Biomaterials in Medicine

Metals (continued) and Ceramics

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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

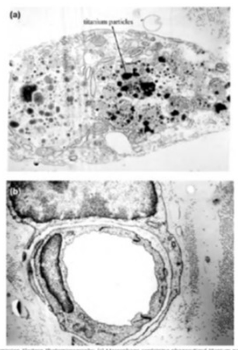


FIGURE II.5.6.17 Transmission Electron Photomicrographs: (a) Macrophage containing phagocytized titanium particles. lining with embedded titanium debris. These specimens were obtained from a tissue sample overlying the posterolateral fu week autograft + titanium) (TEM magnification = 20,000 ×).

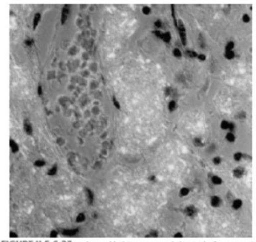


FIGURE II.5.6.22 Polarized light micrograph (190 ×) of para-aortic lymph node demonstrates the abundance and morphology of birefringent particles within macrophages. The larger filamentous particles were identified by infrared spectroscopy to be polyethylene.

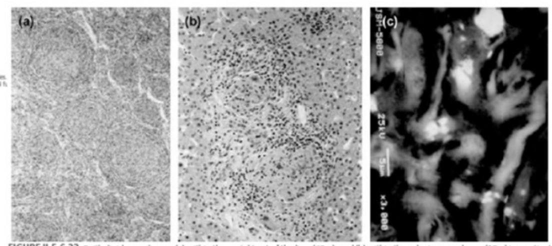


FIGURE II.5.6.23 Epithelioid granulomas: (a) within the portal tract of the liver (40 ×); and (b) within the splenic parenchyma (15 ×) in a patient with a failed titanium-alloy total hip replacement and symptomatic hepatitis. (c) Backscattered SEM of a granuloma in the spleen (3000 ×) demonstrating titanium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

Corrosion and Wear

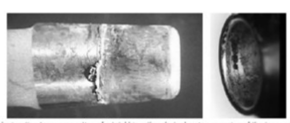


FIGURE II.5.6.15 Modular junction taper connection of a total hip arthroplasty showing corrosion of the taper connections. Macrograph of deposits of $CrPO_4$ corrosion particles on the rim of a modular cobalt-chrome femoral head.

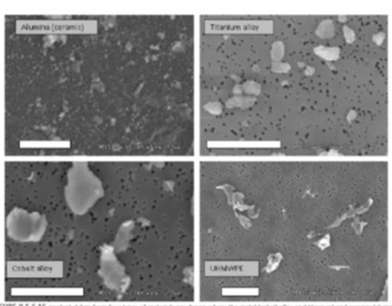


FIGURE II.5.6.16 Implant debris from four types of materials are shown where the metal (cobalt alloy and titanium) and ceramic (alumina) debris are more rounded versus the polymeric (UHMWPE) debris which is more elongated in shape. Note: Bar = 5 μm.

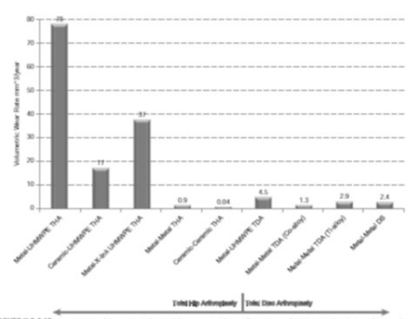


FIGURE II.5.6.13 A comparison of the amount of wear debris generated from different types of total joint arthroplasties. There is relatively less (10×) polymeric debris generated by a total disc arthroplasty with a metal-on-polymer articulation. Note: Figure References: Metal-Poly (Holt et al., 2007); 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).

Fatigue Failure

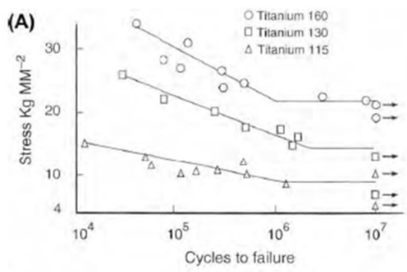
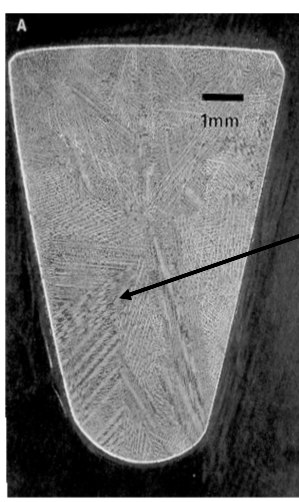


FIGURE I.2.3.4 The smooth part of a 316L stainless steel Harrington spinal distraction rod that fractured by fatigue *in vivo*. Note the bend in the rod (the rod was originally straight) and (insert) the relationship of the crack initiation zone of the fracture surface to the bend. The inserted photo 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.)

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

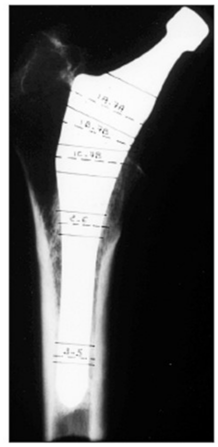
- Fracture surface of the same Co-Cr-Mo ASTM F75 hip stem
- Casting Defect - Large inclusion
  - due to ceramic mold particulate
  - Source of stress concentration
  - lead to fatigue failure in vivo

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	Elastic Modulus (Young's Modulus)	Yield Strength (Elastic limit)	Ultimate Strength	Fatigue Strength (Endurance Limit)	Hardness	Elongation at Fracture
		(Examples)	*(GPa)*	*(MPa)*	*(MPa)*	*(MPa)*	*HVN*	*(%)*
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	Alivium, Biomet CoCrMo, Biomet Endocast SL, 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.

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

Mechanical Properties Composition and Fabrication

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

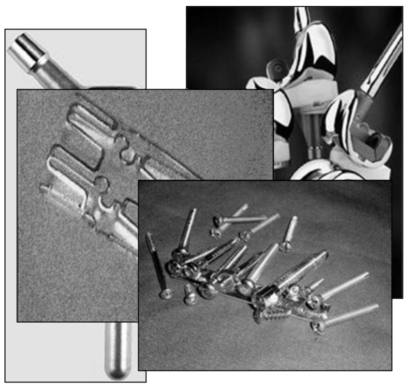
Material	ASTM Designation	Condition	Young's Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Endurance Limit Strength (at 10^7 cycles, $R = -1$[c]) (MPa)
Stainless steel	F745	Annealed	190	221	483	221–280
	F55, F56, F138, F139	Annealed	190	331	586	241–276
		30% Cold-worked	190	792	930	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

Applications

Load bearing conditions
Joint replacement
Fixation device, cardiovascular



Advantages

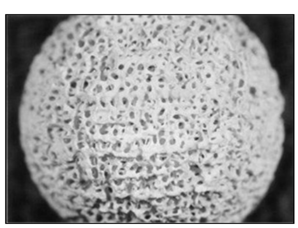
Controllable design
Biocompatible
Blood-compatible

Limitations

Stress Shielding
Corrosion
Fatigue and wear
Lifetime

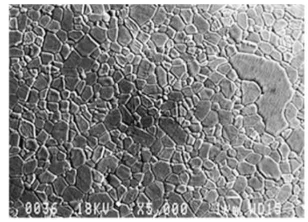
TYPES OF BIOMATERIALS

- **Metals**
- **Polymers**
- **Ceramics**
- **Natural Biomaterials**
- **Composites**

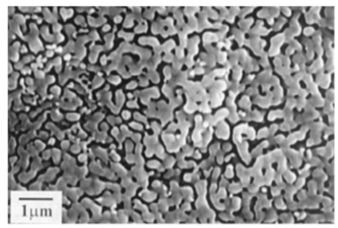


Classes of Bioceramics

- Bioinert Ceramics
- Bioactive Ceramics
- Bioresorbable Ceramics



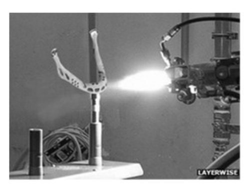
Alumina, SEM, www.cermtec.com



Ca-P Thin Film, SEM, Langstaff et al, 1999

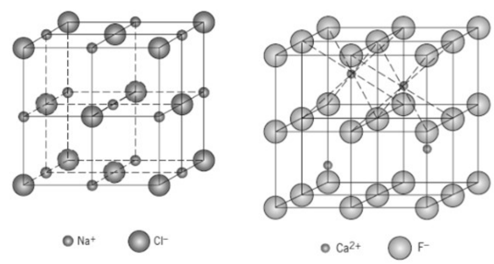
Biomaterial: Ceramics

- Metallic+Non-Metallic elements
- Types of Ceramics used clinically
  - Al_2O_3
  - Calcium phosphate ceramics
  - Glass and Glass ceramics
- Fabrication
  - Casting
  - Solid state sintering-hot isostatic pressing
  - Plasma spraying as coatings on implants



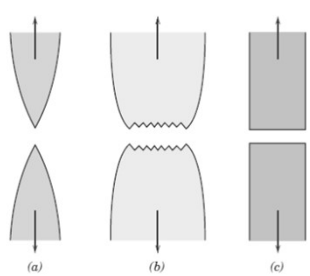
Ceramic Crystal Structure

- **More complex than those of metals**
  - **Two elements or more, ions instead of atoms**
  - **Depends on the magnitude of charge**
  - **Depends on relative size of cation vs. anion**
- **Bioceramics: A_mX_p-type crystal structure**
  - **Cation and Anion not of the same charge mag.**
  - **ZrO_2 and Al_2O_3**



Ceramic Mechanical Properties

Figure 8.1 (*a*) Highly ductile fracture in which the specimen necks down to a point. (*b*) Moderately ductile fracture after some necking. (*c*) Brittle fracture without any plastic deformation.



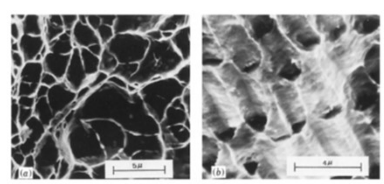


Figure 8.4 (*a*) Scanning electron fractograph showing spherical dimples characteristic of ductile fracture resulting from uniaxial tensile loads. 3300×. (*b*) Scanning electron fractograph showing parabolic-shaped dimples characteristic of ductile fracture resulting from shear loading. 5000×. (From R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition. Copyright © 1989 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

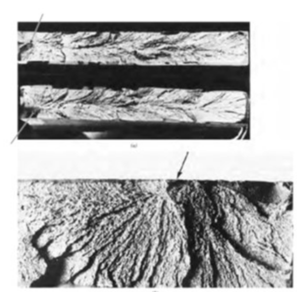


Figure 8.5 (*a*) Photograph showing V-shaped "chevron" markings characteristic of brittle fracture. Arrows indicate origin of crack. Approximately actual size. (*b*) Photograph of a brittle fracture surface showing radial fan-shaped ridges. Arrow indicates origin of crack. Approximately 2×. [(*a*) From R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition. Copyright © 1989 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc. Photograph courtesy of Roger Slutter, Lehigh University. (*b*) Reproduced with permission from D. J. Wulpi, *Understanding How Components Fail*, American Society for Metals, Materials Park, OH, 1985.]

Ceramic Mechanical Properties

Critical stress for crack propagation

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2} \qquad (8.3)$$

E = modulus of elasticity
γ_s = specific surface energy
a = one half the length of an internal crack

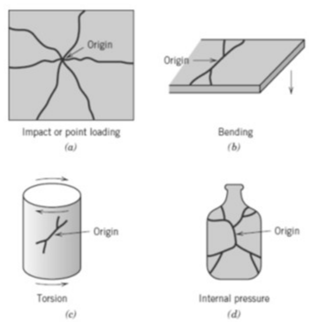
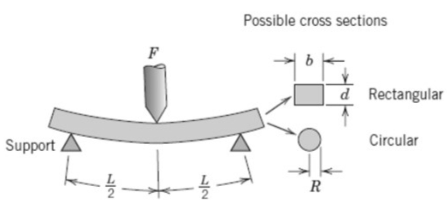


Figure 12.29 For brittle ceramic materials, schematic representations of crack origins and configurations that result from (*a*) impact (point contact) loading, (*b*) bending, (*c*) torsional loading, and (*d*) internal pressure. (From D. W. Richerson, *Modern Ceramic Engineering*, 2nd edition, Marcel Dekker, Inc., New York, 1992. Reprinted from *Modern Ceramic Engineering*, 2nd edition, p. 681, by courtesy of Marcel Dekker, Inc.)

Ceramic Mechanical Properties



σ = stress = $\frac{Mc}{I}$

where M = maximum bending moment
c = distance from center of specimen to outer fibers
I = moment of inertia of cross section
F = applied load

	M	c	I	σ
Rectangular	$\frac{FL}{4}$	$\frac{d}{2}$	$\frac{bd^3}{12}$	$\frac{3FL}{2bd^2}$
Circular	$\frac{FL}{4}$	R	$\frac{\pi R^4}{4}$	$\frac{FL}{\pi R^3}$

sing this flexure test is known as the **flexural strength,** *strength,* or the *bend strength,* an important mechani-
eramics. For a rectangular cross section, the flexural

$$\sigma_{fs} = \frac{3F_f L}{2bd^2} \qquad (12.7a)$$

dard Test Method for Flexural Strength of Advanced
ture."

ure, L is the distance between support points, and
ndicated in Figure 12.32. When the cross section is

$$\sigma_{fs} = \frac{F_f L}{\pi R^3} \qquad (12.7b)$$

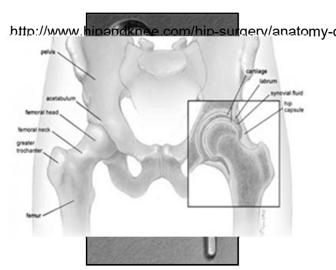
s.

Classes of Bioceramics

- Bioinert Ceramics
  - Exhibit morphological fixation without biochemical bonding
  - Ceramic bearing surfaces
    - Alumina
    - Zirconia
- Bioactive Ceramics
- Bioresorbable Ceramics

Ceramics for Hip: Cartilage or Bone

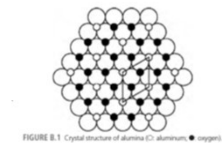
- Most Common
  - Alumina and Zirconia
    - Cartilage
  - Calcium Phosphate Coating
    - Bone bonding
  - Bioactive Glass Coating
    - Bone bonding



Stryker Trident®
Ceramic System

- Readings (Ratner: Sec.I.2.4, 1.2.6, Sec. II.5.6; Callister: Chaps. 12, 13 and 22.10-hip)

Alumina

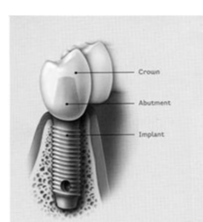


- **Structure**
  - Hexagonal organization with Al ions at octahedral interstitial sites
  - 99.5% Al_2O_3, 0.5% MgO (aids sintering)
- **Properties**
  - High strength and high abrasion resistance
  - Density of 3.9 g/cm^3, E = 380 GPa
  - Kc = 5-6 MPa $\sqrt{m}$ – low fracture toughness
  - Low coefficient of friction
    - Surface roughness <0.02 microns
  - Biocompatible

Alumina

- **Fabrication**
  - Hot isostatic pressing (1600-1700ºC)
  - Small grain size (<4 mm)
    - If increased size to 17 mm, reduces yield stress by 20%
- **Applications**
  - Used as artificial eye, in dental and orthopedics

Source: medgadget.com



Source: premieroralsurgery.com

Ceramic Mechanical Properties

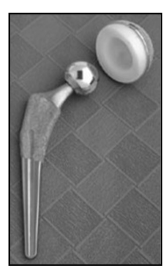
Table 8.1 Room-Temperature Yield Strength and Plane Strain Fracture Toughness Data for Selected Engineering Materials

	Yield Strength		K_{Ic}	
Material	*MPa*	*ksi*	$MPa\sqrt{m}$	$ksi\sqrt{in.}$
Metals				
Aluminum Alloy[a] (7075-T651)	495	72	24	22
Aluminum Alloy[a] (2024-T3)	345	50	44	40
Titanium Alloy[a] (Ti-6Al-4V)	910	132	55	50
Alloy Steel[a] (4340 tempered @ 260°C)	1640	238	50.0	45.8
Alloy Steel[a] (4340 tempered @ 425°C)	1420	206	87.4	80.0
Ceramics				
Concrete	—	—	0.2–1.4	0.18–1.27
Soda-Lime Glass	—	—	0.7–0.8	0.64–0.73
Aluminum Oxide	—	—	2.7–5.0	2.5–4.6
Polymers				
Polystyrene (PS)	—	—	0.7–1.1	0.64–1.0
Poly(methyl methacrylate) (PMMA)	53.8–73.1	7.8–10.6	0.7–1.6	0.64–1.5
Polycarbonate (PC)	62.1	9.0	2.2	2.0

[a] **Source:** Reprinted with permission, *Advanced Materials and Processes,* ASM International, © 1990.

Alumina

- **Advantages**
  - **Relatively chemically inert**
    - **Used for over 20 years in orthopedic applications**
  - **Biocompatible**
    - **Thin fibrous capsule formed which allows cementless fixation of prosthesis**
  - **Good wear resistance and high strength**
  - **Provides lubrication**
- **Disadvantages**
  - **Poor shear strength**
    - **Less useful as screws or plates**
  - **Stress shielding**
    - **380-420 GPa vs. 0.05-5GPa for cancellous or 7-25 for cortical bone**



Stryker Trident® Ceramic System

Zirconia

- ZrO_2
  - Tetragonal structure stabilized by yttrium oxide, Y_2O_3
- Articulating ball in total hip prostheses
- Low surface roughness (Ra) vs. Co-Cr
- Advantages over alumina
  - Lower modulus of elasticity
  - Higher strength

Source: www.bjc-houston.com

Ceramic Mechanical Properties

Table 12.5 Tabulation of Flexural Strength (Modulus of Rupture) and Modulus of Elasticity for Ten Common Ceramic Materials

	Flexural Strength		*Modulus of Elasticity*	
Material	*MPa*	*ksi*	*GPa*	*10^6 psi*
Silicon nitride (Si_3N_4)	250–1000	35–145	304	44
Zirconia[a] (ZrO_2)	800–1500	115–215	205	30
Silicon carbide (SiC)	100–820	15–120	345	50
Aluminum oxide (Al_2O_3)	275–700	40–100	393	57
Glass-ceramic (Pyroceram)	247	36	120	17
Mullite ($3Al_2O_3$-$2SiO_2$)	185	27	145	21
Spinel ($MgAl_2O_4$)	110–245	16–35.5	260	38
Magnesium oxide (MgO)	105[b]	15[b]	225	33
Fused silica (SiO_2)	110	16	73	11
Soda-lime glass	69	10	69	10

[a] Partially stabilized with 3 mol% Y_2O_3.
[b] Sintered and containing approximately 5% porosity.

Ceramic-on-Ceramic (C-on-C) Bearings

- **Used largely in Europe (~50%)**
  - 1970: introduced in France by Pierre Boutin
  - <10% in UK and USA
  - Good for young, active patients
- **Advantages**
  - High level of Harness and Scratch resistance
  - Superior lubrication and wear
  - Inert degradation products
- **Disadvantages**
  - Poor shear strength
    - fracture often occurs at the OR
  - Stress shielding
  - Costly

Comparison of Materials

Orthopedic Reviews 2011; volume 3:e16

Total Hip Arthroplasty - over 100 years of operative history

Stephen Ri
Satya Pras
[1]University
Hospitals o
Leicester; [3]
Kettering, (

Table 1. Comparison of materials used in total hip arthroplasty.

Prosthesis	Advantages	Disadvantages
Metal-on-polyethylene	Large volume of evidence to support use Predictable lifespan Cost effective	Polyethylene debris leading to aseptic loosening
Metal-on-metal	Potentially longer lifespan than polyethylene due to reduced wear Larger femoral head - therefore lower dislocation rate	Metallosis Potential carcinogenic effect of metal ions
Ceramic-on-ceramic	Low friction Low debris particles Inert substance	Expensive Require expert insertion to prevent early damage Can produce noise on movement

Classes of Bioceramics

- **Bioinert Ceramics**
- **Bioactive Ceramics**
  - **Elicit a specific biological response which results in biological bonding**
    - **Formation of carbonated hydroxyapatite layer at tissue-material interface**
    - **Bioactive glasses**
- **Bioresorbable Ceramics**

Tissue-Material Fixation

Type of bioceramic	Type of attachment	Example
1	Dense, nonporous, nearly inert ceramics attach by bone growth into surface irregularities by cementing the device into the tissues, or by press fitting into a defect (termed morphological fixation).	Al_2O_3 (single crystal and polycrystalline)
2	For porous inert implants bone ingrowth occurs, which mechanically attaches the bone to the material (termed biological fixation).	Al_2O_3 (porous polycrystalline) Hydroxyapatite-coated porous metals
3	Dense, nonporous, surface-reactive ceramics, glasses, and glass-ceramics attach directly by chemical bonding with the bone (termed bioactive fixation).	Bioactive glasses Bioactive glass-ceramics Hydroxyapatite
4	Dense, nonporous (or porous), resorbable ceramics are designed to be slowly replaced by bone.	Calcium sulfate (plaster of Paris) Tricalcium phosphate Calcium phosphate salts

Inert vs. Bioactive: Fibrous Capsule

Chapter 4.2, Fig. 9 Fibrous capsule composed of dense, compacted collagen. This fibrous capsule had formed around a Mediport catheter reservoir. Loose connective tissue with small arteries, veins, and a nerve is identified below the acellular fibrous capsule.

Bioactive Materials

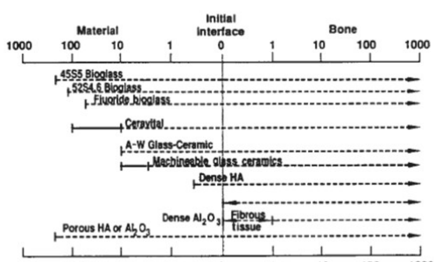


FIGURE I.2.4.2 Comparison of interfacial thickness (μm) of reaction layer of bioactive implants of fibrous tissue of inactive bioceramics in bone.

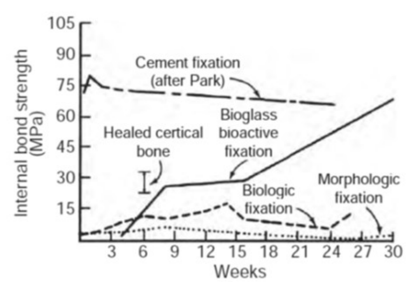


FIGURE I.2.4.7 Time dependence of interfacial bond strength of various fixation systems in bone. (After Hench, 1987.)

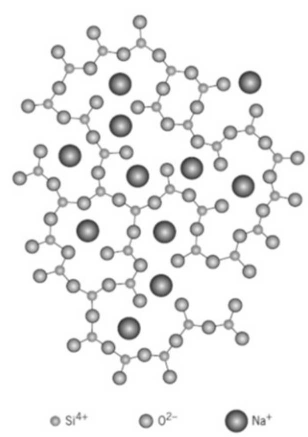
- **Light micrograph of a 45S5 Bioglass® implant (BG) bonded to rat bone (B) after 1 year**
- **Bone cells (O) in conjunction with the hydroxylcarbonate apatite layer (Ca-P) formed on top of the silica gel (S). (Hench et al, 1982)**

Bioactivity

- **Osteointegration**
  - **Chemical integration between bone and implant**
  - **Example: bioactive glass**
- **Osteoconduction**
  - **Materials that provide a scaffold for bone-forming cells and subsequent bone formation**
    - **Interconnecting porosity for cell and vascular ingrowth**
  - **Example: hydroxyapatite**
- **Osteoinduction**
  - **Materials that have a capacity to induce bone**
    - **Recruit stem cells**
    - **Induce proliferation and differentiation**
  - **Example: demineralized bone matrix**

Bioactive Glasses

- **Composition and Structure**
  - **SiO_2, Na_2O, CaO, P_2O_5**
  - **Less than 60% SiO_2**
  - **High network former content**
    - **Na_2O, CaO**
  - **High CaO/P_2O_5 ratio**
  - **Example: 45S5 bioactive glass (CaO/P_2O_5 =5)**
    - **45% SiO_2, 24.5% Na_2O, 24.5% CaO, 6% P_2O_5**

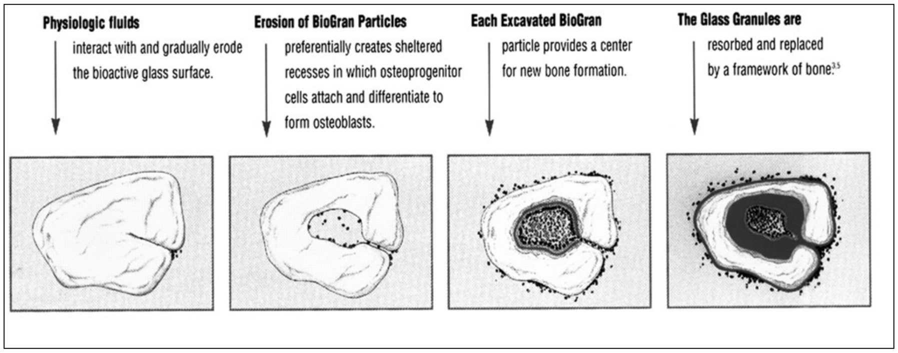


Silica Structure, Callister, 5th Ed, 2000

In Vivo Bioactivity

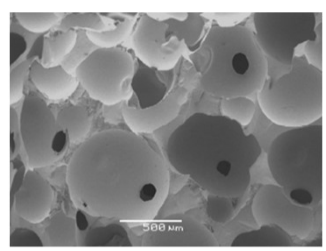
Applications

BIOGRAN® - bone/dental filler, 300-355 μm, Orthovita, Melvern, PA
Dental and orthopedic applications



Bioactive Glasses

- **Advantages**
  - **Can elicit targeted cell response (bioactivity)**
  - **Tissue-material interface formation (biomimetic)**
- **Disadvantages**
  - **Dissolution products**
  - **Poor mechanical properties**



BG Foam, SEM, Jones et al, 2006

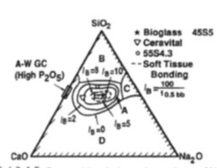


FIGURE I.2.4.5 Compositional dependence (in wt.%) of bone bonding and soft tissue bonding of bioactive glasses and glass-ceramics. All compositions in region A have a constant 6 wt.% of P_2O_5. A-W glass ceramic has higher P_2O_5 content (see Table I.2.4.5 for details). I_B, Index of bioactivity.

Classes of Bioceramics

- Bioinert Ceramics
- Bioactive Ceramics
- Bioresorbable Ceramics
  - Degrade gradually and allow for replacement by host tissue
    - Calcium phosphate ceramics
      - Tricalcium phosphate
      - Hydroxyapatite

Calcium Phosphates

- Calcium sulfate: Plaster of Paris
- Hydroxyapatite: $Ca_{10}(PO_4)_6(OH)_2$
  - Ca/P=1.67, E = 40-116 GPa
  - Carbonate, fluorine, and chlorine Ions incorporated into structure
- Tricalcium Phosphate: $Ca_3(PO_4)_2$
  - Ca/P=1.50
  - Alpha and beta crystal form
  - Ionic substitution with carbonate

Bioceramics

TABLE I.2.4.8 Calcium Phosphates			
Ca:P	Mineral Name	Formula	Chemical Name
1.0	Monetite	$CaHPO_4$	Dicalcium phosphate (DCP)
1.0	Brushite	$CaHPO_4 \cdot 2H_2O$	Dihydrate (DCPD) Dicalcium phosphate
1.33	—	$Ca_8(HPO_4)_2(PO_4)_4 \cdot 5H_2O$	Octocalcium phosphate (OCP)
1.43	Whitlockite	$Ca_{10}(HPO_4)(PO_4)_6$	
1.5	—	$Ca_3(PO_4)_2$	Tricalcium phosphate (TCP)
1.67	Hydroxyapatite	$Ca_{10}(PO_4)_6(OH)_2$	
2.0		$Ca_4P_2O_9$	Tetracalcium phosphate

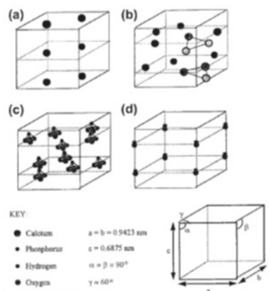
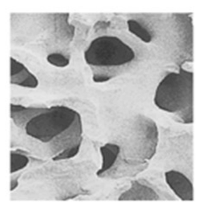


FIGURE I.2.4.12 Theoretical positions of the ionic species within the unit cell of hydroxyapatite. (Hing, 1995).

TABLE I.2.4.10	Typical Mechanical Properties of Dense Hydroxyapatite Ceramics
Theoretical density	3.156 g cm^3
Hardness	500–800 HV, 2000–3500 Knoop
Tensile strength	40–100 MPa
Bend strength	20–80 MPa
Compressive strength	100–900 MPa
Fracture toughness	approx. 1 Mpa $m^{0.5}$
Young's modulus	70–120 GPa

Calcium Phosphates

- Biological or synthetic
  - Porous, derived from coral, pore>100 μm
- Bioactive
  - Osteointegration, osteoconduction, osteoinduction
- Biodegradable
  - β-TCP>HA



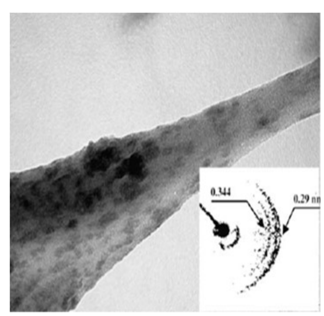
news.bbc.co.uk

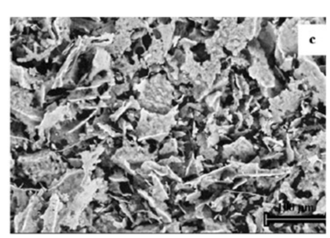
Factors Affecting Biodegradation

- **Physical properties**
  - **Form (particulate or bulk)**
  - **Porosity (interconnectivity, size)**
  - **Crystallinity (grain size, crystal size)**
- **Chemical properties**
  - **Ionic substitutions**
  - **Other elemental impurities**
- **Biological properties**
  - **pH**
  - **Age, species, sex**

Bioinspired Composites

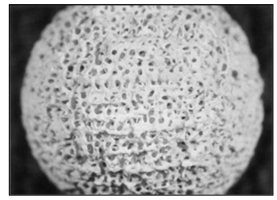
- **Biomimetic design**
  - **Hydroxyapatite-collagen**
    - **HA nanocrystals self-assemble on collagen fibrils**
    - **Similar to natural bone tissue**
  - **Hydroxyapatite-alginate**
    - **Direct nucleation of HA on alginate polymer**
    - **Shown to promote osteoblast growth and functionality**





Tampieri et al, 2003

Porosity vs. Mechanical Properties



- Material Porosity
  - Total void volume
  - Average Pore diameter
  - Total surface area
  - Interconnectivity between pores
- Compressive & Tensile strength
  - Compressive strength (σ_c) vs. total pore volume (Vp)
    - $\sigma_c = 700e^{-5Vp}$
  - Tensile strength (σ_t) vs. volume fraction of microporosity (Vm)
    - $\sigma_t = 200e^{-20Vm}$

Biomaterial: Ceramics

- Advantages
  - Relatively inert and corrosion resistant
  - Excellent biocompatibility
  - Can elicit targeted responses – bone bioactive
  - Higher E, yield strength
  - Lubrication and optical properties

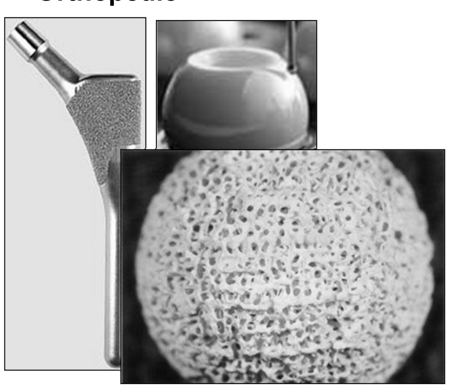
Biomaterial: Ceramics

- Disadvantages
  - Poor shear strength
    - less useful as screws or plates
  - Low ductility
  - Surface defects – poor fatigue properties
  - Brittle fracture
  - Not used in high load-bearing condition
- New direction: bioinspired composites

BIOMATERIALS: Ceramics

Applications

Load bearing conditions
Joint replacement
Orthopedic



Advantages

Controllable design
Biocompatible/Inert
Lubrication
Biomimetic

Limitations

Stress Shielding
Low fracture toughness