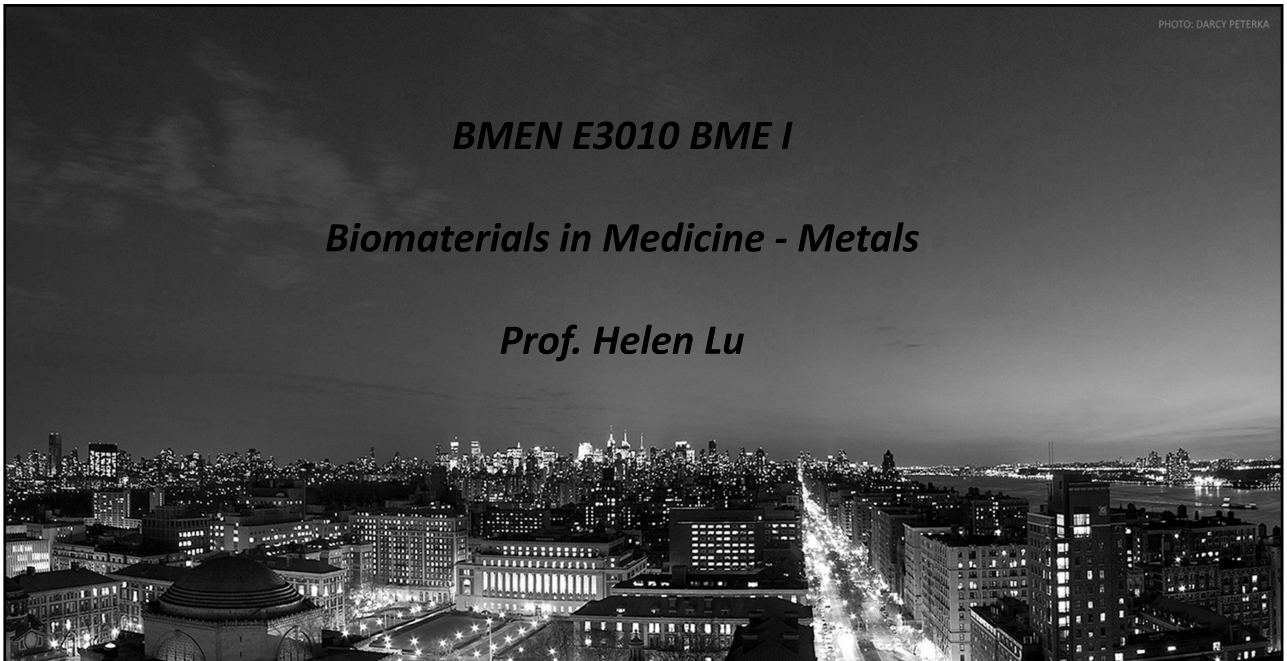


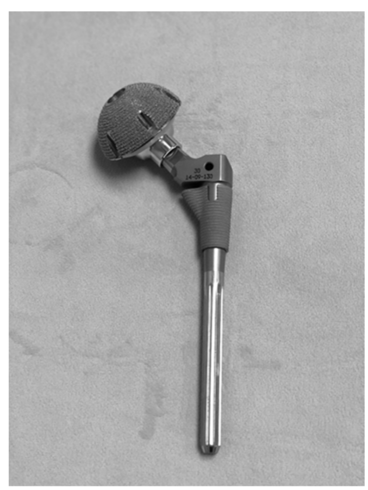
BMEN E3010 BME I

Biomaterials in Medicine - Metals

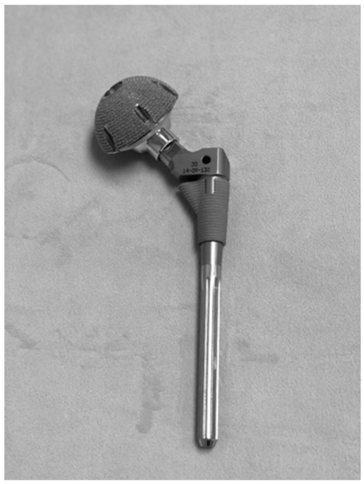
Prof. Helen Lu

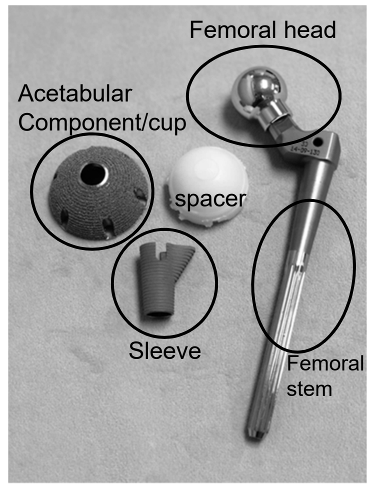
TYPES OF BIOMATERIALS

- **Metals**
- **Ceramics**
- **Polymers**
- **Glasses**
- **Glass-Ceramics**
- **Natural Materials**
- **Composites**



Medical Device Focus
Anatomy of a Prosthesis





For each type of Material: Metals

- **Composition**
- **Crystal structure**
- **Fabrication/Processing**
- **Functional properties - Mechanical**
- **Biocompatibility/Biofunctionality**
- **Of interest – current advances**

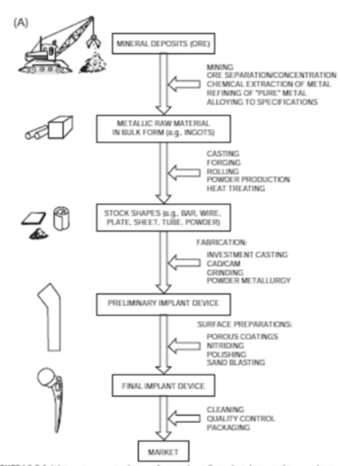
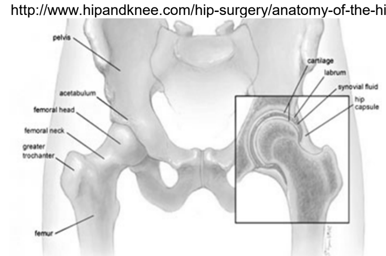


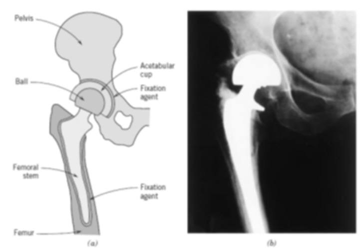
FIGURE I.2.3.1 (A) Generic processing history of a typical metallic implant device, in this case a hip implant.

Human Hip: a few Facts

- **Multi-tissue: Bone, cartilage, synovium, periosteum**
  - **Femur, Femoral head**
  - **Acetabullar cup**
  - **Hip socket**
- **Largest articulating joint with supraphysiologic loading**
- **Arthritis and trauma**
- **Total Hip Arthroplasty(THA)**
- **~450,000 THA/year in US**

http://www.hipandknee.com/hip-surgery/anatomy-of-the-hip/





Hip: Complex Forces/Loading

Example 5.5

F_M is the magnitude of the resultant force exerted by the hip abductor muscles

F_J is the magnitude of the JRF applied by the pelvis on the femur.

W_1 is the weight of the Leg

W is the BW as a ground reaction force on the one leg

Figure 5.24 *Forces acting on the right leg carrying the entire weight of the body.*

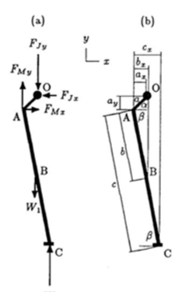


Figure 5.25 *Free-body diagram of the leg (a), and the geometric parameters (b).*

O is the axis of rotation of the hip joint.

A is where the hip abductor muscles attach.

B is the COG of the leg

C is where ground reaction force is applied to the foot

a,b,c are distances as shown, note that a is distance between A and O and gets resolved into ax and Ay

Find the force exerted by the hip abductor muscles (gluteus medius and minimus) and the JRF to support the hip and the leg as shown

the condition for the rotational equilibrium of the leg about O can be utilized to determine the magnitude of the resultant muscle force applied at A. Assuming that the clockwise moments are positive:

$$\sum M_O = 0: \quad a_x F_{My} - a_y F_{Mx} - (c_x - a_x) W + (b_x - a_x) W_1 = 0$$

Substituting Eqs. (*i*) through (*vi*) into the above equation:

$$(a \cos\alpha)(F_M \sin\theta) - (a \sin\alpha)(F_M \cos\theta) - (c \cos\beta - a \cos\alpha) W + (b \cos\beta - a \cos\alpha) W_1 = 0$$

Solving this equation for the muscle force:

$$F_M = \frac{(c W - b W_1) \cos\beta - a (W - W_1) \cos\alpha}{a (\cos\alpha \sin\theta - \sin\alpha \cos\theta)} \quad (vii)$$

Note that the denominator of Eq. (*vii*) can be simplified as $a \sin(\theta - \alpha)$. To determine the components of the joint reaction force, we can utilize the horizontal and vertical equilibrium conditions of the leg:

$$\sum F_x = 0: \quad F_{Jx} = F_{Mx} = F_M \cos\theta \quad (viii)$$

$$\sum F_y = 0: \quad F_{Jy} = F_{My} + W - W_1$$

$$F_{Jy} = F_M \sin\theta + W - W_1 \quad (ix)$$

Therefore, the resultant force acting at the hip joint is:

$$F_J = \sqrt{(F_{Jx})^2 + (F_{Jy})^2} \quad (x)$$

Assume that the geometric parameters of the problem and the weight of the leg are measured in terms of the person's height h and total weight W as follows: $a = 0.05h$, $b = 0.20h$, $c = 0.52h$, $\alpha = 45°$, $\beta = 80°$, $\theta = 70°$, and $W_1 = 0.17W$. The solution of the above equations for the muscle and joint reaction forces will yield $F_M = 2.6W$ and $F_J = 3.4W$, the joint reaction force making an angle $\phi = \tan^{-1}(F_{Jy}/F_{Jx}) = 74.8°$.

- **Articulating joint - supraphysiologic loading**
- **Standing: F-muscle = 2.6W, F-joint = 3.4W**
- **Jogging? Stumbling?**

Metals for Hip: Replace Bone

- **Most Common**
  - **Stainless Steel (SSL)**
    - **Cardiovascular**
    - **Orthopedic**
  - **Titanium & alloys**
    - **Dental**
    - **Orthopedic**
  - **Co-Cr Alloys**
    - **Orthopedics**
  - **Readings (Ratner: Sec.I.2.3, Sec. II.5.6; Calister: Chap.3,6,11, and 22.1-hip)**

Table 22.3 Mechanical Characteristics of Human Long Bone Both Parallel and Perpendicular to the Bone Axis

Property	*Parallel to Bone Axis*	*Perpendicular to Bone Axis*
Elastic modulus, GPa (psi)	17.4 (2.48×10^6)	11.7 (1.67×10^6)
Ultimate strength, tension, MPa (ksi)	135 (19.3)	61.8 (8.96)
Ultimate strength, compression, MPa (ksi)	196 (28.0)	135 (19.3)
Elongation at fracture	3–4%	—

Source: From D. F. Gibbons, "Biomedical Materials," pp. 253–254, in *Handbook of Engineering in Medicine and Biology,* D. G. Fleming and B. N. Feinberg, CRC Press, Boca Raton, FL, 1976. With permission.

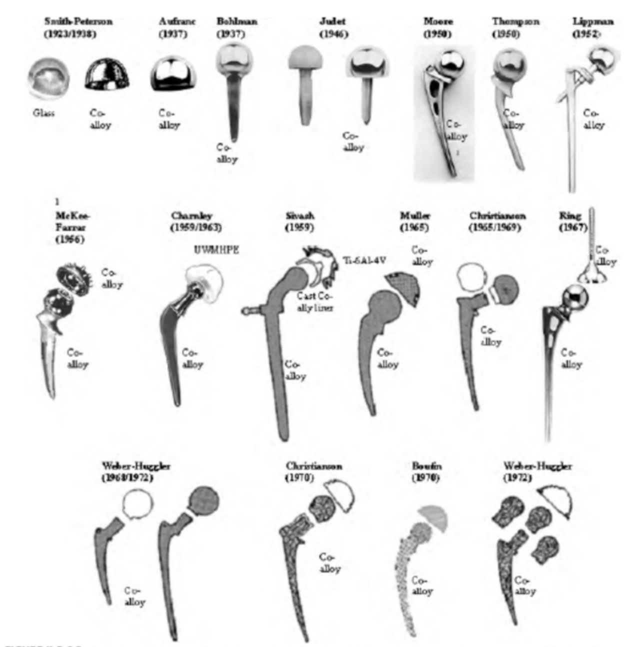


FIGURE II.5.6.2 The history of total hip arthroplasty is particularly pertinent to biomaterials science because it is one of the best illustrations of how an implant first used over a century ago has evolved to the highly successful status it has, primarily because of advances in biomaterials.

Hip: a *Material* History

Sir John Charnley (1911-1982)

https://player.understand.com/hss/en/a9a23aad-281c-45d6-afcd-80ad4cfa2502/3e5caddb-4e86-422c-925d-3e3662646360

Fabrication: Investment Casting

- Procedure (lost-wax process)
  - A wax mold is made with set surface patterns
  - Ceramic (investment) is plastered over wax
  - Heat to melting point of wax
  - Cast molten liquid into the ceramic mold
  - Cooling and solidification
  - Crack open the ceramic cast
- Advantages
  - High accuracy and fine detailing
  - Excellent finish with relatively smooth surface
- Metals and Polymers

FIGURE I.2.3.1 (B) Image of one step during the investment casting ("lost wax") process of manufacturing hip stems; a rack of hip stems can be seen attached to a system of sprues through which molten metal can flow. At this point, ceramic investment material composes the mold into which the molten metal will flow and solidify during casting, thereby replicating the intended shape of a hip stem.

Metals in Medicine: Stainless Steel

- AISI 316L
  - (ASTM F138 or F139, grade 2)
- Composition in wt%: ASTM F138, F139
  - 60-65% Fe
  - 17-20% Cr
  - 12-14% Ni
  - 2-3% Mo, 2% Mg
  - <0.03% C
  - Trace of Cu, N, P, Si, S and Mn

Crystal Structure

- 3-D Organization of Atoms
  - Unit cell: atoms arranged in repeating units
  - Unit cells are repeated spatially to achieve long range order
  - Each atom is bond to its neighbor
  - Found commonly in metals, most ceramics and some polymers
- Crystalline vs. non-crystalline
  - Amorphous
  - some ceramics and most polymers
  - *e.g.* Glass

Unit Cells and Crystal Systems

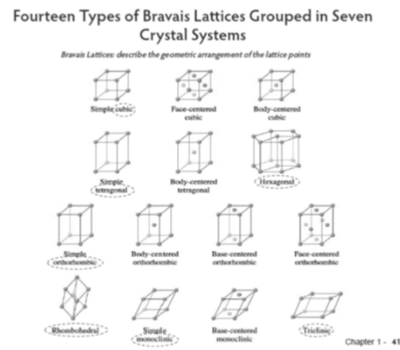
- Components of Unit Cell
  - Axial length (a, b, c)
    - Represents distance between atoms
  - Interstitial angles (α, β, γ)
    - α is b/t b and c, β is b/t a and c, γ is b/t a and b
  - Direction of bonding
  - Atomic packing factor (APF)

$$\text{APF} = \frac{\text{volume of atoms in a unit cell}}{\text{total unit cell volume}} = \frac{V_S}{V_C}$$

- Atomic models
  - Assume that all atoms are spherical
  - Reduced sphere unit cell model
  - Atomic hard sphere unit cell model

Crystal Structure - Lattices

- Seven (7) Crystal systems
  - Cubic, tetragonal, orthorhombic, triclinic, rhombohedral, hexagonal, monoclinic
- Fourteen (14) crystal lattices
  - Face centered cubic (FCC)
  - Body centered cubic (BCC)
  - Hexagonal close packed (HCP)
- For Biomaterials
  - Hexagonal – Titanium
    - $a=b \neq c$, $\alpha=\beta=90^{\circ}$, $\gamma=120^{\circ}$
  - Cubic – Stainless steel, ceramics
    - $a=b=c$, $\alpha=\beta=\gamma=90^{\circ}$
  - Orthorhombic: ceramics and polymers (polyethylene)
    - $a \neq b \neq c$, $\alpha=\beta=\gamma=90^{\circ}$



Crystal Structure: Metals

Table 3.1 Atomic Radii and Crystal Structures for 16 Metals

Metal	*Crystal Structure*[a]	*Atomic Radius*[b] *(nm)*	*Metal*	*Crystal Structure*	*Atomic Radius (nm)*
Aluminum	FCC	0.1431	Molybdenum	BCC	0.1363
Cadmium	HCP	0.1490	Nickel	FCC	0.1246
Chromium	BCC	0.1249	Platinum	FCC	0.1387
Cobalt	HCP	0.1253	Silver	FCC	0.1445
Copper	FCC	0.1278	Tantalum	BCC	0.1430
Gold	FCC	0.1442	Titanium (α)	HCP	0.1445
Iron (α)	BCC	0.1241	Tungsten	BCC	0.1371
Lead	FCC	0.1750	Zinc	HCP	0.1332

[a] FCC = face-centered cubic; HCP = hexagonal close-packed; BCC = body-centered cubic.
[b] A nanometer (nm) equals 10^{-9} m; to convert from nanometers to angstrom units (Å), multiply the nanometer value by 10.

Crystal Structure - Metals

Body Centered Cubic (BCC) Structure

Atoms/unit cell: 1 + 8x⅛ = 2

a = 4R/√3, APF = 0.68, a=b=c

Examples – Fe, Cr, Mo

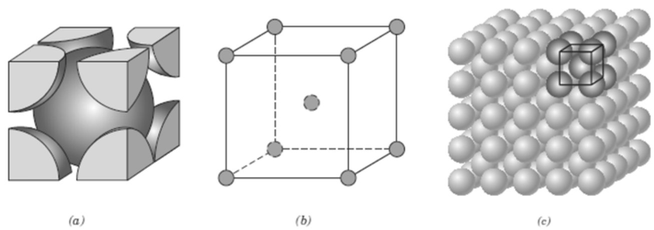


Figure 3.2 For the body-centered cubic crystal structure, (*a*) a hard sphere unit cell representation, (*b*) a reduced-sphere unit cell, and (*c*) an aggregate of many atoms. [Figure (*c*) from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials,* Vol. I, *Structure,* p. 51. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.]

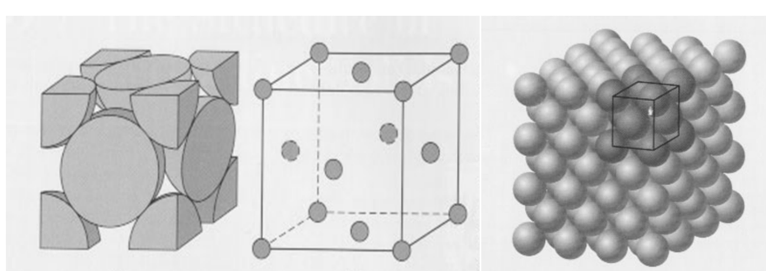
Crystal Structure - Metals

Face-Centered Cubic (FCC) Structure

Atoms/unit cell: 6 x ½ + 8 x ⅛ = 4

a = 2R√2, APF = 0.74, a=b=c

Examples – Al, Ni, Cu, Ag, Pt, Au



Polymorphism

- Elemental solids with more than one types of crystalline structure at a given T or P
- Found in metals, ceramics and polymers
- Relevant in Material fabrication, strengthening and shaping
- Relevant in implant design and fabrication

Phase Diagram: Fe-FeC_3 System

- Iron(Fe)
  - 25ºC – Ferrite, BCC, alpha-Fe, APF=0.68, R=0.1241 nm, CN=8
  - 912ºC – Austenite, FCC, gamma-Fe, APF=0.74, R=0.129nm, CN=12
  - ANSI 316L is an Austenite

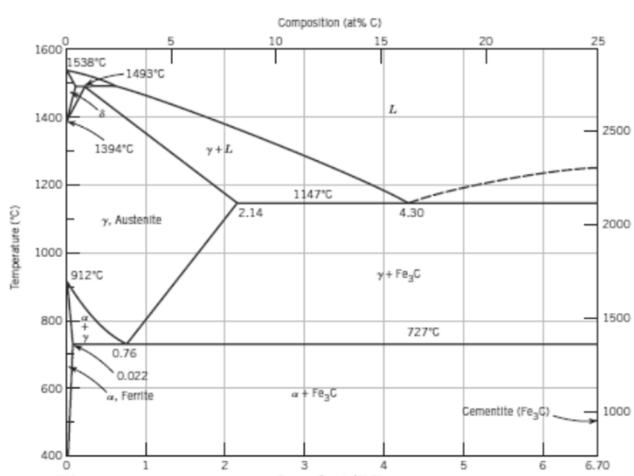


Figure 9.24 The iron–iron carbide phase diagram. [Adapted from *Binary Alloy Phase Diagrams,* 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

Polymorphism: Iron

- Iron(Fe)
  - Crytal structure changes as a function of temperature
  - 25ºC – Ferrite, BCC, alpha-Fe, APF=0.68, R=0.1241 nm, CN=8
  - 912ºC – Austenite, FCC, gamma-Fe, APF=0.74, R=0.129nm, CN=12
  - 1394ºC – Ferrite, BCC, delta-Fe
  - 1538ºC – melting point, liquid (L)
- Relevant in implant design and fabrication (heart valves, stents, hip prosthesis)
  - ANSI 316L: Fe 60-65%, Cr 17-19%, Ni 12-14%
  - Processed to stabilize the austenite (FCC) structure because it is stronger than the BCC

Solid Solution Hardening

- Alloying with impurity atoms
  - Substitution or interstitial
- Used to modify solvent surface and bulk properties
- Formation process driven by *Diffusion*
- Hinders dislocation motion
- Phase diagrams
  - determine solution hardening range
  - Heat treatment and composition range
- Economical

AISI 316L – Alloying Elements

- **Cr**
  - Oxidized to form transparent film on SSL surface (shine!)
  - Prevents corrosion by forming the Cr_2O_3 oxide layer
  - Shielding the surface from other oxide reaction

$$4Fe + 3O_2 \rightarrow 2Fe_2O_3$$

  - Minimal effective concentration at 11 wt%
  - Maintains the BCC form of Fe (α ferrite)

AISI 316L – Alloying Elements

- **Ni: 12-14%**
  - Stabilizes the FCC form of Fe (austenite, γ)
  - Enhances corrosion resistance
  - Effects of Ni, Cr on phase maintenance of SSL
    - Fe (bcc) → 912ºC Fe (fcc) → 1400ºC → Fe (bcc)
  - Minimal effective concentration at 10 wt%

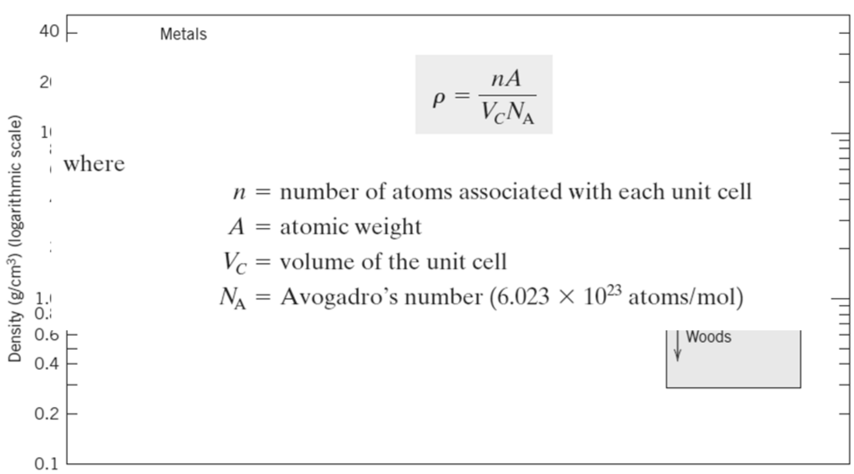
AISI 316L – Alloying Elements

- **Mo: 2 - 4%**
  - **prevents pitting corrosion, especially in Cl^- containing solutions**
  - **Maintains the BCC form of Fe**

- **C: low carbon content <0.03% (L in 316L)**
  - **>0.03% lead to formation of $Cr_{23}C_6$ instead**
  - **Formation of chromium carbide at grain boundaries**
  - **Depletion of Cr, reduce corrosion resistance**
  - **Result in formation of *sensitized* steel which often fails via corrosion-assisted fracture at the grain boundaries**

Material Properties: Density

- **Theoretical Density**



$$\rho = \frac{nA}{V_C N_A}$$

where

n = number of atoms associated with each unit cell
A = atomic weight
V_C = volume of the unit cell
N_A = Avogadro's number (6.023×10^{23} atoms/mol)

Stress-Strain Curve

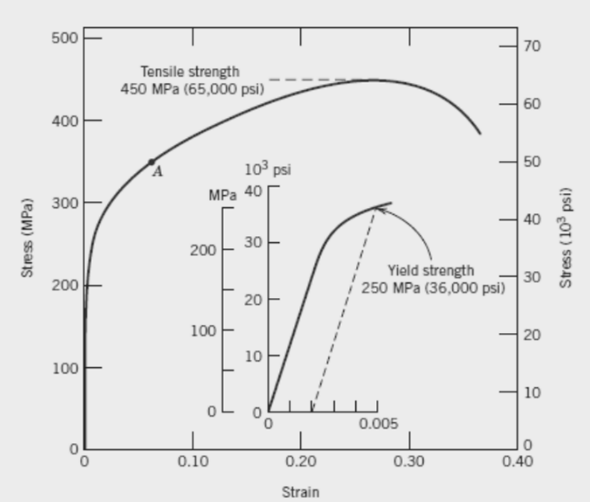


Figure 6.12 The stress–strain behavior for the brass specimen discussed in Example Problem 6.3.

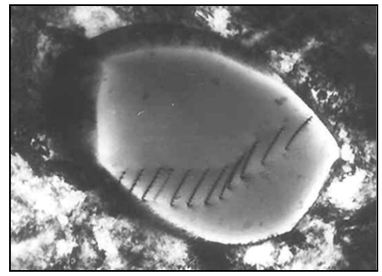
- Elastic Region
- Plastic Region
- Elastic Modulus
- Yield strength
- Tensile Strength
- Ductility (%elongation)

Plastic Forming and Annealing

- Plastic Forming
  - shaping by applying external force
- Suitable for ductile materials
- Two Methods
  - Hot working: > recrystallization temperature
    - Forging, rolling, extrusion
    - Requires less time
  - Cold working: < recrystallization temperature
    - Forging, rolling, drawing
    - Controlled surface finish

Plastic Forming and Annealing

- Hinders dislocation motion
- Procedure
  - After casting, > σ_y applied during hardening process
  - Forms rods, wires, tube, plates
- Advantages
  - Mechanical deformation at high T
    - less chance of fracture
  - Low rate of oxidation
  - Can be used with samples with relatively small cross sectional area
  - Economical



Dislocations in Austenite (TEM)
http://en.wikipedia.org/

Cold Working

- Rolling
- Drawing
- % cold working
- % change in cross sectional area

$$\%\,\mathrm{CW} = \left(\frac{A_0 - A_d}{A_0}\right) \times 100$$

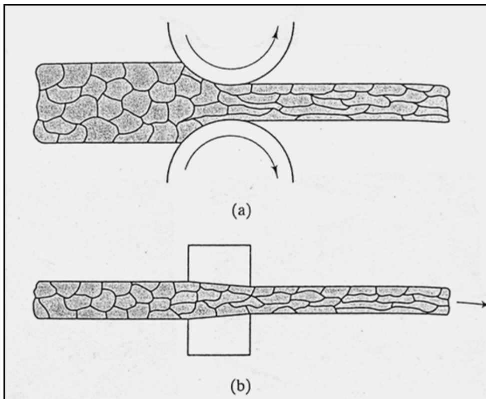
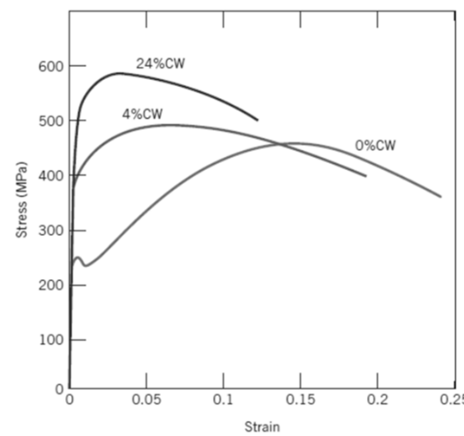


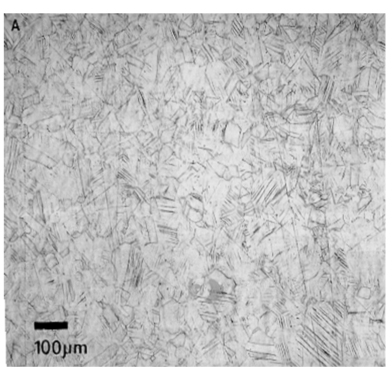
Figure 10-29 *Examples of cold-working operations: (a) cold-rolling of a bar or sheet and (b) cold-drawing a wire. Note in these schematic illustrations that the reduction in area caused by the cold-working operation is associated with a preferred orientation of the grain structure.*

AISI 316L – Post Fabrication

- **Cold worked 30%**
- **Annealed to release internal stress**
- **Controlled uniformity of heat treatment**
  - **Minimize formation of chromium carbide**
  - **Formation of surface oxide scales: sandblasted off or removed chemically via acid treatment**



Stainless Steel
Effects of Cold Working



Typical microstructure of cold-worked AISI 316L
- **Uniform grain size**
- **Fine grains**

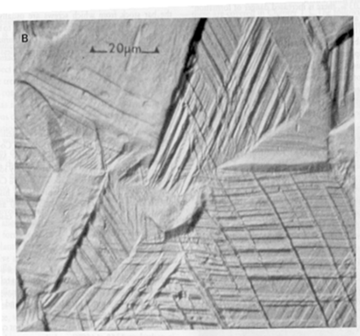


FIG. 4. (A) Typical microstructure of cold-worked 316L stainless steel, ASTM F138, in a transverse section taken through a spinal distraction rod. (B) Detail of grains in cold-worked 316L stainless steel showing evidence of plastic deformation. (Photo courtesy of Zimmer USA, Warsaw, IN.)

30% CW 316L surface with marks due to plastic deformation

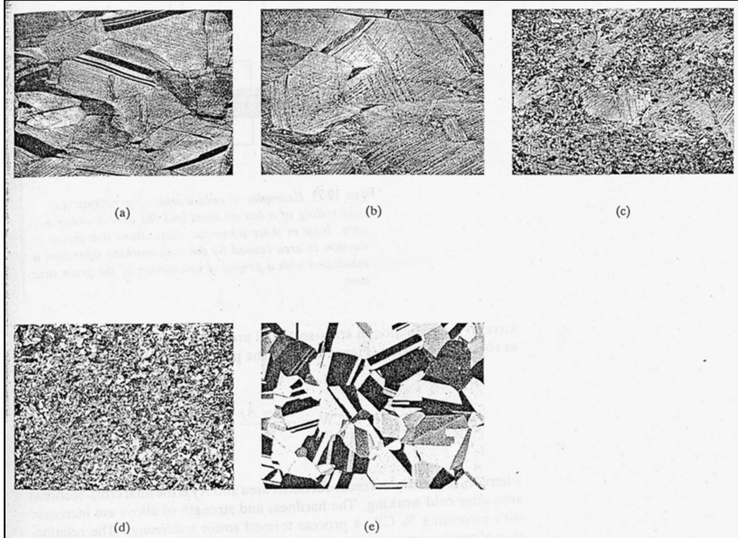


Figure 10-30 *Annealing can involve the complete recrystallization and subsequent grain growth of a cold-worked microstructure. (a) A cold-worked brass (deformed through rollers such that the cross-sectional area of the part was reduced by one-third). (b) After 3 s at 580° C, new grains appear. (c) After 4 s at 580° C, many more new grains are present. (d) After 8 s at 580° C, complete recrystallization has occurred. (e) After 1 h at 580° C, substantial grain growth has occurred. The driving force for this is the reduction of high-energy grain boundaries. The predominant reduction in hardness for this overall process had occurred by step (d). All micrographs at magnification of 75×. (Courtesy of J. E. Burke, General Electric Company, Schenectady, N.Y.)*

Biomaterial: ANSI 316L

- **Advantages**
  - **Strength**
  - **Ease in manufacture and molding into desired shapes**
  - **More economical compared to other metallic biomaterials**
- **Disadvantages**
  - **Corrosive *in vivo***
  - **Strength mismatch: stress shielding**

Metals for Hip: Replace Bone

- Most Common
  - Stainless Steel (SSL)
    - Cardiovascular
    - Orthopedic
  - Co-Cr Alloys
    - Orthopedics
  - Titanium & alloys
    - Dental
    - Orthopedic

Cobalt-Chromium (Co-Cr-Mo) Alloy

- As femoral head (Co-Cr-Mo)
- As prosthetic stems (Co-Ni-Cr-Mo-Ti)
- Two types of CoCrMo alloys used clinically
  - Co-Cr-Mo (ASTM F75, Vitallium®, Howmedica)
    - 58.9-69.5% Co, 27-30% Cr, 5-7% Mo,
    - ≤0.35% C, <2.5% Fe, Ni, Si, Mn,
    - Formed by investment casting (1350-1450ºC)
  - Co-Ni-Cr-Mo-Ti (ASTM F562)
    - 35% Co, 19-21% Cr, 35-37% Ni, 9-10.5% Mo,
    - 0.15% of Mn, 0.15% of Si
    - Hot worked - forged

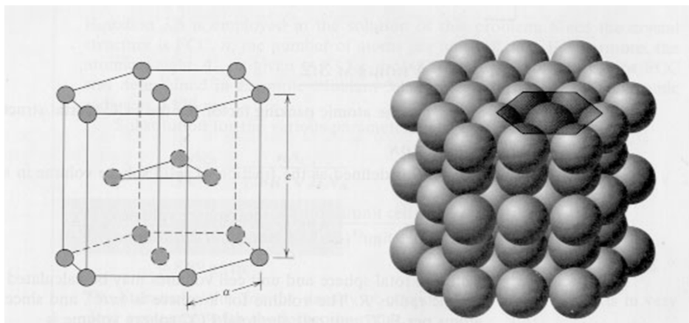
Crystal Structure - Metals

Hexagonal Closed Pack (HCP) Structure

Atoms/unit cell: 3 + 12x(1/6) + 2x(1/2) = 6

APF = 0.74, a = b ≠ c

Examples – Mg, Zn, Ti, Co



From W. Callister, Material Science and Engineering

Crystal Structure - Metals

Body Centered Cubic (BCC) Structure

Atoms/unit cell: 1 + 8x⅛ = 2

a = 4R/√3, APF = 0.68, a=b=c

Examples – Fe, Cr, Mo

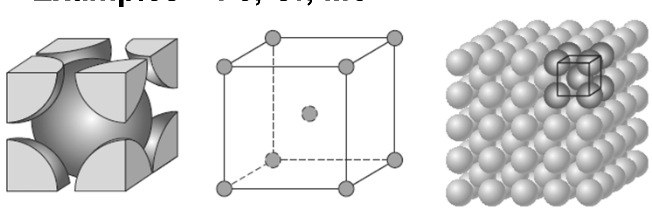


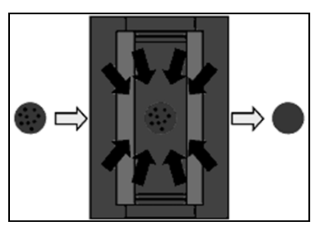
Figure 3.2 For the body-centered cubic crystal structure, (*a*) a hard sphere unit cell representation, (*b*) a reduced-sphere unit cell, and (*c*) an aggregate of many atoms. [Figure (*c*) from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 51. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.]

Cobalt-Chromium (Co-Cr-Mo) Alloy

- **Cr**
  - **Corrosion resistance by Cr_2O_3**
- **Mo**
  - **Corrosion resistance in Cl^- solutions**
  - **Results in finer grains and in higher yield strength**

Example: Hot Isostatic Pressing (HIP)

- **Procedure**
  - **Material in powder form**
  - **Compacted and heated**
  - **Uniform pressure applied on all sides**
  - **Constant P and higher T accelerate bonding**
  - **Isotropic material with grain size of 500 – 10,000 µm**
- **Mechanism:**
  - **surface/bulk diffusion, evaporation, condensation**
- **Advantages**
  - **Uniform solidification process**
  - **Increased bonding strength**
- **Ceramics, Metals, Polymers**



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Microstructure of As-Casted CoCrMo

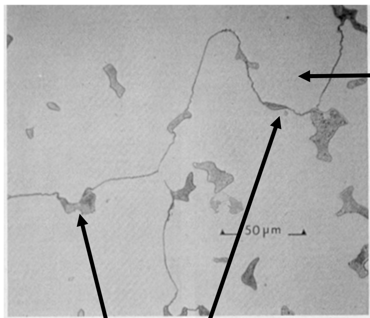


FIG. 6. Microstructure of as-cast Co–Cr–Mo ASTM F75 alloy, showing a large grain size plus grain boundary and matrix carbides. (Photo courtesy of Zimmer USA, Warsaw, IN.)

Grain boundary carbides

- ASTM F75 Alloy
- 85% α-phase rich in Co
- 15% carbide phase at the grain boundaries
- Large grain size (>100μm)
- Large grain boundaries and matrix carbides

Cobalt Alloy F75 Hot Isostatic pressing

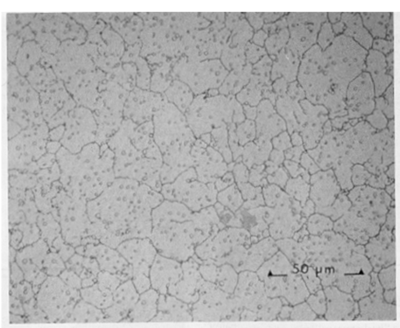


FIG. 8. Microstructure of the Co–Cr–Mo ASTM F75 alloy made via hot isostatic pressing (HIP), showing the much smaller grain size relative to that in Fig. 6. (Photo courtesy of Zimmer USA, Warsaw, IN.)

Bar = 50 microns

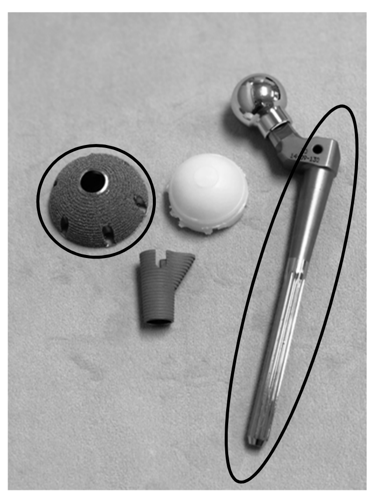
- Hot Isostatic Pressing 1100°C for 1hr, 100MPa
- Forged and shaped
- Smaller grain size (8μm) than as cast alloy
- Finer distribution of carbides (hardening)
- Alloy with improved yield strength, UTS strength and fatigue properties
  - E = 220 GPa

Biomaterial: CoCrMo Alloys

- **Advantages**
  - Better fatigue strength than AISI 316L
  - Good for applications with long service life
  - Improved corrosion resistance under stress
- **Disadvantages**
  - Poor wear properties
  - Toxic wear products
  - Stress shielding
  - Corrosive *in vivo*

Metals for Hip: Replace Bone

- **Most Common**
  - Stainless Steel (SSL)
    - Cardiovascular
    - Orthopedic
  - Co-Cr Alloys
    - Orthopedics
  - Titanium & alloys
    - Dental
    - Orthopedic



Metals: Ti and Ti Alloys

- Two types of Ti used clinically
  - ASTM F67: 98.9 – 99% Ti
  - ASTM F136-179: Ti-6Al-4V (wt%)
    - 88.3-90.8% Ti, 5.5-6.5% Al, 3.5-4.5% V
    - ≤ 0.08% C, trace of C, N, Fe, O, H
- σ_y related to oxygen content
    - σ_y at 0.18% O_2 = 170 MPa
    - σ_y at 0.40% O_2 = 485 MPa
- Polymorphism
  - αTi at ≤882ºC, HCP
  - βTi at > 882ºC, BCC

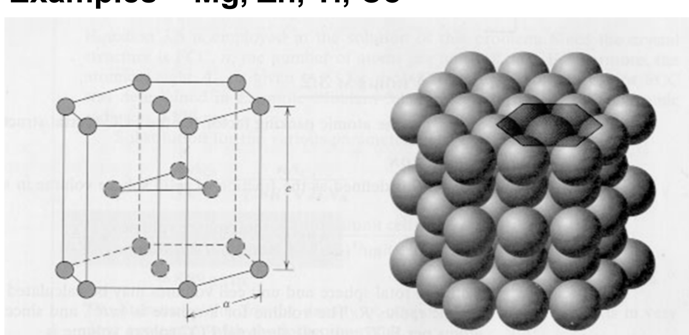
Crystal Structure - Metals

Hexagonal Closed Pack (HCP) Structure

Atoms/unit cell: 3 + 12x(1/6) + 2x(1/2) = 6

APF = 0.74, a = b ≠ c

Examples – Mg, Zn, Ti, Co



From W. Callister, Material Science and Engineering

Microstructure of Titanium ASTM F67

- **30% cold-worked HCP Ti (ASTM F67) used as an oral implant**
- **Single phased αTi (HCP)**
- **Grain size 10-150 μm**
- **Interstitial O,C,N strengthen the metal (solid solution hardening)**
- **Disrupts surface oxide**

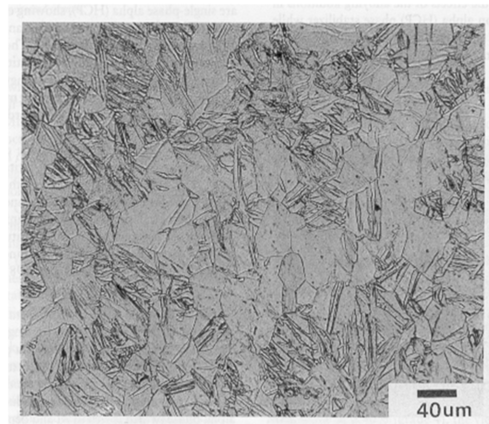


FIG. 10. Microstructure of moderately cold-worked commercial purity titanium, ASTM F67, used in an oral implant.

Metals: Ti and Ti Alloys

- **Ti-6Al-4V (ASTM F136)**
  - **Al: stabilize the αTi (HCP), increase the transformation temperature required to change αTi to βTi**
  - **V: stabilize the βTi (bcc), decrease the transformation temperature required to change αTi to βTi**
  - **Alloy contains both αTi and βTi**
  - **NOT cold-worked to protect surface oxide**

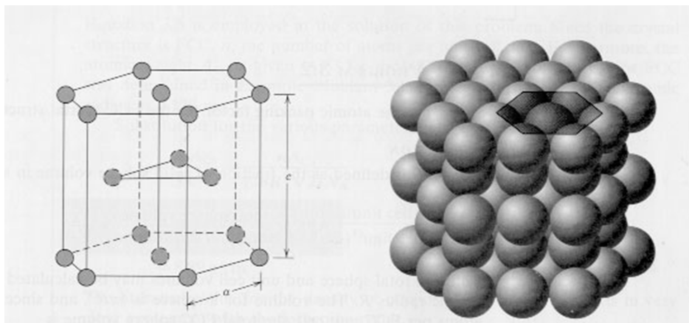
Crystal Structure - Metals

Hexagonal Closed Pack (HCP) Structure

Atoms/unit cell: 3 + 12x(1/6) + 2x(1/2) = 6

APF = 0.74, a = b ≠ c

Examples – Mg, Zn, Ti, Co



From W. Callister, Material Science and Engineering

Crystal Structure - Metals

Body Centered Cubic (BCC) Structure

Atoms/unit cell: 1 + 8x⅛ = 2

a = 4R/√3, APF = 0.68, a=b=c

Examples – Fe, Cr, Mo

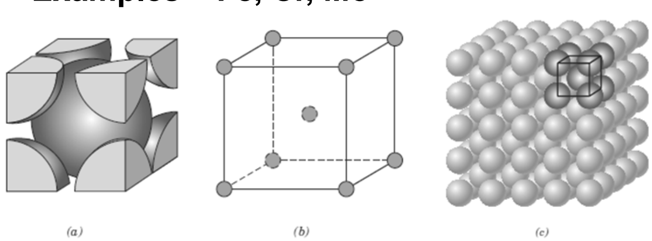


Figure 3.2 For the body-centered cubic crystal structure, (*a*) a hard sphere unit cell representation, (*b*) a reduced-sphere unit cell, and (*c*) an aggregate of many atoms. [Figure (*c*) from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials,* Vol. I, *Structure,* p. 51. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.]

Forming and Cooling

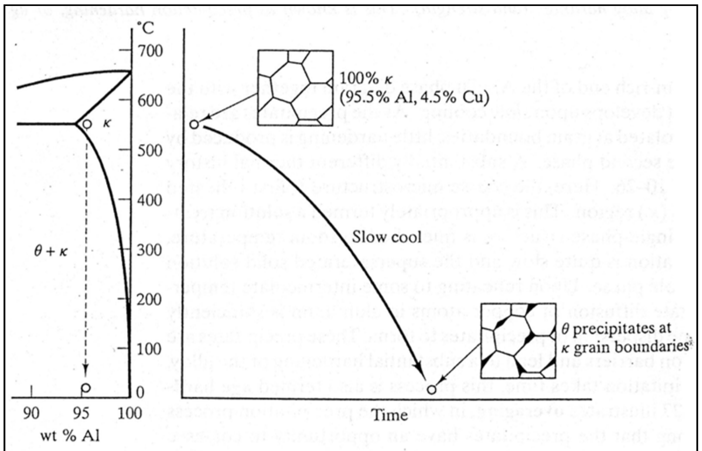


Figure 10-25 *Coarse precipitates form at grain boundaries in an Al–Cu (4.5 wt %) alloy when slowly cooled from the single-phase (κ) region of the phase diagram to the two-phase (θ + κ) region. These isolated precipitates do little to affect alloy hardness.*

Precipitation Hardening

- **Goal: Refinement or formation of extremely small, uniformly particles or precipitates dispersed in the bulk**
- **Hinders dislocation motion**
- **Age hardening as strength is developed over time as the alloy ages**
  - ***e.g.* Ti-6Al-4V**
- **Cooling lead to second phase precipitation**
- **For Ti-6Al-4V**
  - **Precipitation hardening at 950°C, quenched in water then aged at 600°C and finally air cooled**

Precipitation Hardening

- ***Step 1 – Solution heat treatment***
  - Heating to a temperature T_0 so that all solute atoms are solubilized to form single solid phase solution (β)
- ***Step 2 – Quenching***
  - Rapid cooling (T_1) to prevent the formation of a second phase α in solid β, prevent ion diffusion
- ***Step 3 – Precipitation heat treatment (Aging)***
  - Heat to intermediate temperature T_2 to generate a heat-saturated solid solution
  - Within the β region to allow α phase to precipitate as finely dispersed particles
- ***Step 4 – Cooling to room temperature***

Precipitation Hardening

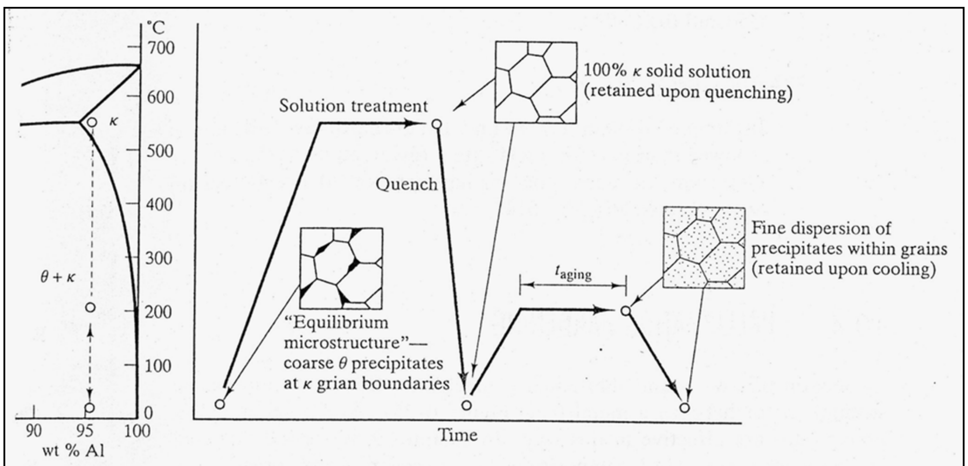


Figure 10-26 *By quenching and then reheating an Al–Cu (4.5 wt %) alloy, a fine dispersion of precipitates forms within the κ grains. These precipitates are effective in hindering dislocation motion and, consequently, increasing alloy hardness (and strength). This is known as precipitation hardening, or age hardening.*

Ti-6Al-4V: As casted

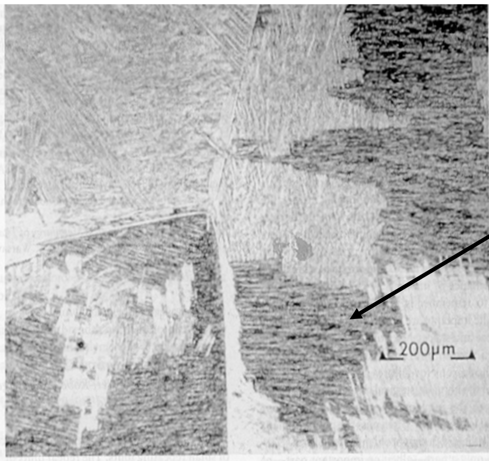


FIG. 11. Widmanstatten structure in cast Ti–Al–4V, ASTM F136. Note prior beta grains (three large grains are shown in the photo) and platelet alpha structure within grains. (Photo courtesy of Zimmer USA, Warsaw, IN.)

- <u>**cooled slowly to 25ºC**</u>
- **αTi phase (HCP, rich in Al) precipitate out and as plates or needles within grains of βTi (BCC, rich in V) matrix**
- **σ_y = 795 MPa,**
- **σ_{UTS} = 860 MPa,**
- **E=110 GPa, ε = 10%**

Ti-Al-4V: Annealing

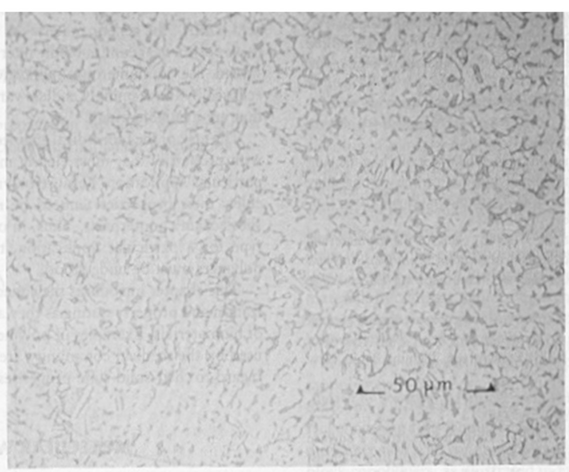


FIG. 12. Microstructure of wrought and mill-annealed Ti–6Al–4V, showing small grains of alpha (light) and beta (dark). (Photo courtesy of Zimmer USA, Warsaw, IN.)

- **Alloy heated above 1000ºC where beta is stable**
- **Annealed**
  - **fine-grained αTi**
  - **βTi particles**
- **Small grains of alpha (light) and beta (dark)**
- **Improved mechanical strength, ductility and fatigue properties**

Ti-Al-4V: Precipitation Hardening

Microstructure and Hardness of Subzero Quenched and Heat Treated Ti-6Al-4V Alloy

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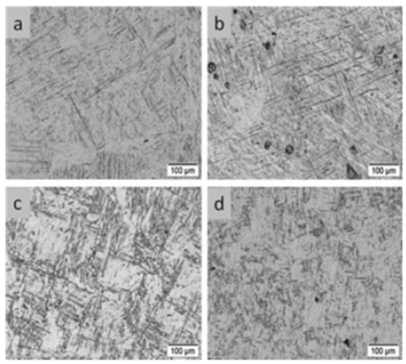
Abstract Titanium is one of the most important materials nowadays with promising lightweight demanding applications. However, despite its high strength-to-weight ratio, high temperature stability and high corrosion resistance, it has relatively low hardness. It is shown in this work that enhanced hardness values could be obtained for Ti-6Al-4V Alloy after heat treatment consisting of subzero quenching in a medium made up of dry ice and alcohol, followed by an aging treatment. The proposed heat treatment resulted an increase of 25% in the hardness of the alloy, compared to 5% reported in literature.

Keywords Ti-6Al-4V · Heat treatment · Hardness

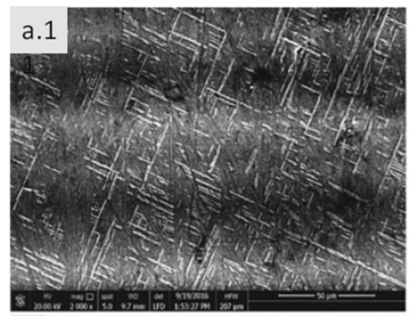
Table 3 Tensile strength of quenched and tempered samples

Condition	Sample ID	0.2% yield stress (MPa)	Tensile strength (MPa)	Elongation (%)
As forged as received	11	870	934	10
Solution treated for 30 min at 1000 °C and cooled in dry ice/alcohol	1	824	917	5.01
Solution treated for 30 min at 1000 °C and cooled in dry ice/alcohol and aged at 650 °C for 24 h	1 + aged	925	960	5.3

Fig. 2 Microstructure obtained after cooling: **a**, **d** dry ice martensite structure α′ and retained β, **b** water quenched coarser martensite lathes, **c** air cooled Widmanstätten structure



a.1 Solution treated at 1000C and quenched then aged at 650C and cooled



Biomaterial: Ti and Ti Alloys

- **Advantages –**
  - **Lightweight compared to other metals**
    - $\rho_{Ti\ alloy}$ = 4.51 g/cm^3
    - ρ_{316L} = 7.9 g/cm^3
    - $\rho_{CoCrMo\ alloy}$ = 9.2 g/cm^3
  - **Greater strength/density than other metals**
  - **Improved corrosion resistance**
    - Surface oxide layer – TiO_2
  - **Improved biocompatibility**
- **Disadvantages –**
  - **Stress shielding**
  - **Poor shear strength**
    - less useful as screws or plates
  - **Corrosive *in vivo* (long term)**
  - **Expensive**
    - inert atmosphere and high T required in fabrication

Comparison of Mechanical Properties

TABLE A.1 Titanium Alloys Developed for Orthopedic Applications and Their Mechanical Properties (Adapted from Long and Rack, 1998)

Alloy	Microstructure	Elastic Modulus E (GPa)	Yield Strength YS (MPa)	Ultimate Strength UTS (MPa)
cpTi	α	105	692	785
Ti-6Al-4V	α/β	110	850–900	960–970
Ti-6Al-7Nb	α/β	105	921	1024
Ti-5Al-2.5Fe	Metastable β	110	914	1033
Ti-15Mo-5Zr-3Al	Metastable β	82	771	812
Ti-Zr	Cast α'/β	N/A	N/A	900
Ti-13Nb-13Zr	α'/β	79	900	1030
Ti-15Mo-3Nb-0.30	Metastable β + silicides	82	1020	1020
Ti-35Nb-5Ta-7Zr	Metastable β	55	530	590
Ti-35Nb-5Ta-7Zr-0.40	Metastable β	66	976	1010
Stainless steel 316L	–	205–210	170–750	465–950
Co–Cr–Mo	–	220–230	275–1585	600–1785
Bone	–	10–40		90–140

Metal and Metal Alloys

- Composition
- Crystal structure
- Fabrication/Processing
- Functional properties - Mechanical
- Biocompatibility/Biofunctionality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HEALTH CARE

Hip Joints Set Off New Rush to Court

By Jonathan D. Rockoff And Dionne Searcey

July 8, 2011

First came a flood of lawsuits blaming Toyota Motor Corp. cars for unintended acceleration, then a wave of litigation over BP PLC's massive oil spill. Now, artificial hip joints made by Johnson & Johnson have plaintiffs' attorneys flocking to the courthouse.

CORROSION

- Definition
  - Chemical reaction between a metal and ions (electrolytes) in the physiological environment
- Results in the formation of
  - *Oxides, hydroxides, metallic ion complexes*
- Involves Oxidation Reactions
- Occurs at the metal surface
- Release/Depletion of metal over time
- Function of material fabrication process
- Dictated by the physiological environment

Oxidation Reactions

- *Loss* of electron
- Metal acts as the *electron donor*

  $M = M^{n+} + ne^-$ (oxidation)

  $2M^+ + O^{2-} = M_2O$ (reduction)

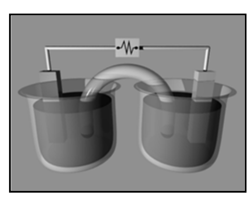
- Metals are ionized or oxidized into solution
- Reaction involves an *oxygenated* environment
- Corrosion products are in granular form or are flake-like (platelets, sheets)

Electrochemical Consideration of Corrosion

- Oxides –
  - Lowest free energy form for solids
  - Preferred state for most metals in service in an *oxygenated* and *hydrated* environment
  - Biological environment promote the formation of oxides or corrosion

Electrochemical Cell

- Migration of ions between anode (+) and cathode (-)
- Generates electric potential (V)
- Anode (+)
  - positively charged due to the loss of electrons
  - Serves as supplier of electrons
- Cathodes (-)
  - Negatively charged
  - Serves as receiver of electrons



http://en.wikepedia.org

Electrochemical Cell

- Anode is the region which corrodes in the electrochemical cell
- Oxidization and corrosion of the anode

$$M \rightarrow M^{n+} + ne^-$$

- Electroplating takes place at the Cathode
- Reduction reaction occurs at the Cathode

$$M^{n+} + ne^- \rightarrow M$$
$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH^-)$$
$$M^{2+} + OH^- + 2e^- \rightarrow MOH$$

Oxidation of Fe - Rust

- Oxidization of Fe to form rust [$Fe(OH)_3$] in water

$$Fe + \frac{1}{2} O_2 + 2H_2O \rightarrow Fe^{2+} + 2OH^-$$
$$2Fe(OH)_2 + \frac{1}{2} O_2 + H_2O \rightarrow \boxed{Fe(OH)_3}$$

- Metals after corrosion can exist in either ion form or as oxidized compounds

http://en.wikepedia.org

Standard emf series

- Based on Reduction Reactions
- Positive value will not corrode: $M^{n+} + ne^- \rightarrow M$, E=?

Increasing	$\frac{1}{3}Au^{3+} + e^- \rightarrow \frac{1}{3}Au$	+1.420
inertness	$Fe^{3+} + e^- \rightarrow Fe^{2+}$	+0.771
↑	$\frac{1}{2}Cu^{2+} + e^- \rightarrow \frac{1}{2}Cu$	+0.340
(arbitrary reference →)	$H^+ + e^- \rightarrow \frac{1}{2}H_2$	0.000
↓	$\frac{1}{2}Fe^{2+} + e^- \rightarrow \frac{1}{2}Fe$	–0.440
Increasing	$\frac{1}{3}Cr^{3+} + e^- \rightarrow \frac{1}{3}Cr$	–0.744
reactivity	$\frac{1}{2}Zn^{2+} + e^- \rightarrow \frac{1}{2}Zn$	–0.763

In Situ: the Body

- Biological Environment
  - AGGRESSIVE environment when compared to external conditions
    - Aqueous solution
    - Electrolyte solution
    - High concentration of chloride ions
    - Protein adhesion
  - Chemical and thermal parameters
  - Instantaneous mechanical loading

Nernst Equation

- **Potential for an electrochemical reaction, by Walther Hermann Nernst (*c.* 1889)**

$$E = E^{\circ} - \frac{RT}{nF} \ln Q_c$$

  - **E is the cell potential at some moment in time**
  - **E_o is the cell potential when the reaction is at standard-state conditions**
  - **R is the ideal gas constant in units of J/mole**
  - **T is the temperature in Kelvin**
  - **n is the number of moles of electrons transferred**
  - **F is the charge on a mole of electrons**
  - **Q_c is the reaction quotient at time t**

Nernst Equation – Electrochemical Cell

- **Describes the relationship between electrochemical potential and pH and ion activity**

$$E = E^{\circ} - \frac{RT}{nF} \ln Q_c$$

- **Activity of ions (a_i): $Q_c = a_{products}/a_{reactants}$**
  - **Apparent concentration of ions in an electrolyte solution**
  - **Chemical effectiveness of ion depends on the concentration of other ions in the same solution**
  - **Varying solution concentration will alter a_i**
  - **In dilute solutions, a_i = ion concentration**
  - **In electrolyte solutions, $a_i \neq$ concentration, can vary by a factor of 5**
  - **Ion activity determines the type/rate of reaction**

Standard EMF Series

Less likely to corrode ↑

- $Au^{3+} + 3e^{-} \rightarrow Au$ $\Delta E = +1.42$ V
- $Pt^{2+} + 2e^{-} \rightarrow Pt$ $\Delta E = +1.20$ V
- $Cu^{2+} + 2e^{-} \rightarrow Cu$ $\Delta E = +0.34$ V

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- $Fe^{2+} + 2e^{-} \rightarrow Fe$ $\Delta E = -0.44$ V
- $Cr^{3+} + 3e^{-} \rightarrow Cr$ $\Delta E = -0.56$ V
- $Ti^{4+} + 4e^{-} \rightarrow Ti$ $\Delta E = -2.00$ V
- $Mg^{2+} + 2e^{-} \rightarrow Mg$ $\Delta E = -2.363$ V

Galvanic Series

- **Isotonic solution with 0.9% NaCl**
- **Accounts for Oxides**
  - Ti: 30 to 40 Å
  - AISI 316L: 200 Å
- **Ti: inert**
- **Stainless steel (316L)**
  - corrosive

Table 18.2 The Galvanic Series

Increasingly inert (cathodic) ↑

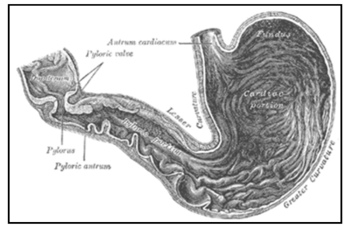
Platinum
Gold
Graphite
Titanium
Silver
316 Stainless steel (passive)
304 Stainless steel (passive)
Inconel (80Ni-13Cr-7Fe) (passive)
Nickel (passive)
Monel (70Ni-30Cu)
Copper-nickel alloys
Bronzes (Cu-Sn alloys)
Copper
Brasses (Cu-Zn alloys)
Inconel (active)
Nickel (active)
Tin
Lead
316 Stainless steel (active)
304 Stainless steel (active)
Cast iron
Iron and steel
Aluminum alloys
Cadmium
Commercially pure aluminum
Zinc
Magnesium and magnesium alloys

Increasingly active (anodic) ↓

Source: M. G. Fontana, *Corrosion Engineering,* 3rd edition. Copyright 1986 by McGraw-Hill Book Company. Reprinted with permission.

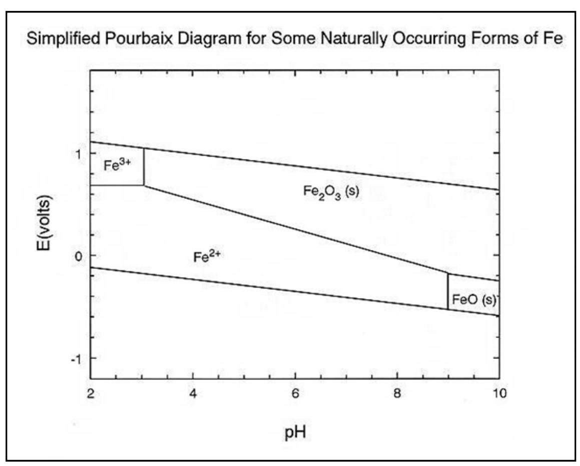
BIOLOGICAL ENVIRONMENT

- **pH – ranges from 1.0 to 7.35**
  - **Gastric contents: pH=1.0**
  - **Intracellular: pH = 6.8**
  - **Interstitial: pH = 7.0**
  - **Blood: pH = 7.14-7.35 (diet dependent)**
- **Temperature**
  - **T= 37ºC core**
  - **Diseased: 20 - 42.5ºC**
  - **Location dependent**
    - **Skin: ranges from 0 – 45ºC**



Pourbaix Diagram (PBD)

- **Immunity**
  - **Cathodic protection**
  - **$[M^{n+}] < 10^{-6}$ M**
- **Passivation**
  - **Oxidation**
  - **$[M^{n+}] < 10^{-6}$ M**
- **Corrosion**
  - **$[M^{n+}] > 10^{-6}$ M**



Corrosion and Wear

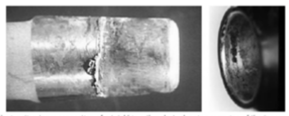


FIGURE II.5.6.15 Modular junction taper connection of a total hip arthroplasty showing corrosion of the taper connections. Macrograph of deposits of $CrPO_4$ corrosion particles on the rim of a modular cobalt-chrome femoral head.

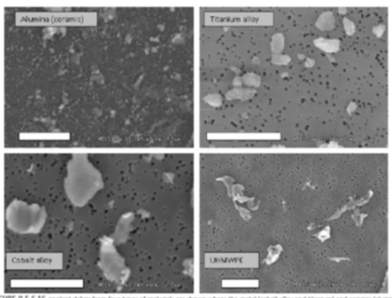


FIGURE II.5.6.16 Implant debris from four types of materials are shown where the metal (cobalt alloy and titanium) and ceramic (alumina) debris are more rounded versus the polymeric (UHMWPE) debris which is more elongated in shape. Note: Bar = 5 µm.

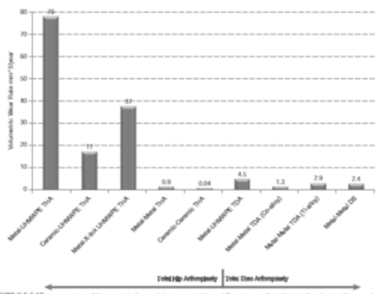


FIGURE II.5.6.13 A comparison of the amount of wear debris generated from different types of total joint arthroplasties. There is relatively less (10×) polymeric debris generated by a total disc arthroplasty with a metal-on-polymer articulation. Note: Figure References: Metal-Poly (Holt et al., 2007); Ceramic-Poly (Jacobs et al., 1994c); Metal-X-linked Poly (Martinon et al., 2006); Metal-X-linked Poly (Jacobs et al., 1994c); Metal-X-linked Poly (Hallab, 2009); Metal-X-linked Poly (Hallab, 2009); Metal-Metal (Huk et al., 1994); Ceramic-Ceramic (Hallab, 2009); Metal-UHMWPE TDA (Hallab, 2009); Metal-Metal TDA (Hallab, 2009).

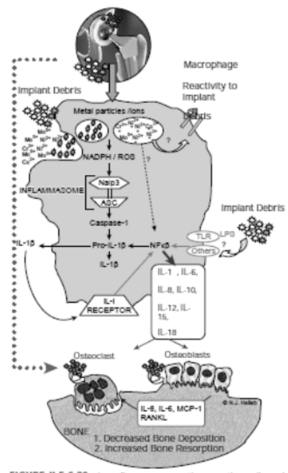
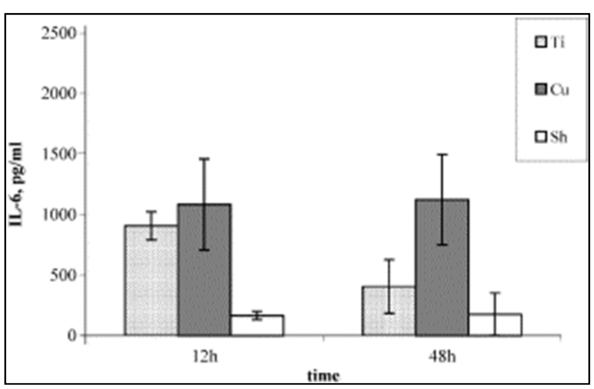


FIGURE II.5.6.20 The inflammasome pathway within cells such as macrophages has recently been reported to be central to implant debris-mediated proinflammatory reactivity. (Picture courtesy of BioEngineering Solutions, Inc.)

Biocompatibility of Ti vs. Cu

- **In vivo (subcu.) secretion of IL-6 (pg/ml) at 12 to 48 hours** ***(Suska et al., Biomaterials, 2005)***
- **Exudate of cells surrounding Cu implants measured higher IL-6 production**
- **IL-6: found at sites of implant loosening**



Inflammatory Cells around Implants

- Number of inflammatory cells over time increased surrounding the Cu implant vs. the Ti implant

Time (h)	No. of infl. cells±SEM, % mono, % poly		
	Ti	Cu	Sh
12	150.9±42.5, 20, 80	251.6±83.7, 11, 89	78.1±27.4, 21, 79
48	85.2±43.1, 34, 67	649.5±303.4, 6, 94	22.8±4.2, 50, 50

- Conclusion
  – Toxicity of Cu implant is greater than Ti

Fate of Metals in the Body

TABLE II.5.6.5 Approximate Average Concentrations of Metal in Human Body Fluids With and Without Total Joint Replacements (Michel et al., 1984; Stulberg et al., 1994; Jacobs et al., 1998a,b, 1999.)

Fluid		Ti (ng/ml or ppb)	Al	V	Co	Cr	Mo	Ni
Serum	Normal	2.7	2.2	<0.8	0.18	0.05–0.15	*	0.4–3.6
	THA	4.4	2.4	1.7	0.2-0.6	0.3	*	<9.1
	THA-F	8.1	2.2	1.3	*	0.2	*	*
	THA-F	8.1	2.2	1.3	*	0.2	*	*
	TKA	3.2	1.9	<0.8	*	*	*	*
	TKA-F	135.6	3.7	0.9	*	*	*	*
Urine	Normal	<1.9	6.4	0.5	*	0.06	*	*
	TJA	3.55	6.53	<0.4	*	0.45	*	*
Synovial fluid	Normal	13	109	5	5	3	21	5
	TJA	556	654	62	588	385	58	32
Joint capsule	Normal	723	951	122	25	133	17	3996
	TJA	1540	2053	288	1203	651	109	2317
	TJA-F	19173	1277	1514	821	3329	447	5789
Whole blood	Normal	17	13	6	0.1–0.1.2	2.0–4.0	0.5–1.8	2.9–7.0
	TJA	67	218	23	20	110	10	29

Normal: Subjects without any metallic prosthesis (not including dental).
THA: Subjects with well-functioning total hip arthroplasty.
THA-F: Subjects with a poorly-functioning total hip arthroplasty (needing surgical revision).
TKA: Subjects with well-functioning total knee arthroplasty.
TKA-F: Subjects with a poorly-functioning total knee arthroplasty (needing surgical revision).
TJA: Subjects with well-functioning total joint arthroplasty.
TJA-F: Subjects with a poorly-functioning total joint arthroplasty (needing surgical revision).
*Not tested.

TABLE II.5.6.6 Concentrations of Metal in Body Tissue of Humans With and Without Total Joint Replacements (μg/g)

		Cr	Co	Ti	Al	V
Skeletal Muscle	Normal	<12	<12	*	*	*
	TJA	570	160	*	*	*
Liver	Normal	<14	120	100	890	14
	TJA	1130	15200	560	680	22
Lung	Normal	*	*	710	9830	26
	TJA	*	*	980	8740	23
Spleen	Normal	10	30	70	800	<9
	TJA	180	1600	1280	1070	12
Psuedocapsule	Normal	150	50	<65	120	<9
	TJA	3820	5490	39400	460	121
Kidney	Normal	<40	30	*	*	*
	TJA	<40	60	*	*	*
Lymphatic tissue	Normal	690	10	*	*	*
	TJA	690	390	*	*	*
Heart	Normal	30	30	*	*	*
	TJA	90	280	*	*	*

TJA: Subjects with a well-functioning total joint arthroplasty.
* Not tested.

Fate of Metals In Vivo

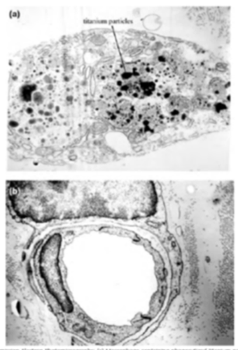


FIGURE II.5.6.17 Transmission Electron Photomicrographs: (a) Macrophage containing phagocytized titanium particles. (b) Endothelial cell lining with embedded titanium debris. These specimens were obtained from a tissue sample overlying the posterolateral fusion mass (sixteen-week autograft + titanium) (TEM magnification × 20,000 ×).

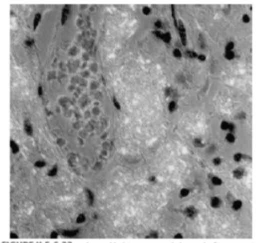


FIGURE II.5.6.22 Polarized light micrograph (190 ×) of para-aortic lymph node demonstrates the abundance and morphology of birefringent particles within macrophages. The larger filamentous particles were identified by infrared spectroscopy to be polyethylene.

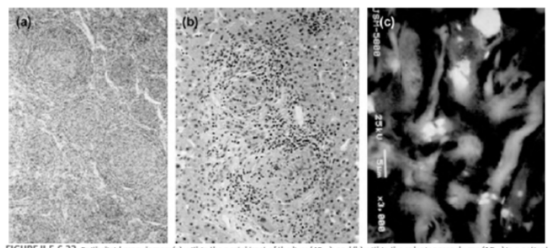
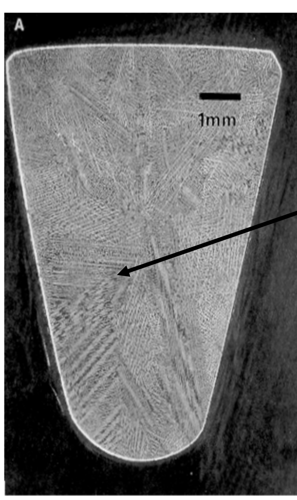


FIGURE II.5.6.23 Epithelioid granulomas: (a) within the portal tract of the liver (40 ×); and (b) within the splenic parenchyma (15 ×) in a patient with a failed titanium-alloy total hip replacement and symptomatic hepatitis. (c) Backscattered SEM of a granuloma in the spleen (3000 ×) demonstrating titanium alloy particles.

Cobalt-based Alloys-ASTM F75



- **Macrostructure of As-Casted Co-Cr-Mo ASTM F75 hip stem**
- **Alpha phase rich in Co**
- **interdendritic structures depleting Cr forming carbides**
- **Decreased mechanical strength**
- **Decreased fatigue properties**

Cobalt-based Alloy: F75 Casting Defects

- Fracture surface of the same Co-Cr-Mo ASTM F75 hip stem
- Casting Defect - Large inclusion
  - due to ceramic mold particulate
  - Source of stress concentration
  - lead to fatigue failure in vivo

Fatigue Failure

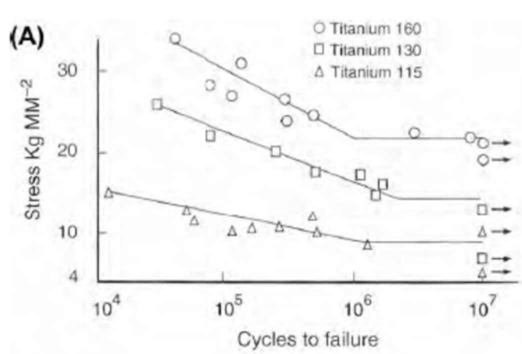


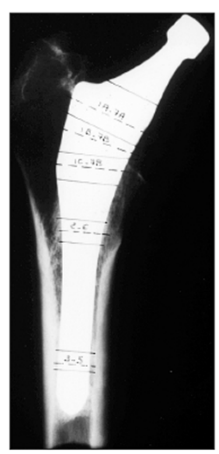
FIGURE I.2.3.4 The smooth part of a 316L stainless steel Harrington spinal distraction rod that fractured by fatigue *in vivo*. Note the bend in the rod (the rod was originally straight) and (insert) the relationship of the crack initiation zone of the fracture surface to the bend. The inserted photo shows the nature of the fatigue fracture surface, which is characterized by a region of "beach marks" and a region of sudden overload failure. (Photo courtesy of Brunski, J. B., Hill, D. C. & Moskowitz, A. (1983). Stresses in a Harrington distraction rod: Their origin and relationship to fatigue fractures *in vivo*. *J. Biomech. Eng.*, 105, 101–107.)

Wound Healing: Remodeling

- **Rate of Wound Healing depends on**
  - **Severity of injury**
  - **Size of defect**
  - **Location of defect**
    - ***Ex:*** **Bone, skin: regeneration**
      Cartilage or ligament: fibrous capsule
- **Implant Response**
  - **Capsule Formation**
  - **Tissue Ingrowth: *mechanical* fixation**
  - **Tissue Integration: *biological* fixation**

Mechanical Fixation: Tissue Ingrowth

- **Tissue Ingrowth is GOOD!**
- **Tissue ingrowth enables mechanical fixation of the implant**
- **Minimal motion between implant and surrounding tissue**
- **Implant surface must promote cell adhesion**



Mechanical Fixation: Tissue Ingrowth

- Degree of Tissue Ingrowth depends on
  - Total surface area
  - Pore size - Tissue type dependent
  - Interconnectivity of Pores
  - Blood vessel 1-5 μm
  - Bone 50-100 μm
  - Soft tissue 200-250 μm
- Tissue ingrowth enables mechanical fixation of the implant

Biomaterials: Metals Composition

TABLE II.5.6.3 Approximate Weight Percent of Different Metals Within Popular Orthopaedic Alloys

Alloy	Ni	N	Co	Cr	Ti	Mo	Al	Fe	Mn	Cu	W	C	Si	V
Stainless steel (ASTM F138)	10–15.5	<0.5	*	17–19	*	2–4	*	61–68	*	<0.5	<2.0	<0.06	<1.0	*
Co–Cr–Mo alloys (ASTM F75)	<2.0	*	61–66	27–30	*	4.5–7.0	*	<1.5	<1.0	*	*	<0.35	<1.0	*
(ASTM F90)	9–11	*	46–51	19–20	*	*	*	<3.0	<2.5	*	14–16	<0.15	<1.0	*
(ASTM F562)	33–37	*	35	19–21	<1	9.0–11	*	<1	<0.15	*	*	*	<0.15	*
Ti alloys														
CPTi (ASTM F67)	*	*	*	*	99	*	*	0.2–0.5	*	*	*	<0.1	*	*
Ti-6Al-4V (ASTM F136)	*	*	*	*	89–91	*	5.5–6.5	*	*	*	*	<0.08	*	3.5–4.5
45TiNi	55	*	*	*	45	*	*	*	*	*	*	*	*	*
Zr Alloy (95% Zr, 5% Nb)	*	*	*	*	*	*	*	*	*	*	*	*	*	*

* Indicates less than 0.05%.
Note: Alloy compositions are standardized by the American Society for Testing and Materials (ASTM vol. 13.01).

Mechanical Properties

TABLE II.5.6.2 Mechanical Properties of Dominant Orthopedic Biomaterials

Orthopedic Biomaterial	ASTM Designation	Trade Name and Company (Examples)	Elastic Modulus (Young's Modulus) (GPa)	Yield Strength (Elastic limit) (MPa)	Ultimate Strength (MPa)	Fatigue Strength (Endurance Limit) (MPa)	Hardness HVN	Elongation at Fracture (%)
Cortical Bone$								
Low strain			15.2	114t	150c/90t	30–45	–	–
High strain			40.8	–	400c–270t	–	–	–
Polymers								
UHMWPE			0.5–1.3	20–30	30–40t	13–20	60–90 (Mpa)	130–500
PMMA			1.8–3.3	35–70	38–80t	19–39	100–200 (Mpa)	2.5–6
Ceramics								
Al_2O_3			366	–	3790c/310t	–	20–30 (Gpa)	–
ZrO_2			201	–	7500c/420t	–	12 (Gpa)	–
Metals								
Stainless steels	ASTM F138	Protusul S30, Sulzer	190	792	930t	241–820	130–180	43–45
Co–Cr Alloys								
	ASTM F75	Alvium, Biomet CoCrMo, Biomet Endocast SIL, Krupp Francobal, Benoist Girard Orthochrome, DePuy Protosul 2, Sultzer Vinertia, Deloro Vitallium C, Howmedica VitalliumFHS, Howmedica Zimaloy, Zimmer Zimalloy, Micrograin	210–253	448–841	655–1277t	207–950	300–400	4–14
	ASTM F90	Vitallium W, Howdmedica	210	448–1606	1896t	586–1220	300–400	10–22
	ASTM F562	HS25l, Haynes Stellite MP35N, Std Pressed Steel Corp.	200–230	300–2000	800–2068t	340–520	8–50 (RC)	10–40
	ASTM 1537	TJA 1537, Allvac Metasul, Sulzer	200–300	960	1300t	200–300	41 (RC)	20
Ti Alloys								
CPTi	ASTM F67	CSTi, Sulzer	110	485	760t	300	120–200	14–18
Ti-6Al-4V	ASTM 136	Isotan, Aesculap Werke Protosul 64WF, Sulzer Tilastan, Waldemar Link Tivaloy 12, Biomet Tivanium, Zimmer	116	897–1034	965–1103t	620–689	310	8

ASTM: American Society for Testing and Materials (ASTM International).
$: Cortical bone is both anisotropic and viscoelastic thus properties listed are generalized.
c: Compression.
t: Tension.
RC: Rockwell Hardness Scale.

Mechanical Properties Composition and Fabrication

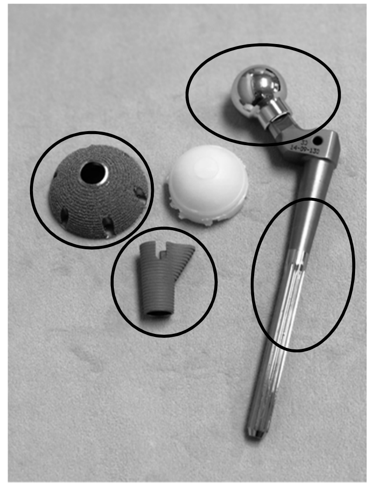
TABLE I.2.3.1 Typical Mechanical Properties of Implant Metals[a]

Material	ASTM Designation	Condition	Young's Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Endurance Limit Strength (at 10^7 cycles, $R = -1$[c]) (MPa)
Stainless steel	F745	Annealed	190	221	483	221–280
	F55, F56, F138, F139	Annealed	190	331	586	241–276
		30% Cold-worked	190	792	930	310–448
		Cold forged	190	1213	1351	820
Co–Cr alloys	F75	As-cast/annealed	210	448–517	655–889	207–310
		P/M HIP[b]	253	841	1277	725–950
	F799	Hot forged	210	896–1200	1399–1586	600–896
	F90	Annealed	210	448–648	951–1220	Not available
		44% Cold-worked	210	1606	1896	586
	F562	Hot forged	232	965–1000	1206	500
		Cold-worked, aged	232	1500	1795	689–793 (axial tension $R = 0.05$, 30 Hz)
Ti alloys	F67	30% Cold-worked Grade 4	110	485	760	300
	F136	Forged annealed	116	896	965	620
		Forged, heat treated	116	1034	1103	620–689

[a] Data collected from references noted at the end of this chapter, especially Table 1 in Davidson and Georgette (1986).
[b] P/M HIP: Powder metallurgy product, hot-isostatically pressed.
[c] R is defined as $\sigma_{min}/\sigma_{max}$.

Biomaterials: Metals

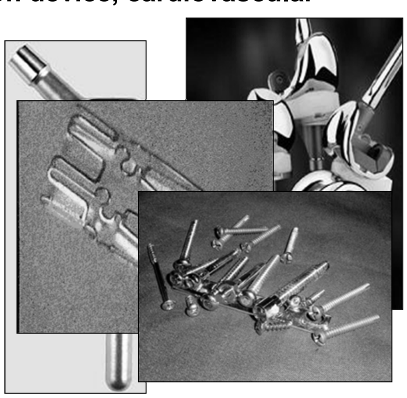
- **Most Common**
  - **Stainless Steel**
    - **Cardiovascular**
    - **Orthopedic**
  - **Co-Cr Alloys**
    - **Orthopedic**
  - **Titanium and alloys**
    - **Dental**
    - **Orthopedic**



Biomaterials: Metals

Applications

Load bearing conditions
Joint replacement
Fixation device, cardiovascular



Advantages

Controllable design
Biocompatible
Blood-compatible

Limitations

Stress Shielding
Corrosion
Fatigue and wear
Lifetime