CERAMICS

- Structure and Properties of Ceramics
- Traditional Ceramics
- New Ceramics
- Glass
- Some Important Elements Related to Ceramics
- Guide to Processing Ceramics

Ceramic Defined

An inorganic compound consisting of a metal (or semi-metal) and one or more nonmetals

- Important examples:
  - *Silica* - silicon dioxide (SiO_2), the main ingredient in most glass products
  - *Alumina* - aluminum oxide (Al_2O_3), used in various applications from abrasives to artificial bones
  - More complex compounds such as hydrous aluminum silicate ($Al_2Si_2O_5(OH)_4$), the main ingredient in most clay products

Properties of Ceramic Materials

- High hardness, electrical and thermal insulating, chemical stability, and high melting temperatures
- Brittle, virtually no ductility - can cause problems in both processing and performance of ceramic products
- Some ceramics are translucent, window glass (based on silica) being the clearest example

Ceramic Products

- *Clay construction products* - bricks, clay pipe, and building tile
- *Refractory ceramics* - ceramics capable of high temperature applications such as furnace walls, crucibles, and molds
- *Cement* used in *concrete* - used for construction and roads
- *Whiteware products* - pottery, stoneware, fine china, porcelain, and other tableware, based on mixtures of clay and other minerals

Ceramic Products (continued)

- *Glass* - bottles, glasses, lenses, window pane, and light bulbs
- *Glass fibers* - thermal insulating wool, reinforced plastics (fiberglass), and fiber optics communications lines
- *Abrasives* - aluminum oxide and silicon carbide
- *Cutting tool materials* - tungsten carbide, aluminum oxide, and cubic boron nitride

Ceramic Products (continued)

- *Ceramic insulators* - applications include electrical transmission components, spark plugs, and microelectronic chip substrates
- *Magnetic ceramics* – example: computer memories
- *Nuclear fuels* based on uranium oxide (UO_2)
- *Bioceramics* - artificial teeth and bones

Three Basic Categories of Ceramics

1. *Traditional ceramics* - clay products such as pottery and bricks, common abrasives, and cement
2. *New ceramics* - more recently developed ceramics based on oxides, carbides, etc., and generally possessing mechanical or physical properties superior or unique compared to traditional ceramics
3. *Glasses* - based primarily on silica and distinguished by their noncrystalline structure
   – In addition, *glass ceramics* - glasses transformed into a largely crystalline structure by heat treatment

Strength Properties of Ceramics

- Theoretically, the strength of ceramics should be higher than metals because their covalent and ionic bonding types are stronger than metallic bonding
- However, metallic bonding allows for slip, the basic mechanism by which metals deform plastically when subjected to high stresses
- Bonding in ceramics is more rigid and does not permit slip under stress
- The inability to slip makes it much more difficult for ceramics to absorb stresses

Imperfections in Crystal Structure of Ceramics

- Ceramics contain the same imperfections in their crystal structure as metals - vacancies, displaced atoms, interstitialcies, and microscopic cracks
- Internal flaws tend to concentrate stresses, especially tensile, bending, or impact
  - Hence, ceramics fail by brittle fracture much more readily than metals
  - Performance is much less predictable due to random imperfections and processing variations

Compressive Strength of Ceramics

- The frailties that limit the tensile strength of ceramic materials are not nearly so operative when compressive stresses are applied
- Ceramics are substantially stronger in compression than in tension
- For engineering and structural applications, designers have learned to use ceramic components so that they are loaded in compression rather than tension or bending

Methods to Strengthen Ceramic Materials

- Make starting materials more uniform
- Decrease grain size in polycrystalline ceramic products
- Minimize porosity
- Introduce compressive surface stresses
- Use fiber reinforcement
- Heat treat

Physical Properties of Ceramics

- Density – in general, ceramics are lighter than metals and heavier than polymers
- Melting temperatures - higher than for most metals
  - Some ceramics decompose rather than melt
- Electrical and thermal conductivities - lower than for metals; but the range of values is greater, so some ceramics are insulators while others are conductors
- Thermal expansion - somewhat less than for metals, but effects are more damaging because of brittleness

Traditional Ceramics

Based on mineral silicates, silica, and mineral oxides found in nature

- Primary products are fired clay (pottery, tableware, brick, and tile), cement, and natural abrasives such as alumina
- Products and the processes to make them date back thousands of years
- Glass is also a silicate ceramic material and is sometimes included among traditional ceramics

Raw Materials for Traditional Ceramics

- Mineral silicates, such as *clays* of various compositions, and *silica*, such as quartz, are among the most abundant substances in nature and constitute the principal raw materials for traditional ceramics
- Another important raw material for traditional ceramics is *alumina*
- These solid crystalline compounds have been formed and mixed in the earth's crust over billions of years by complex geological processes

Clay as a Ceramic Raw Material

- Clays consist of fine particles of hydrous aluminum silicate
  - Most common clays are based on the mineral *kaolinite*, ($Al_2Si_2O_5(OH)_4$)
- When mixed with water, clay becomes a plastic substance that is formable and moldable
- When heated to a sufficiently elevated temperature (*firing*), clay fuses into a dense, strong material
  - Thus, clay can be shaped while wet and soft, and then fired to obtain the final hard product

Silica as a Ceramic Raw Material

- Available naturally in various forms, most important is *quartz*
  - The main source of quartz is *sandstone*
- Low in cost; also hard and chemically stable
- Principal component in glass, and an important ingredient in other ceramic products including whiteware, refractories, and abrasives

Alumina as a Ceramic Raw Material

- *Bauxite* - most alumina is processed from this mineral, which is an impure mixture of hydrous aluminum oxide and aluminum hydroxide plus similar compounds of iron or manganese
  - Bauxite is also the principal source of metallic aluminum
- *Corundum* - a more pure but less common form of Al_2O_3, which contains alumina in massive amounts
- Alumina ceramic is used as an abrasive in grinding wheels and as a refractory brick in furnaces

Traditional Ceramic Products

- Pottery and Tableware
- Brick and tile
- Refractories
- Abrasives

New Ceramics

Ceramic materials developed synthetically over the last several decades

- The term also refers to improvements in processing techniques that provide greater control over structures and properties of ceramic materials
- In general, new ceramics are based on compounds other than variations of aluminum silicate, which form most of the traditional ceramic materials
- New ceramics are usually simpler chemically than traditional ceramics; for example, oxides, carbides, nitrides, and borides

Oxide Ceramics

- Most important oxide new ceramic is *alumina*
- Although also included as a traditional ceramic, alumina is today produced synthetically from bauxite, using an electric furnace method
- Through control of particle size and impurities, refinements in processing methods, and blending with small amounts of other ceramic ingredients, strength and toughness of alumina are improved substantially compared to its natural counterpart
- Alumina also has good hot hardness, low thermal conductivity, and good corrosion resistance

Products of Oxide Ceramics

- Abrasives (grinding wheel grit)
- Bioceramics (artificial bones and teeth)
- Electrical insulators and electronic components
- Refractory brick
- Cutting tool inserts
- Spark plug barrels
- Engineering components

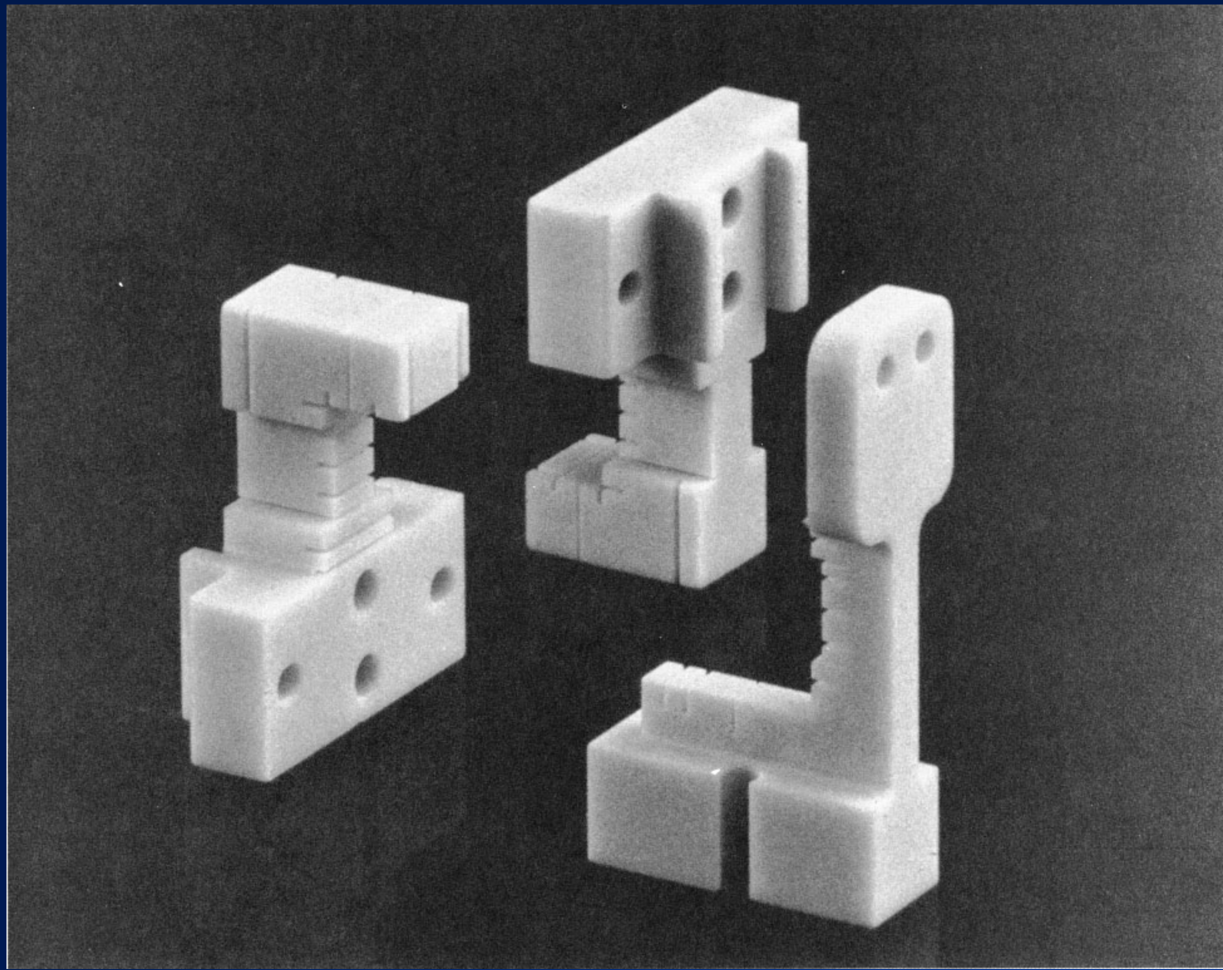

Figure 7.1 - Alumina ceramic components
(photo courtesy of Insaco Inc.)

Carbides

- Silicon carbide (SiC), tungsten carbide (WC), titanium carbide (TiC), tantalum carbide (TaC), and chromium carbide (Cr_3C_2)
- Although SiC is a man-made ceramic, its production methods were developed a century ago, and it is generally included in traditional ceramics group
- WC, TiC, and TaC are valued for their hardness and wear resistance in cutting tools and other applications requiring these properties
- WC, TiC, and TaC must be combined with a metallic binder such as cobalt or nickel in order to fabricate a useful solid product

Nitrides

- The important nitride ceramics are silicon nitride (Si_3N_4), boron nitride (BN), and titanium nitride (TiN)
- Properties: hard, brittle, high melting temperatures, usually electrically insulating, TiN being an exception
- Applications:
  - Silicon nitride: components for gas turbines, rocket engines, and melting crucibles
  - Boron nitride and titanium nitride: cutting tool material and coatings

Glass

- A state of matter as well as a type of ceramic
- As a state of matter, the term refers to an amorphous (noncrystalline) structure of a solid material
  - The glassy state occurs in a material when insufficient time is allowed during cooling from the molten state for the crystalline structure to form
- As a type of ceramic, *glass* is an inorganic, nonmetallic compound (or mixture of compounds) that cools to a rigid condition without crystallizing

Why So Much SiO_2 in Glass?

- Because SiO_2 is the best *glass former*
  - Silica is the main component in glass products, usually comprising 50% to 75% of total chemistry
  - It naturally transforms into a glassy state upon cooling from the liquid, whereas most ceramics crystallize upon solidification

Other Ingredients in Glass

- Sodium oxide (Na_2O), calcium oxide (CaO), aluminum oxide (Al_2O_3), magnesium oxide (MgO), potassium oxide (K_2O), lead oxide (PbO), and boron oxide (B_2O_3)
- Functions:
  - Act as flux (promoting fusion) during heating
  - Increase fluidity in molten glass for processing
  - Improve chemical resistance against attack by acids, basic substances, or water
  - Add color to the glass
  - Alter index of refraction for optical applications

Glass Products

- Window glass
- Containers – cups, jars, bottles
- Light bulbs
- Laboratory glassware – flasks, beakers, glass tubing
- Glass fibers – insulation, fiber optics
- Optical glasses - lenses

Glass-Ceramics

A ceramic material produced by conversion of glass into a polycrystalline structure through heat treatment

- Proportion of crystalline phase range = 90% to 98%, remainder being unconverted vitreous material
- Grain size - usually between 0.1 - 1.0 μm (4 and 40 μ-in), significantly smaller than the grain size of conventional ceramics
  - This fine crystal structure makes glass-ceramics much stronger than the glasses from which they are derived
- Also, due to their crystal structure, glass-ceramics are opaque (usually grey or white) rather than clear

Processing of Glass Ceramics

- Heating and forming operations used in glassworking create product shape
- Product is cooled and then reheated to cause a dense network of crystal nuclei to form throughout
  - High density of nucleation sites inhibits grain growth, leading to fine grain size
- Nucleation results from small amounts of nucleating agents in the glass composition, such as TiO_2, P_2O_5, and ZrO_2
- Once nucleation is started, heat treatment is continued at a higher temperature to cause growth of crystalline phases

Advantages of Glass-Ceramics

- Efficiency of processing in the glassy state
- Close dimensional control over final product shape
- Good mechanical and physical properties
  - High strength (stronger than glass)
  - Absence of porosity; low thermal expansion
  - High resistance to thermal shock
- Applications:
  - Cooking ware
  - Heat exchangers
  - Missile radomes

Elements Related to Ceramics

- Carbon
  - Two alternative forms of engineering and commercial importance: *graphite* and *diamond*
- Silicon
- Boron
- Carbon, silicon, and boron are not ceramic materials, but they sometimes
  - Compete for applications with ceramics
  - Have important applications of their own

Graphite

Form of carbon with a high content of crystalline C in the form of layers

- Bonding between atoms in the layers is covalent and therefore strong, but the parallel layers are bonded to each other by weak van der Waals forces
- This structure makes graphite anisotropic; strength and other properties vary significantly with direction
  - As a powder it is a lubricant, but in traditional solid form it is a refractory
  - When formed into graphite fibers, it is a high strength structural material

Diamond

Carbon with a cubic crystalline structure with covalent bonding between atoms

- This accounts for high hardness

- Industrial applications: cutting tools and grinding wheels for machining hard, brittle materials, or materials that are very abrasive; also used in dressing tools to sharpen grinding wheels that consist of other abrasives
- Industrial or synthetic diamonds date back to 1950s and are fabricated by heating graphite to around 3000°C (5400°F) under very high pressures

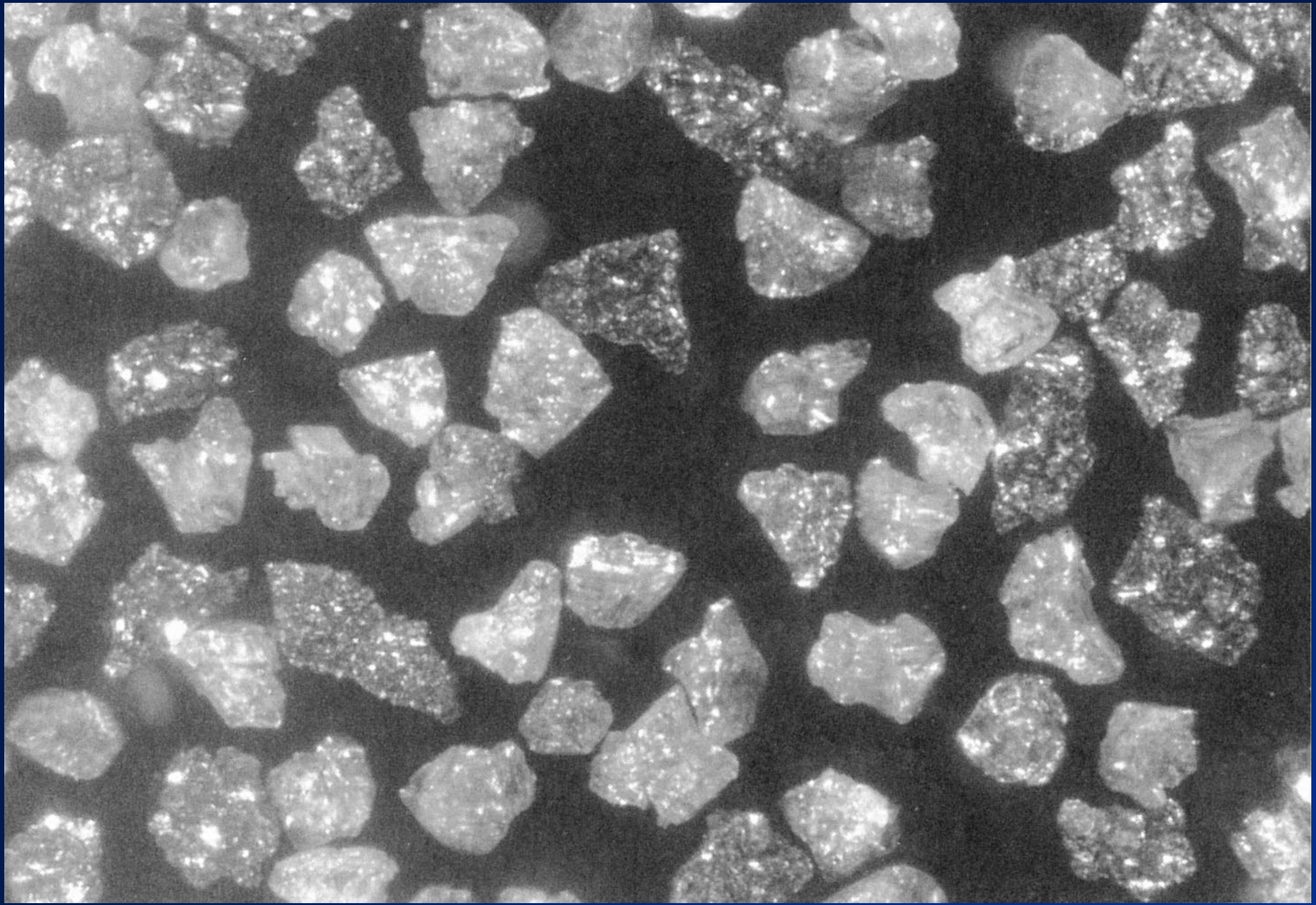

Figure 7.2 - Synthetically produced diamond powders (photo courtesy GE Superabrasives, General Electric Company)

Silicon

Semi-metallic element in the same periodic table group as carbon

- One of the most abundant elements in Earth's crust, comprising ~ 26% by weight
- Occurs naturally only as chemical compound - in rocks, sand, clay, and soil - either as silicon dioxide or as more complex silicate compounds
- Properties: hard, brittle, lightweight, chemically inactive at room temperature, and classified as a semiconductor

Applications and Importance of Silicon

- Greatest amounts in manufacturing are in ceramic compounds (SiO_2 in glass and silicates in clays) and alloying elements in steel, aluminum, and copper
- Also used as a reducing agent in certain metallurgical processes
- Of significant technological importance is pure silicon as the base material in semiconductor manufacturing in electronics
- The vast majority of integrated circuits produced today are made from silicon

Boron

Semi-metallic element in same periodic group as aluminum

- Comprises only about 0.001% of Earth's crust by weight, commonly occurring as minerals *borax* ($Na_2B_4O_7$- $10H_2O$) and *kernite* ($Na_2B_4O_7$-$4H_2O$)
- Properties: lightweight, semiconducting properties, and very stiff (high modulus of elasticity) in fiber form
- Applications: B_2O_3 used in certain glasses, as a nitride (cBN) for cutting tools, and in nearly pure form as a fiber in polymer matrix composites

Guide to Processing Ceramics

- Processing of ceramics can be divided into two basic categories:
  1. Molten ceramics - major category of molten ceramics is glassworking (solidification processes)
  2. Particulate ceramics - traditional and new ceramics (particulate processing)