16.982 Bio-Inspired Structures
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Ceramics and Glasses

Definitions

Ceramic: Inorganic compounds that contain metallic and non-metallic elements, for which inter-atomic bonding is ionic or covalent, and which are generally formed at high temperatures.

Glass: (i) An inorganic product of fusion that has cooled to a rigid condition without crystallization; (ii) An amorphous solid.

Definitions

Amorphous: (i) Lacking detectable crystallinity; (ii) possessing only short-range atomic order; also *glassy* or *vitreous*

Glass-ceramic: Polycrystalline solids prepared by the controlled crystallization (devitrification) of glasses.

Bioactive material: A material that elicits a specific biological response at the interface of the material, resulting in the formation of a bond between the tissues and the material.

Crystal versus Glassy Ceramics

- Crystalline ceramics have long-range order, with components composed of many individually oriented grains.
- Glassy materials possess short-range order, and generally do not form individual grains.
- The distinction is made based on x-ray diffraction characteristics.
- Most of the structural ceramics are crystalline.

Metal- Ceramic Comparison

Property	Units	Ti6A1 4V	316 SS	CoCr Alloy	TZP	Alumina
Young's modulus	GPa	110	200	230	210	380
Strength	MPa	800	650	700	900-1200	>500
Hardness	HV	100	190	300	1200	2200

Figure by MIT OpenCourseWare.

- Stiffness is comparable to the metal alloys
- The biggest problem is fracture toughness (sensitivity to flaws).
- <u>Rigid plastics</u> < <u>Ceramics</u> = <u>Metals</u>

Advantages:

- inert in body (or bioactive in body); Chemically inert in many environments
- high wear resistance (orthopedic & dental applications)
- high modulus (stiffness) & compressive strength
- esthetic for dental applications

Disadvantages

- brittle (low fracture resistance, flaw tolerance)
- low tensile strength (fibers are exception)
- poor fatigue resistance (relates to flaw tolerance)

Basic Applications:

Orthopedics:

- bone plates and screws
- total & partial hip components (femoral head)
- coatings (of metal prostheses) for controlled implant/tissue interfacial response
- space filling of diseased bone
- vertebral prostheses, vertebra spacers, iliac crest prostheses

Dentistry:

- dental restorations (crown and bridge)
- implant applications (implants, implant coatings, ridge maintenance)
- orthodontics (brackets)
- glass ionomer cements and adhesives

Veneers: Before and after

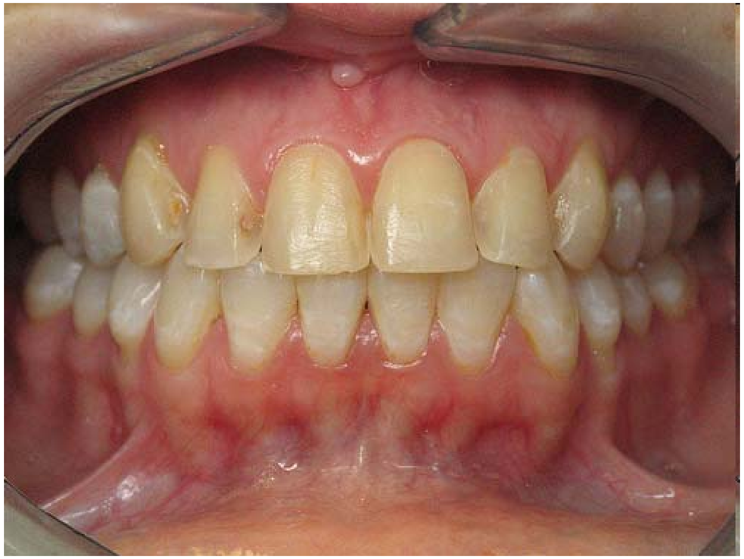

Image by daftgirly on Flickr.

Other:

- inner ear implants (cochlear implants)
- drug delivery devices
- ocular implants
- heart valves

Ceramics

- Alumina, Zirconium, Hydroxyapatite, Calcium phosphates, Bioactive glasses are common
- Porous ceramic materials exhibit much lower strengths but have been found extremely useful as coatings for metallic implants.
- The coating aids in tissue fixation of the implant by providing a porous surface for the surrounding tissue to grow into and mechanically interlock.
- Certain ceramics are considered bioactive ceramics if they establish bonds with bone tissue.

Hip Implant

Osteointegration

- Fast mineralization of the surface
- Surface colonization by the osteoblasts
- Stable binding between the formed mineral phase and the implant surface
- Structural continuity to the surrounding bone

Types of Bioceramic-Tissue Interactions:

Dense, inert, nonporous ceramics attach to bone (or tissue) growth into surface irregularities by press fitting into a defect as a type of adhesive bond (termed "morphological fixation")-Al_2O_3

Porous inert ceramics attach by bone resulting from ingrowth (into pores) resulting in mechanical attachment of bone to material (termed "biological fixation")-Al_2O_3

Dense, nonporous surface-reactive ceramics attach directly by chemical bonding with bone (termed "bioactive fixation")-bioactive glasses & Hydroxyapatite.

Processing of Ceramics

1. Compounding

- Mix and homogenize ingredients into a water based suspension = slurry

  or, into a solid plastic material containing water called a clay

2. Forming

- The clay or slurry is made into parts by pressing into mold (sintering). The fine particulates are often fine grained crystals.

3. Drying

- The formed object is dried, usually at room temperature to the so-called "green" or leathery state.

4. Firing

- Heat in furnace to drive off remaining water. Typically produces shrinkage, so producing parts that must have tight mechanical tolerance requires care.
- Porous parts are formed by adding a second phase that decomposes at high temperatures forming the porous structure.

Alumina (Al_2O_3) and Zirconia (ZrO_2)

The two most commonly used structural bioceramics.

- Primarily used as modular heads on femoral stem hip components.
- wear less than metal components, and the wear particles are generally better tolerated.

Alumina (Al_2O_3):

- single crystal alumina referred to as “Sapphire”
- “Ruby” is alumina with about 1% of Al3+ replaced by Cr3+; yields red color
- “Blue sapphire” is alumina with impurities of Fe and Ti; various shades of blue

Structure and Properties:

- most widely used form is polycrystalline
- unique, complex crystal structure
- strength increases with decreasing grain size
- elastic modulus (E) = 360-380 GPa

Fabrication of Biomedical devices from Al_2O_3 & (ZrO_2):

- devices are produced by pressing and sintering fine powders at temperatures between 1600 to 1700ºC.
- Additives such as MgO added (<0.5%) to limit grain growth

Dental Porcelain:

- ternary Composition = Mixture of K_2O-Al_2O_3-SiO_2 made by mixing *clays, feldspars, and quartz*

  CLAY = Hydrated alumino silicate

  FELDSPAR = Anhydrous alumino silicate

  QUARTZ = Anydrous Silicate

Calcium Phosphates

- Calcium phosphate compounds are abundant in nature and in living systems.
- Biologic apatites which constitute the principal inorganic phase in normal calcified tissues (e.g., enamel, dentin,bone) are carbonate hydroxyapatite, CHA.
- In some pathological calcifications (e.g., urinary stones, dental tartar or calculus, calcified soft tissues – heart, lung, joint cartilage)

Calcium hydroxyapatite $(Ca_{10}(PO_4)_6(OH)_2)$: HA

- Hydroxyapatite is the primary structural component of bone. As its formula suggests, it consists of Ca2+ ions surrounded by $PO_4$2– and OH– ions.

Calcium hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$): HA

- gained acceptance as bone substitute
- repair of bony defects, repair of periodontal defects, maintenance or augmentation of alveolar ridge, ear implant, eye implant, spine fusion, adjuvant to uncoated implants.

HA is : $Ca_{10}(PO4)_6(OH)_2$

- Since collagen is closely associated with HA in normal bone, it is a logical candidate for induction of a host response. In some cases bone growth in or near implanted HA is more rapid than what is found with control implants. In the literature HA is sometimes referred to as an "osteoinductive“ material. However, HA does not seem to induce bone growth in the same way as, say, BMP.

Bioceramic Coatings

- Coatings of hydroxyapatite are often applied to metallic implants (most commonly titanium/titanium alloys and stainless steels) to alter the surface properties.
- In this manner the body sees hydroxyapatite-type material which it appears more willing to accept.
- Without the coating the body would see a foreign body and work in such a way as to isolate it from surrounding tissues.
- To date, the only commercially accepted method of applying hydroxyapatite coatings to metallic implants is plasma spraying.

Bone Fillers

- Hydroxyapatite may be employed in forms such as powders, porous blocks or beads to fill bone defects or voids.
- These may arise when large sections of bone have had to be removed (e.g. bone cancers) or when bone augmentations are required (e.g maxillofacial reconstructions or dental applications).
- The bone filler will provide a scaffold and encourage the rapid filling of the void by naturally forming bone and provides an alternative to bone grafts.
- It will also become part of the bone structure and will reduce healing times compared to the situation, if no