resistance
- In crystalline ceramics the crack propagation is usually through the grains (transgranular) and along specific crystallographic (or cleavage) planes, which are planes of high atomic density

Main drawback is brittleness and low toughness

Stress-Strain Curve from Flexure Test

$$\sigma = \frac{3FL}{2bd^2}$$

$$\sigma = \frac{FL}{bd^2}$$



Influence of porosity

$$UTS = (UTS)_O \exp(-nP)$$

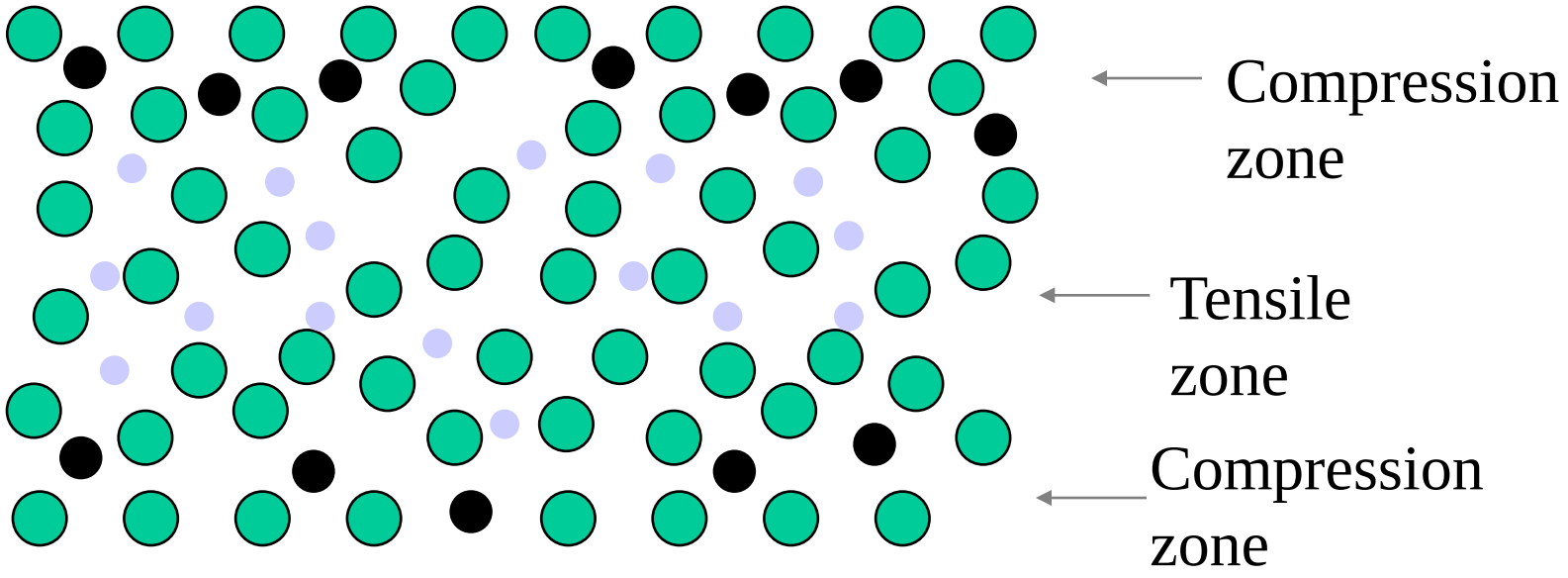
$$E = E_o\left(1 - 1.9P + 0.9P^2\right)$$

where $(UTS)_o$ is the tensile strength at zero porosity and n lies between 4 and 7 and E_0 –Youngs modulus at zero porosity

Fraction of pores = Volume of pores/total volume

Surface Compression

- Tempering glass - solidifying surface quickly, and allowing interior to cool slowly - puts interior in tension and surface in compression
- Ion exchange replace small ions with large ions (e.g K^+ for Na^+) at the surface.



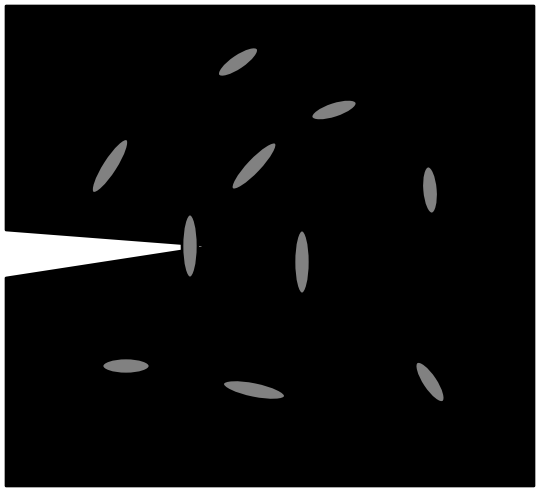
Strengthening of Ceramics

- All ceramic materials, due to the way they are manufactured, contain a certain population of small flaws (e.g. cracks, voids etc.) with different sizes, orientations, and geometries
- The finer the grain size; the higher are the strength & toughness.
- The properties of ceramics are very sensitive to defects such as cracks, impurities, and porosity: Reduce defects and pores (e.g etch glass)
- Composite approach by addition of second phase particles, whiskers or fibers: Add second phase crack inhibitor, transformation toughening (e.g PSZ)
- Put surface in tension (e.g tempered glass)

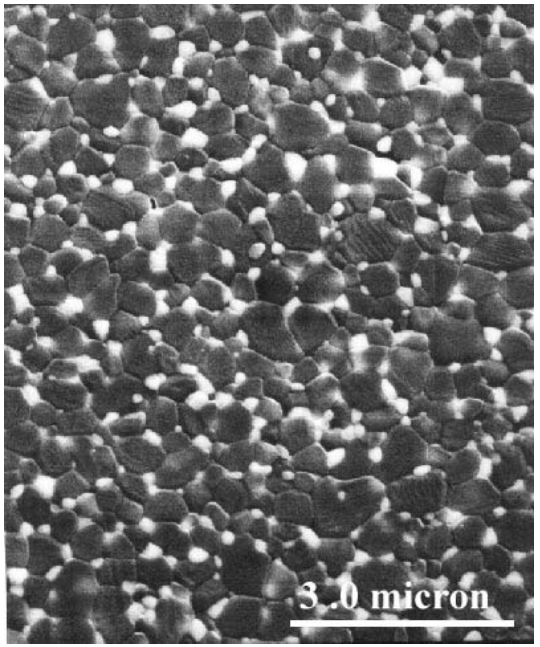
Strengthening Mechanisms

(a) Add Microcracks : Blunts the crack tip, increasing ρ_t the crack tip radius

(b) Zirconia toughened Alumina: Stress induced transformation of the zirconia increases the toughness and wear resistance



(a)



(b)

Zirconia Toughened Alumina (ZTA)

Zirconia toughened alumina

Zirconia toughened alumina

Some Special Ceramics and their Properties

ALUMINA

Alumina is the most widely used oxide ceramics. Mullite is a ceramic made by mixing Alumina with other oxides like Silica.

Characteristics of Mullite are:

- High hardness
- Moderate strength
- Withstands high temperature
- Good electrical and thermal insulator

Application: As refractory material for high temperature, spark plug insulators, centrifuge linings, thermal barrier coatings, plain bearings etc.

Zirconia

Characteristics

- High Toughness
- Good resistance to thermal shock
- Resistance to wear
- Resistance to corrosion
- Low thermal conductivity
- High hardness

Applications: Zirconia beads are used in grinding ball-mills, Used as sensors (O_2) in automotive, sensors and actuators (piezoelectric property)

Partially Stabilized Zirconia (PSZ)

PSZ is Zirconia doped with oxides of calcium, yttrium or magnesium.

PSZ has all the advantageous mechanical characteristics of Zirconia and in addition it has the following special characteristics:

- Coefficient of thermal expansion is only 20% lower than that of cast iron
- Thermal conductivity is about 30% of that of other ceramics

Because of these special characteristics it is very suitable for heat engine components, such as cylinder liners and valve bushings.

Carbides

Useful Carbides are:

- Tungsten carbide
- Titanium carbide
- Silicon carbide

Characteristics:

- Good resistance to wear
- Good resistance to thermal shock
- Withstand high temperatures
- Good resistance to corrosion
- Low coefficient of friction at high temperatures

Applications:

- Tungsten carbide with cobalt as binder is used for cutting tools and dies
- Silicon carbide is used as abrasive and for heat engine components.
- Mechanical seal faces, bearings, gas turbine rotors, hydraulic plungers and pistons

Nitrides

Useful Nitrides are:

- Cubic boron nitride
- Titanium nitride
- Silicon nitride

Characteristics and applications:

Cubic boron nitride is the hardest material next to diamond. It is used for cutting tools and as abrasive in grinding wheels.

Titanium nitride is used as a coating material on cutting tools

Silicon nitride is used for high temperature applications such as: automotive engine and gas turbine components, engine part valves, turbocharger rotors, bearings etc.

Properties

- Lightweight (60% Lighter than Steel)
- High Fracture Toughness
- Wear Resistant
- Electrical Insulator
- Low Coefficient of Friction
- Contact Fatigue Resistant
- High Dielectric Strength
- Excellent Thermal Shock Resistance
- Unique Dielectric Properties

Electical Insulators, Bearings, Seal Rings, Wear Plates

Applications

- Electrical Insulators
- Radomes
- Bearings
- Seal Rings
- Wear Plates

www.ceramicbearings.com

Graphite

Graphite is a crystalline form of carbon having a layered structure.

Characteristics:

- High electrical conductivity
- High thermal conductivity
- Highly anisotropic
- Withstands high temperatures

Applications:

- Heating elements
- Brushes for motors
- High temperature fixtures
- Furnace parts
- Crucibles

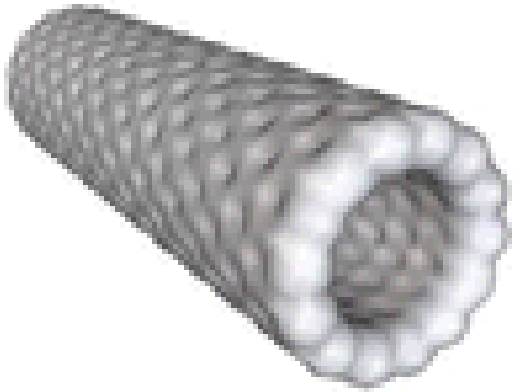
Diamond

Diamond is the hardest substance known. It is a brittle material which decomposes at 700^{o}C.

Applications:

- Abrasive machining
- Crystal cutting
- Grinding
- Coating in cutting tools and dies
- Dies for drawing wires

Carbon Nanotube and Fullerene Molecule (C_{60})



Fullerene

By adding belts of atoms to the basic structure of C_{60} it is possible to make a nanotube, C_{80}.

Applications of nanotubes: Novel semiconductor devices, chemical sensors, ultra-sensitive electromechanical sensors etc.

Glasses

- Amorphous solid with a structure of liquid
- Supercooled i.e. cooled at high rate to allow crystals to form
- Made up of at least 50 % silica known as glass former
- Commercial glasses are categorized by
  a. Soda-lime glass
  b. Lead-alkali glass
  c. Borosilicate glass
  d. Aluminosilicate glass
  e. 96 % - silica glass
  f. Fused silica glass

Applications

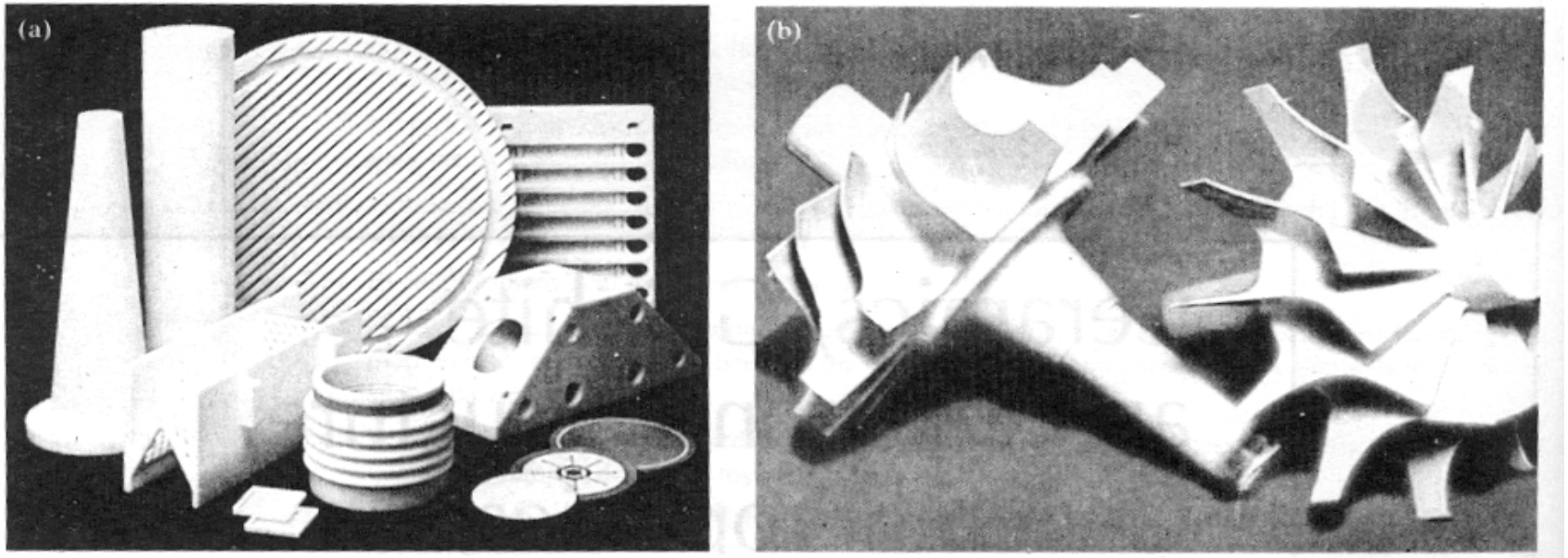
- In spark plug insulators (Silicon Nitride).
- Glass windows (early 1920s).
- All catalytic converters in modern automobiles have ceramic honeycomb supports for the catalyst, which has been instrumental in reducing automobile exhaust emissions.
- Ceramic oxygen sensors are used in concert with computer controls to optimize combustion and reduce exhaust emissions.
- Computer controls and other electronics in automobiles use a large number of ceramic substrates and components which are critical to the performance of the devices.
- Ceramic clutch (Porsche)
- Piezoelectric sensors: Air bag sensor, air flow sensor, audible alarms, fuel atomiser, keyless door entry, seat belt, buzzers, knock sensors

Applications in Automobiles

- Ceramic magnets are used in many of the electrical motors in modern cars for automated adjustment of seats, windows, etc.
- Ceramic components have been introduced in fuel systems and valve trains of heavy-duty diesel engines
- Ceramic composite brake rotors, standard equipment of Formula One racecars, are now used in high-performance passenger vehicles.
- Ceramic brakes reduce vehicle weight, resist heat-induced fading and are expected to last the life of the vehicle.

Rotors

Gas-turbine engine components (as rotors) : silicon nitride, silicon carbide, and partially stabilized zirconia.



(a) High strength alumina for high temperature applications; (b) Gas-turbine rotors made of silicon nitride; Source : Wergo Div..GTE

Applications : Ceramic Ball Bearings

- Silicon nitride ceramic ball bearings are being used in machines, particularly in high-performance spindle bearings for machine tools.
  - Have a diameter tolerance of 0.13 μm, a surface roughness of 0.02 μm with coefficient of thermal expansion one-fourth that of steel, can withstand temperatures of up to 1400^0C
  - Have high wear resistance and high fracture toughness, and they perform well with little or no lubrication
- A more recent development is ball bearings and braces made of a hybrid of metal and ceramic
  - Produced from titanium and carbon nitride by the use of powder-metallurgy techniques, the full-density titanium carbonitride (TiCN) material is twice as hard as chromium steel and 40% lighter.
  - Components up to 300 mm in diameter are produced.

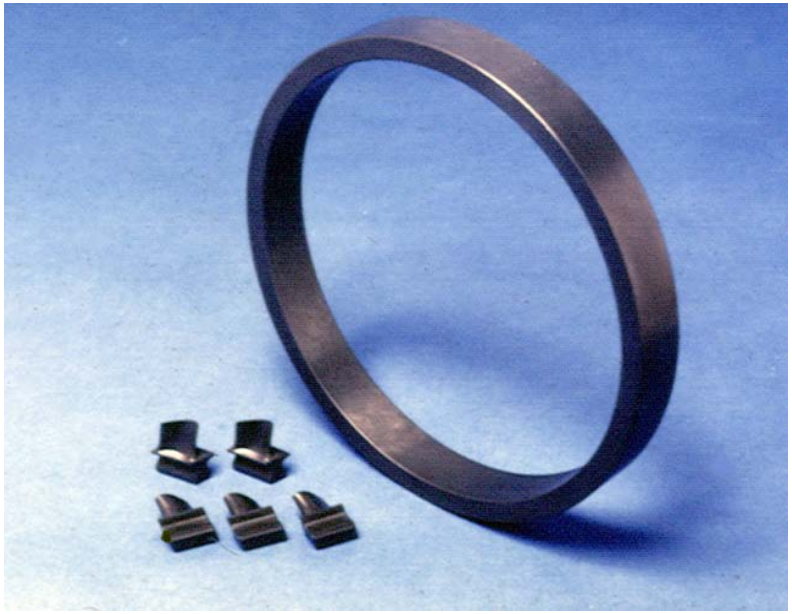
Applications as Bearings and Pistons

www.ceramicbearings.com

Ceramic Sleeves and Turbine Components

Ceramic Sleeve

Ceramic Ferrule



Gas turbine components

Shroud ring and turbine blades for a small helicopter engine fabricated from sintered silicon nitride

www.ferrules.com/ferrules/sleeves

Pump face seals, Polishing supports and sealing rings made from sintered Silicon Carbide

www.SiC .com/outerspace-apps-brochure

Ceramic Parts

Spark plugs

Si_3N_4 parts

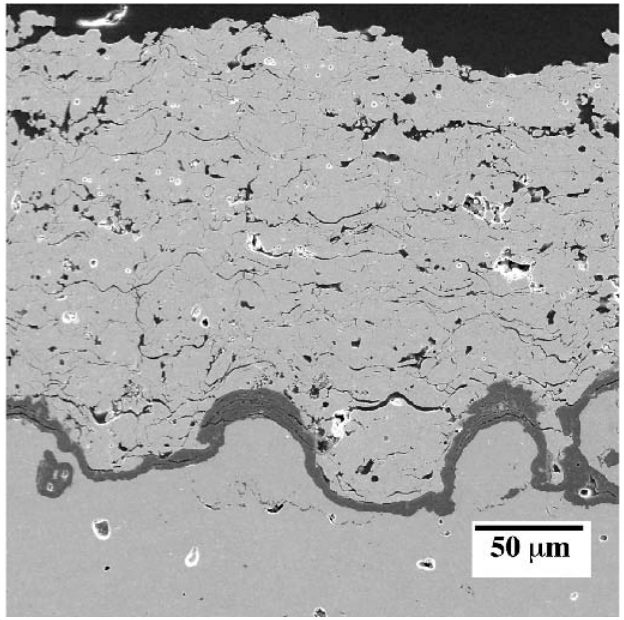
Applications

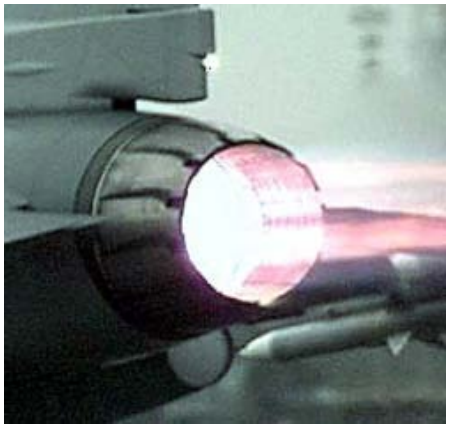
- Used in electronic and electrical appliances (because of their high electrical resistance and high dielectric strength)
- Cylinder liners, engine antiwear coatings and also scratch proof coatings on automotive bodies.
- Bushings and Seals
- Honeycomb Cordierite is used for automobile and waste gas catalyst support
- Used in Solid Oxide Fuel Cells (SOFs)
- Space Shuttle tiles (because of their low thermal conductivity, high temperature capability (up to 1400^{o}C)
- Replacement of joints in human body (because of their bio-compatibility)

Applications: Thermal Barrier Coatings

Coating metal with ceramics is another application; it may be done to reduce wear, to prevent corrosion, or to provide a thermal barrier

Low thermal conductivity
reduces metal temperatures

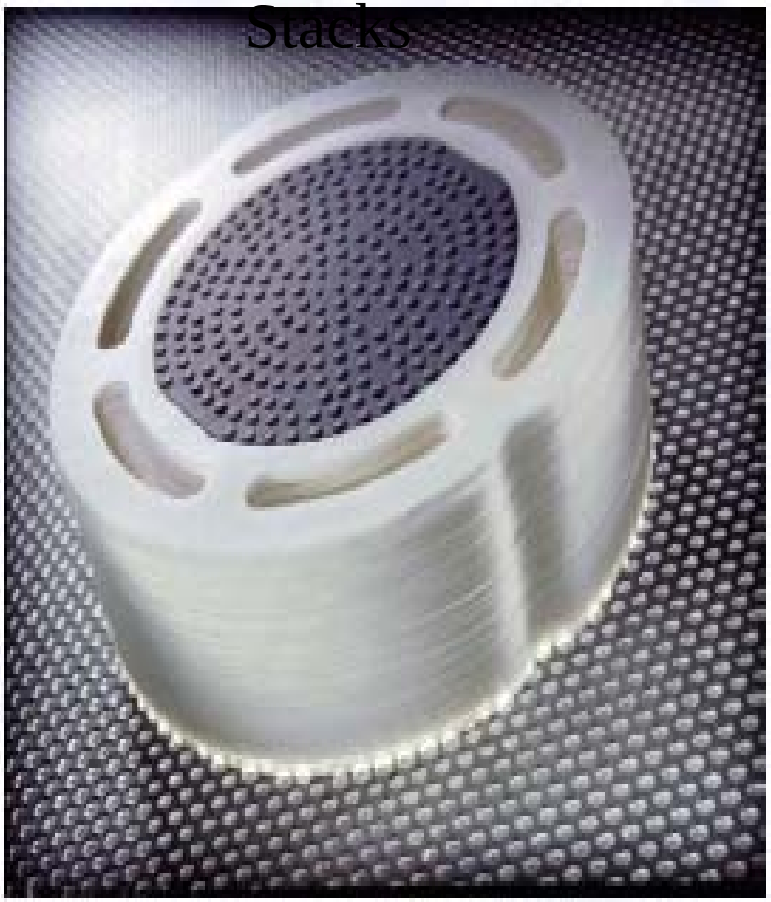




SOFC

Cells

Stacks



Applications

Thermal	
Insulation	High temperature furnace linings for insulation (oxide fibers such as alumina, silica and zirconia)
Refractoriness	High temperature furnace linings for insulation and containement of molten metal and slags
Thermal Conductivity	Heat sinks for electronic packages
Magnetic and superconductivity	
Hard Magnets	Ferrite magnets [$(Ba,Sr)O.6Fe_2O_3$]
Soft magnets	Transformer cores [$(Zn,M)Fe_2O_3$ with M= Mn, Co, Mg]; magnetic tapes (rare earth garnets)
Superconductivity	Wires and SQUID magnetometers ($YBa_2Cu_3O_7$)

Applications

Optical	
Transparency	Windows (soda-lime glasses), cables for optical communication (ultra-pure silica)
Translucency and chemical inertness	Heat and corrosion-resistant materials, usually for Na lamps (Al_2O_3)
Nonlinearity	Switching devices for optical computing ($LiNbO_3$)
IR transparency	Infrared laser windows (CaF_2, SrF_2, NaCl)
Nuclear applications	
Fission	Nuclear fuel (UO_3, UC), fuel cladding (C, SiC), neutron moderators (C, BeO)
Fusion	Tritium breeder materials (zirconates and silicates of Li, Li_2O_3); fusion reactor lining (C, SiC, Si_3N_4, B_4C)

Applications

Chemical	
Catalysis	Filters (zeolites); purification of exhaust gases
Anticorrosion properties	Heat exchangers (SiC), chemical equipment in corrosive environments
Biocompatibility	Artificial joint prostheses (Al_2O_3)
Mechanical	
Hardness	Cutting tools (SiC whisker reinforced Al_2O_3, Si_3N_4)
High temperature strength	Stators and turbine blades, ceramic engines (Si_3N_4)
Wear resistance	Bearings (Si_3N_4)

Applications

- Electric and dielectric

Conductivity	Heat elements for furnaces (SiC, ZrO_2, $MoSi_2$)
Ferroelectricity	Capacitors (Ba-titanate-based materials)
Low-voltage insulators	Ceramic insulation (porcelain, steatite, forsterite)
Insulators in electronic applications	Substrates for electronic packaging and electrical insulators in general (Al_2O_3, AlN)
Insulators in hostile environments	Spark plugs (Al_2O_3)
Ion-conducting	Sensors, fuel cells, solid electrolytes (ZrO2, β-alumina, etc.)
Semiconducting	Thermistors and heating elements (oxides of Fe, Co, Mn)
Nonlinear *I-V* characteristics	Current surge protectors (Bi-doped ZnO, SiC)
Gas-sensitive conductivity	Gas sensors (SnO_2, ZnO)

Summary

- Ceramics are compounds of metallic and nonmetallic elements possess high hardness, high compressive strength, high elastic modulus, low thermal expansion, low density etc.
- It is possible to obtain ceramic materials of any required properties, mechanical, electrical, chemical or magnetic by suitable processing techniques and by composite approach and hence has a wide range range of applications
- They have special advantages of light weight, can withstand very high temperatures and aggressive environments compared to metals used mainly as coatings and sensors