Metals and alloys for biomedical applications

Fundamental of Materials Engineering
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Biomaterial

- A biomaterial is any substance (other than drugs) or combination of substances synthetic or natural in origin, which can be used for any period of time, as a whole or as a part of a system which treats, augments, or replaces any tissue, organ, or function of the body.
Biomaterials and applications

- Polymers
  - Skin/cartilage
  - Ocular implants
- Metals
  - Orthopedic screws/fixation
- Synthetic BIOMATERIALS
  - Bone replacements
  - Heart valves
- Ceramics
  - Dental implants
- Semiconductor Materials
  - Implantable microelectrodes
  - Biosensors

Drug Delivery Devices
# Materials for use in the body

<table>
<thead>
<tr>
<th>Materials</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymers (nylon, silicon Rubber, polyester, PTFE, etc)</td>
<td>Resilient Easy to Fabricate</td>
<td>Not strong Deforms with time May degrade</td>
<td>Blood vessels, Sutures, ear, nose, Soft tissues</td>
</tr>
<tr>
<td>Metals (Ti and its alloys Co-Cr alloys, stainless Steels)</td>
<td>Strong Tough ductile</td>
<td>May corrode, dense, Difficult to make</td>
<td>Joint replacement, Bone plates and Screws, dental root Implant, pacer, and suture</td>
</tr>
<tr>
<td>Ceramics (Aluminum Oxide, calcium phosphates, including hydroxyapatite carbon)</td>
<td>Very biocompatible Inert strong in compression</td>
<td>Difficult to make Brittle Not resilient</td>
<td>Dental coating Orthopedic implants Femoral head of hip</td>
</tr>
<tr>
<td>Composites (Carbon-carbon, wire Or fiber reinforced Bone cement)</td>
<td>Compression strong</td>
<td>Difficult to make</td>
<td>Joint implants Heart valves</td>
</tr>
</tbody>
</table>
(1) Toxicology

• A biomaterial should not be toxic, unless it is specifically engineered for such requirements (for example, a "smart bomb" drug delivery system that targets cancer cells and destroys them).

• Toxicology for biomaterials deals with the substances that migrate out of the biomaterials.

• It is reasonable to say that a biomaterial should not give off anything from its mass unless it is specifically designed to do so.
(2) Biocompatibility

• It is the ability of a material to perform with an appropriate host response in a specific application.

• "Appropriate host response" includes lack of blood clotting, resistance of bacterial colonization and normal heating.

• The operational definition of biocompatible "the patient is alive so it must be biocompatible".
(3) Dependence on Specific Anatomical Sites of Implantation

- Consideration of the anatomical site of an implant is essential.
- An intraocular lens may go into the lens capsule or the anterior chamber of the eye.
- A hip joint will be implanted in bone across an articulating joint space.
- A heart valve will be sutured into cardiac muscle and will contact both soft tissue and blood.
- Each of these sites challenges the biomedical device designer with special requirements for geometry, size, mechanical properties, and bioresponses.
Important biomaterials’ properties

(4) Mechanical and Performance Requirement

- Mechanical performance

<table>
<thead>
<tr>
<th>Device</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>A hip prosthesis</td>
<td>Must be strong and rigid</td>
</tr>
<tr>
<td>A tendon material</td>
<td>Must be strong and flexible</td>
</tr>
<tr>
<td>A heart valve leaflet</td>
<td>Must be flexible and tough</td>
</tr>
<tr>
<td>An articular cartilage substitute</td>
<td>Must be soft and elastomeric</td>
</tr>
<tr>
<td>A dialysis membrane</td>
<td>Must be strong and flexible but not elastomer</td>
</tr>
</tbody>
</table>

- Mechanical durability

- Physical and Chemical properties
  - Mechanical, Thermal and Corrosion properties
Metals as Biomaterials

- Excellent electrical, thermal and mechanical properties
- Some metals are used as passive substitutes for hard tissue replacement
  - Total hip
  - Knee joints
  - Bone plates and screws
  - Spinal fixation
  - Dental implant
  - Vascular stent
Metals in Orthopedic Devices

Hip Joints
Metal processing overview

Metal fabrication techniques

Forming operations
- Forging
- Rolling
- Extrusion
- Drawing

Casting
- Sand
- Die
- Investment
- Continuous

Miscellaneous
- Powder metallurgy
- Welding
Forming operations (forging, rolling, drawing, extrusion) are where the shape of metal is changed by plastic deformation.

Deformation must be induced by an external force or stress. The magnitude of which must exceed the yield strength of the material.

Forming processes are commonly classified into cold-working and hot-working operations.
Forming operation

- **Rolling (Hot or Cold Rolling)**
  (I-beams, rails, sheet & plate)

- **Forging (Hammering; Stamping)**
  (wrenches, crankshafts)
  
  - Often at elev. $T$
  
- **Drawing**
  (rods, wire, tubing)
  
  - Die must be well lubricated & clean

- **Extrusion**
  (rods, tubing)
  
  - Ductile metals, e.g. Cu, Al (hot)
Cold-working

- Temperature at which the deformation take place is “cold” relative to the absolute melting temperature.
- Cold-working (plastic deformation) of metal results in an increase in strength or hardness and a decrease in ductility.
- Close dimensional control of the finished piece.
- Good quality surface finish.
- When cold-working is excessive, the metal will fracture before reaching the final shape.
Cold working

• The phenomenon whereby ductile metal becomes harder and stronger as it is plastically deformed is called “strain hardening” or “work hardening” or “cold working”

\[
\%CW = \left( \frac{A_0 - A_d}{A_0} \right) \times 100
\]

• Dislocation density increases with deformation or cold work. As the dislocation density increases, the resistance to dislocation motion by other dislocations become more pronounced.
Impact of cold work

Cold work will lead to:

- Increase of Yielding Strength
- Increase of Tensile Strength
- Reduction of Elongation

Material becomes stronger but more brittle
Microstructure Change after Cold Work

Oriented grain structure after cold work

Alteration of the grain structure of a polycrystalline metal as a result of plastic deformation. (a) Before deformation the grains are equiaxed. (b) The deformation has produced elongated grains. 170x.

Work (strain) hardening

Work hardening (or cold working) is the strengthening of a metal by plastic deformation.

Reason: Increasing dislocation density and the interaction between dislocations, which reduces dislocation mobility. As a result, larger stresses must be applied in order that additional deformation may take place.

\[
\sigma_T = K \varepsilon^n_T
\]

\[n = \text{strain hardening exponent} \quad \text{measures the ability of a metal to harden}\]
Work hardening: Mechanism

Dislocation Interactions make it difficult to move

With each other:
  • annihilate
  • entangle
  • form generators

With grain boundaries:
  • disappear
  • pileups

Thus, small grained material is stronger because more grain boundary area -> more pileups
Summary - Cold Working

The effects of plastically deformed polycrystalline metal at temperature less than its melting temperature are:

(a) change in grain shape;
(b) strain hardening;
(c) increased dislocation density and
(d) stored energy.

The properties of the cold worked metal (partially or totally) can be restored by Recovery, Recrystallization and Grain Growth
Cold-working operations are usually carried out in several steps with annealing used to soften the cold-worked metal and restore ductility.
Recovery and Recrystallization

Recovery

- Elevated temperature enhances atomic diffusion.
- Reduction in number of dislocation and dislocation configurations are produced having low strain energy.

Recrystallization

- Formation of a new set of strain-free and equiaxed grains that have low dislocation density
- Extent of recrystallization depends on both time and temperature
- Driving force to produce new grain structure is the difference in internal energy between strained and unstrained material
Recrystallization Temperature

<table>
<thead>
<tr>
<th>Metal</th>
<th>Recrystallization Temperature °C</th>
<th>Melting Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>-4</td>
<td>327</td>
</tr>
<tr>
<td>Tin</td>
<td>-4</td>
<td>232</td>
</tr>
<tr>
<td>Zinc</td>
<td>10</td>
<td>420</td>
</tr>
<tr>
<td>Aluminum (99.999 wt%)</td>
<td>80</td>
<td>660</td>
</tr>
<tr>
<td>Copper (99.999 wt%)</td>
<td>120</td>
<td>1085</td>
</tr>
<tr>
<td>Brass (60 Cu–40 Zn)</td>
<td>475</td>
<td>900</td>
</tr>
<tr>
<td>Nickel (99.99 wt%)</td>
<td>370</td>
<td>1455</td>
</tr>
<tr>
<td>Iron</td>
<td>450</td>
<td>1538</td>
</tr>
<tr>
<td>Tungsten</td>
<td>1200</td>
<td>3410</td>
</tr>
</tbody>
</table>

Recrystallization temperature is minimum temperature at which complete recrystallization will occur within ~1 hour.

Increasing %CW enhances the rate of recrystallization, with the result that the recrystallization temperature is lowered.

Recrystallization temperature is $\frac{1}{3} < T_m < \frac{1}{2}$.
Hot-working

- **Hot working** refers to processes where metals are plastically deformed **above their recrystallization temperature**. This allows the materials to recrystallize during deformation and prevents the materials from strain hardening.

- Material remains relatively soft and ductile during deformation because it **does not strain harden**, hence **large deformations** are possible.

- Hot-working processes (rolling, extrusion or forging) is typically used in the first step of **converting cast ingot into wrought product**.
Hot-working

• Deformation energy requirements are less than that for cold-working.
• However, most metals experience some surface oxidation, which results in material loss and a poor final surface finish.
• The lower limit of the hot working temperature is determined by its recrystallization temperature. The upper limit for hot working is determined by excessive oxidation, grain growth, and undesirable phase transformation.
Forging

• Forging is the process where metal (Fe, Ti, Al) is heated and shaped by plastic deformation (compressive forces)
• The compressive force typically comes from successive blow or continuous pressing)
• Forged articles have outstanding grain structures and best combination of mechanical properties.
• Wrenches, automotive crankshafts and piston connecting rods generally formed by forging
Forging

- With proper design, the grain flow can be oriented in the direction of principal stresses encountered in actual use. Grain flow is the direction of the pattern that the crystals take during plastic deformation.

- Physical properties (such as strength, ductility and toughness) are much better in a forging than in the base metal that has crystals randomly oriented.

- Forgings are consistent from piece to piece, without any of the porosity, voids, inclusions and other defects. Also coating operations such as plating or painting are straightforward due to a good surface that needs very little preparation.
Die Forging

Open-Die Forging

Closed-Die Forging

- Ram
- Upper die
- Lower die
- Anvil
- Pre-heated metal billet
- Flash
- Load
- Completed forging
Metal processing overview

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Casting

- **Casting** is pouring liquid metal into carefully designed mould cavity and solidifies into a desired shape under controlled conditions

- The **first step** in all manufacturing processes involving metal
Casting techniques are used when

1. The finished shape is so large or complicated that any other method would be impractical

2. A particular alloy is so low in ductility that forming by either hot or cold working would be difficult

3. In comparison to other fabrication processes, casting is the most economical.
Investment Casting

**Investment casting** - A casting process that is used for making complex shapes or casting of precious metals, also known as the lost wax process.

- The pattern is made of low melting materials (such as plastic or wax) which is then coated with ceramic to form a mould.
- After the wax is melted and drained, metal is poured into the mould.
Investment Casting

- The process is more expensive than sand casting but provide superior surface finish and better controlled solidification conditions
- Very thin sections can be produced and the process allows for high dimensional accuracy

Applications:

complex shapes (e.g. superalloys turbine blade and turbocharger)

Costly materials (gold and silver jewellery, bronze sculpture and titanium medical parts)
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Additive Manufacturing (AM)

- A process of joining materials to make objects from 3D model data, usually layer upon layer.
- This definition is broadly applicable to all classes of materials including metals, ceramics, polymers, composites, and biological systems.

Directed Energy Deposition (DED)  Powder Bed Fusion (PBF)

Ref: Trumpf
State-of-the-Art Powder bed fusion

1. First layer.
2. n\textsuperscript{th} layer.
3. Loose powder removed, finished part revealed.
Selective Laser Melting (SLM)
Laser Powder Bed Fusion

In LPBF process, a laser beam scans across a thin layer of metallic powders, and locally melts the powders through to the layer below.

Many highly dynamic and transient physical phenomena involved because of the extremely high heating and cooling rates:

- Melting and partial vaporization of metallic powders
- Flow of the molten metal
- Powder ejection and re-distribution
- Rapid solidification
- Non-equilibrium phase transition
- etc.

Ref: Fraunhofer IWU
SLM processing parameters

The reliability and performance of the printed parts relies heavily on the final microstructure, embedded material discontinuities and surface quality.

Laser energy density, $E$, applied to a certain volume of powder material

$$E = \frac{P}{v \cdot t \cdot s}$$

- $P$ is the laser power (W)
- $v$ is the scan speed (mms$^{-1}$)
- $t$ is the layer thickness (mm)
- $s$ is scan spacing (mm)