ADVANCED CERAMICS MATERIALS

Abstract

The document discusses advanced ceramics, highlighting their classification, properties, methods of fabrication, and applications. Advanced ceramics, also known as engineering or technical ceramics, are characterized by their hardness, chemical stability, high melting points, and resistance to heat, wear, and corrosion. They are primarily classified into crystalline and non-crystalline types and further into traditional and advanced ceramics based on usage. Key fabrication techniques include slip casting, isostatic pressing (cold and hot), and sintering. Each method suits specific applications based on shape, size, and desired properties. Advanced ceramics have diverse applications in electronics, structural materials, chemical processing, and medical fields, including bioceramics for implants and prosthetics. Their advantages include biocompatibility and durability, while disadvantages such as brittleness and production complexity limit their use in some cases.

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I. ADVANCED CERAMICS

Ceramics are inorganic,non metallic materials, which includes oxides, nitrides, carbides,borides, fall under the category of ceramics. It is also known as Engineering ceramics or technical ceramics. With a predominately ionic character, the atomic bonding in ceramics is largely ionic and partially covalent. Pure or almost pure ceramic materials can be used alone, in combination, or as the foundation for ceramics.

Examples:- Aluminium Oxides (Al_2O_3),Zirconia (ZrO_2),Silicon Carbide (SiC),Silicon nitrides (Si_3N_4),Barium titanate ($BaTiO_3$) and High temperature superconductors

Classification:
Ceramic materials are divided into two groups

- Traditional ceramics: Clay products, refractories and cement
- Advanced ceramics: Silicon carbide, alumina and silicon nitride are used in high technology applications like cutting tool material, abrasive etc.

Advanced ceramics are formed utilizing a variety of composition blends and processing procedures, and their raw ingredients must be properly treated in order to generate a regulated product. Currently, materials like glass, porcelain, bricks, tiles, etc. are typically categorized as ceramics.

1. Properties of Advanced Ceramics:

- Advanced ceramics are hard, stiff and Inert.
- They are poor conductors of heat and electricity
- They also have better corrosion resistance
- They are chemically very stable
- They have very low fracture toughness
- They possess high melting points due to their strong chemical bonds.
- They have high wear resistance

2. **Structural Classification**: Anion and cation make up the majority of the ionic bonding found in ceramics. The radius of the ions affects the crystal structure of ceramics.The radius ratio of the bonding ion determines the coordination number. Ceramics are categorized into AX, AX_2, ABX_3, and AB_2X_4 categories based on their crystal structure. Examples under each type are given below

   AX: NaCl,ZnS,CsCl
   AX_2:SiO_2,CaF_2,PuO_2
   ABX_3: $BaTio_3$,$SrZrO_3$
   ABX_4:$MgAl_2O_4$,$FeAl_2O_4$

Ceramics can be divided into two categories based on their structural makeup:

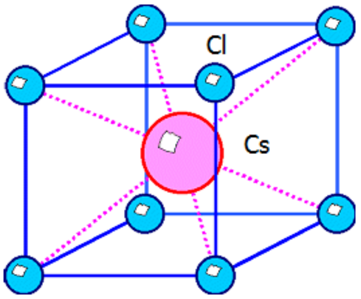
- Crystalline ceramics and
- Non-crystalline ceramics.

- **Crystalline Ceramics**
  - ➢ Crystalline ceramics have regular arrangement of atoms with simple structure.
  - ➢ They are most often produced by compacting the powder and firing at high temperature.
  - ➢ The crystal structure of ceramics is due to the assembly of different size atoms.

Common Crystal Structures in Crystalline Ceramics are

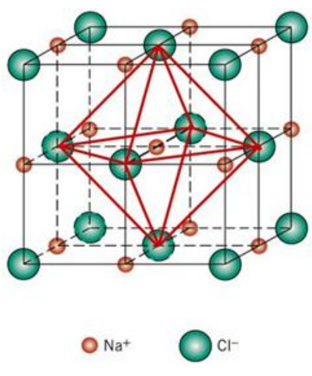
Cesium Chloride Structure

- ❖ It is simple cubic structures that are found in metal type ceramics.
- ❖ In this structure chlorine ions are arranged in a simple cubic structure with interstice occupied by cesium ions.
- ❖ If the positive and negative ions are about the same size the structure becomes a simple cubic (CsCl) structure.

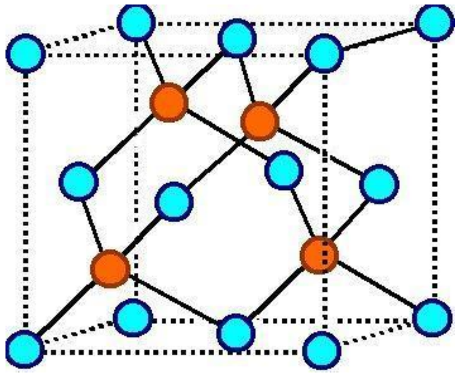


Rock Salt Structure

- ❖ The rock salt structure has a face-centered cubic (fcc) structure, where the positive (Na^+) and negative (Cl^-) ions are surrounded by 6 opposite ions (CN = 6).
- ❖ MgO, CaO, SrO, BaO, CdO, MnO, FeO, CoO, and NiO belong to the same group.
- ❖ The face centered cubic structure arises if the relative size of the ions is quite different

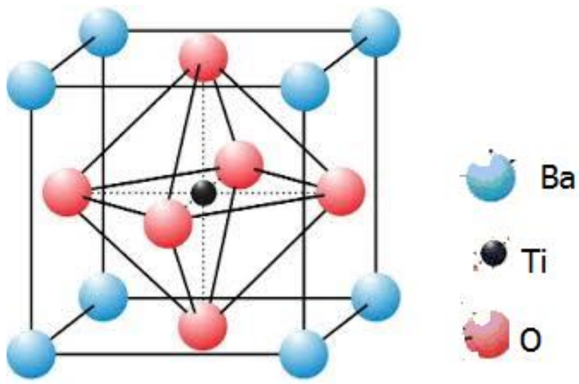


- **Zinc Blende Structure:** Two other cubic ceramic compounds with atoms in the 4-fold locations are silicon carbide (SiC) and zinc blende (ZnS). There are four atomic coordinates. Every kind of atom creates a unique fcc structure. With the exception of the alternating atoms being of different elements, the structure is the same as the diamond cubic.



Perovskite Crystal Structure

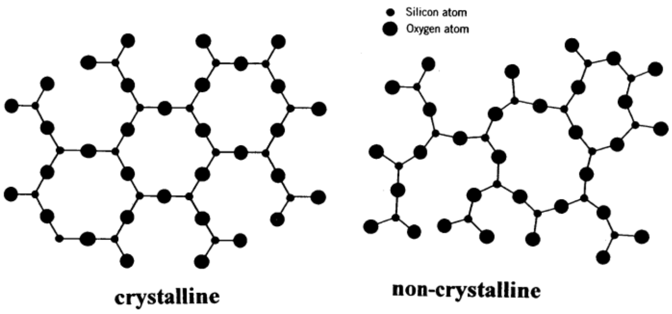
- A unit cell of this structure is shown in figure. In this ceramic compounds more than two cations. For example Barium titanate having both $Ba^{2+}$and Ti^{4+} cations are present
- Ba^{2+} ions are situated at all eight corners of the cube and a single Ti^{4+} is at the cube−center. The O^{2+} ions are located at the center of each of the six faces of the unit cell.



- **Non - Crystalline Ceramics**

  - Because the materials feature random structures rather than three-dimensional ones, they are referred to be glassy or amorphous. Numerous metal alloys, oxide compounds, and non-oxide compounds combine to generate glassy structures. Vitreous silica, or fused silica, has an extremely high atomic randomness.
  - Silica and Silicates Silicates are made up of silicon and oxygen, both of which are abundant in the Earth's crust.
  - A unit cell of silicate is a tetrahedron on which each silicon atom is limited to four oxygen atoms, as seen in the figure. Within a tetrahedron structure, silicon atoms are located in the center, and oxygen atoms are located on its periphery.

- There are three polymorphic forms of silica: (1) quartz, (2) cristobalite and (3) tridymite. This silica is used in the manufacture of different varieties of glasses.



II. BONDED CERAMICS

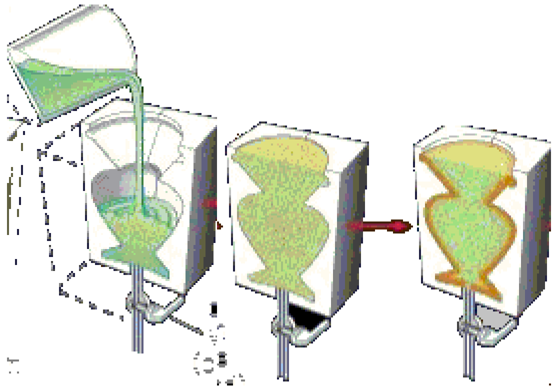
These ceramics are made up of both crystalline and non-crystalline elements that, when fired, are joined by a glassy matrix. The lining and clay items are included in this group. Bonded ceramics find applications in spark plugs, furnace refractory, electrical insulators, and other areas.[1]

1. **Fabrication of Advanced Ceramics:** Advanced ceramics are created using a multitude of techniques. A product's process selection is determined by its materials, shape complexity, cost, and suitability requirements. Ceramics are manufactured by the application of heat upon processed clays or other raw materials to form rigid products. The common shape forming methods for ceramics are

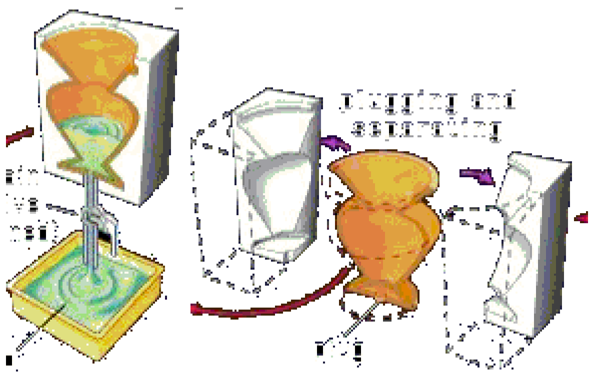
(a) Slip casting method
(b) Isostatic pressing method

(a) Slip Casting method: One of the more sophisticated methods of manufacturing ceramics into complex shapes that we use today is called slip casting. It is a method of producing ceramics with different shapes and sizes without use of heat

- **Step 1 -**Mix a fine ceramic powder in water, along with some chemicals that help the powder to disperse throughout the liquid, you create what is called a slip.
- **Step 2-** The slip is poured into a mold that removes some of the liquid from the slip near the mold wall



1. Fill mold with slip   2 Formation of Cast



3 Excess slip draining   4 Removing Cast

- **Step3** Now soda ash is added to the slip to break the cluster of particles into uniform dispersed individual particles
- **Step 4** The water from slurry begins to move out through porous mold by capillary action
- **Step 5** When a sufficiently thicker cast is formed the rest of the slurry is removed. This process is called **drain casting**
- **Step 6** Mold and cast is allowed to dry. After drying casting (green ceramics) is removed from the mold
- **Step 7** The green ceramic is then dried and sintered at high temperature

Use of Slip Casting

1. Low cost to make complex shapes
2. Use to make teapot, jugs, statues etc
3. standard method to make alumina crucible

(b) Isostatic Pressing: It involves application of hydrostatic pressure to a powder in a flexible container. It results in uniform compaction of the powder. Isostatic pressing can be done either with or without applied heat.

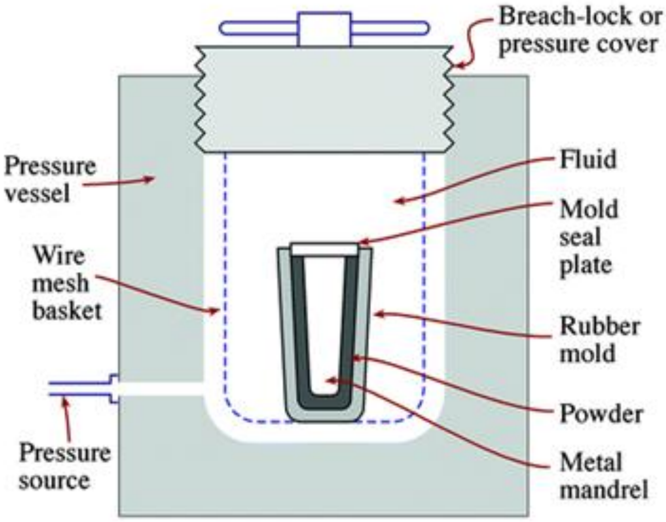
The two types of isostatic pressing are

1. Cold isostatic pressing
2. Hot isostatic pressing

1. **Cold Isostatic Pressing:** A Powder-shaping technique with hydrostatic pressure without any high temperature is called cold isostatic pressing(CIP). There are two processes used in CIP. They are

- Wet-bag cold isostatic pressing
- ❖ Dry-bag cold isostatic pressing

- ❖ **Wet-bag cold Isostatic Pressing:** The wet-bag CIP process is illustrated in figure



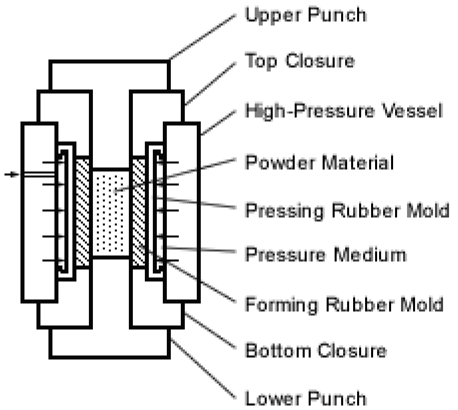
The following steps were adopted during the processing

- **Step 1** The powder is weighed into a rubber mold
- **Step2 T**he rubber bag is sealed by a metal mandrel over which mold seal plate is fixed
- **Step 3** The sealed rubber bag is placed inside a high pressure chamber that is filled with a fluid which is hydrostatically pressed
- **Step 4** The pressure is varied from about 20 MPa to 1GPa depending upon the application
- **Step 5** Once the pressing is complete the pressure is released slowly
- **Step 6** After the pressure is released the mold is removed from the chamber
- **Step 7** Finally the component is removed from the mold

Advantage
1. Wide range of shape and size can be produced
2. Pressed products have uniform density
3. Tooling cost is low

Disadvantage
1. It has poor shape
2. Needs green machining after pressing
3. It takes long cycle time with low product rates

❖ **Dry-Bag Cold Isostatic Pressing:** The Schematic diagram of a mol;d for the dry-bag CIP is shown in figure



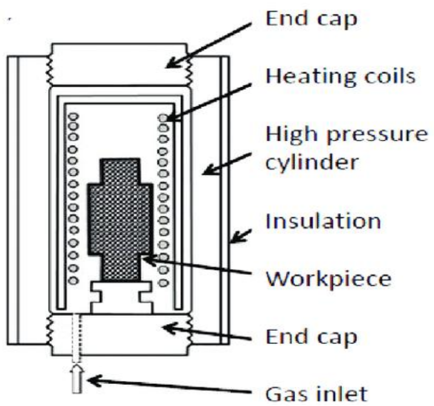
Process
The following steps were adopted during the processing

- **Step 1** Powder is taken in rubber mold which is the integral part of the process
- **Step 2** High pressure fluid nis applied using high pressure vessel
- **Step 3** The top & bottom closure and upper & lower punch help to hold the mold tightly while pressing
- **Step 4** the pressed ceramic part is removed without disturbing the mold

Advantage
1. The process can be fully automated
2. the production rates up to 1 part per second are being achieved

Uses
1. dry-bag CIP is used in the production of spark plug insulators
2. AC spark plugs are also produced by this method

2. **Hot Isostatic Pressing (HIP):** HIP is a method used to densify a material by imposing the heat and pressure simultaneously. The pressure is applied from all the direction via the pressurized gas such as argon gas



- **Construction**
  - It consists of water cooled pressure vessel within which a furnace, thermally insulated form the pressure vessel
  - Heating element is arranged in multiple banks which can be controlled individually to obtain uniform temperature
  - Temperature is controlled by thermocouple while the gas pressure is controlled by compressor system
  - Excess pressure is released using vacuum pumps and materials pump
  - Furnaces are generally convection type heating elements covered by upper cover and cooling jacket.

- **Working**
  - The material to be prepared is kept inside the furnace
  - The mold is degassed after filling the powder, then after sealed using upper cover
  - The furnace heats tha material to be pressed, at the same time a pressuring medium, usually argon gas, is used to apply high pressure.
  - The temperature and the pressure is raised to the desire level
  - Furnace allowed to cool followed by depressuring the chamber and remove the parts
  - In this process isotropic properties, parts with zero pores are obtained in continuous materials.

Advantage

1. Various size and shape can be made
2. HIP results in improved and enhanced mechanical property
3. Tooling and machining is not required
4. HIP produces dense material without growing grains
5. Increase in design flexibility

Disadvantage

1. Cost is High
2. Design of equipments is complex

Uses

1. Used to fabricate components of metal
2. Used for bonding dissimilar material
3. Used for the formation of piezoelectric ceramics such as $BaTiO_3$ for acoustic wave fibrand oscillators

- **Properties of Ceramic Fibers**

  The ceramics possess the following properties

  a) Thermal properties
  b) Mechanical Properties
  c) Electrical properties
  d) Chemical Properties

a) Thermal Properties

- Ceramic Fibers is basically in amorphous state may be changes to crystalline state at **devitrification temperature**
- The ceramics fibers possess very low thermal conductivity and act as a insulators and it increases when density increases
- Ceramics are unaffected by thermal shock i.e no cracks or disintegration for sudden change in temperature
- Ceramic Fibers are zero coefficient of thermal expansion

b) Mechanical properties

- Ceramic fibers exhibit high tensile strength
- Compressive strength is several times more than tensile strength
- It has a high modulus of elasticity. This elastic modulus decreases with increase in the temperature.
- Non-crystalline ceramics are brittle

c) Electrical properties

- In general oxide ceramics (Al_2O_3) are poor electrical conductors than non-oxide ceramics fibers (SiC)
- Cubic boron nitride are good conductors of electricity
- SiC used as semiconductors in high temperature applications
- High temperature superconductors ($YBa_2Cu_3O_{7-x+)}$ is ceramic material

d) Chemical Properties

- Several ceramic fibers (Al_2O_3, SiC) are highly resistant to all chemicals except Hydrofluoric acid.
- Oxide ceramic fibers are resistant to oxidation even at high temperature
- It is corrosion characteristics similar to glass fiber

❖ **Various Applications of Ceramics:** Based on its principal purpose or application, advanced ceramics can be further split into structural and electronic ceramics. Ceramics are useful in a variety of applications based on their mechanical strength and its usage in industrial applications. Some of the important advanced ceramics are discussed below.

S.No	Fields	uses
1	Electronics	Ceramics are utilized in electronic packaging, substrates, chip carriers, resistors, capacitors, inducers, and electrical insulation transducers, as well as in capacitors, seers, and electrode igniters. Spark plug insulators and motor magnets

2	Advanced structural materials	Cutting tools, wear-resistant inserts, engine components, resistant coatings, dental and orthopedic prosthesis, and high-efficiency lighting are some applications for advanced structural materials.
3	Chemical processing components	Currently, catalyst support, liquid and gas filters, emission control components, and ion exchange medium all use chemical processing components.
4.	Refractory materials	Refractory materials are employed in many different fields these days, including heating elements, filters, molds, recuperators, regenerators, furnace linings, thermo insulation, and recyclables.
5	Construction materials	Cement, concrete, tile, and structural clay products are examples of construction materials.
6	Institutional and domestic products	Products used in homes and institutions, including kitchenware, dinnerware and china from hotels, bathroom fixtures, decorative fixtures, and household goods

III. BIOCERAMIC MATERIALS

Bioceramic materials are specially prepared with high density, small and uniform grain sizes of 5 micrometer. They have been used for hip implants dental implants middle ear implants and heart valves.

Ceramics made of Alumina, Zirconia and Carbon are called bio inert ceramics. Alumina has excellent corrosion resistance good biocompatibility, high strength and high wear resistance.

Alumina, Zirconia-It is used for morphological fixation (Nearly inert).

Hydroxyapatite (HA) it is a bioactive glass which can form strong bonding with bones. HA has very good biocompatibility with hard tissues, skin and muscle tissue.

Porous HA has better biocompatibility but poor mechanical properties. Porous HA cannot be used for heavy loaded implants such as artificial teeth or bones. It is medical application are limited to small unloaded implants, powders coating and low loaded porous implants.

Medical application	materials
Prosthetic Joints (hip, knee, shoulder elbow wrist)	Co-Cr-Mo alloys Ti Ti-Al- alloys
Artificial Tendon and ligaments	Carbon fibre composites
Spinal surgery	Bio active glass/ceramics HA
Artificial heart values	Pyrolytic carbon coating
Heart pacemaker	Can 316 stainless steel Electrode Pl-Pt-Ir

Advantages of ceramics:

Very biocompatibility:- Biocompatibility has also been described as the ability of a material to perform with an appropriate host response in a specific application.

Inert strong in compression

Disadvantages of ceramics:

Brittle

Difficult to make

Not resilient

IV. CONCLUSION

Advanced ceramics play a critical role in modern engineering and technology due to their unique properties such as high hardness, wear resistance, chemical stability, and excellent thermal and electrical performance. Their versatility allows for diverse applications across fields like electronics, construction, medicine, and advanced structural materials. The development of advanced fabrication techniques, including slip casting, isostatic pressing, and sintering, has enabled the production of high-precision components tailored for specific needs.

Bioceramics, with their biocompatibility and specialized properties, have revolutionized medical applications, particularly in implants and prosthetics. However, challenges such as brittleness and production complexity must be addressed to expand their scope further. Despite these limitations, advanced ceramics remain indispensable in pushing the boundaries of innovation and technology. Their evolving capabilities continue to drive advancements across industries, proving their importance in the modern material landscape.

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