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Biomaterials for orthopaedic applications

Newcastle University Postgraduate Programme 2010

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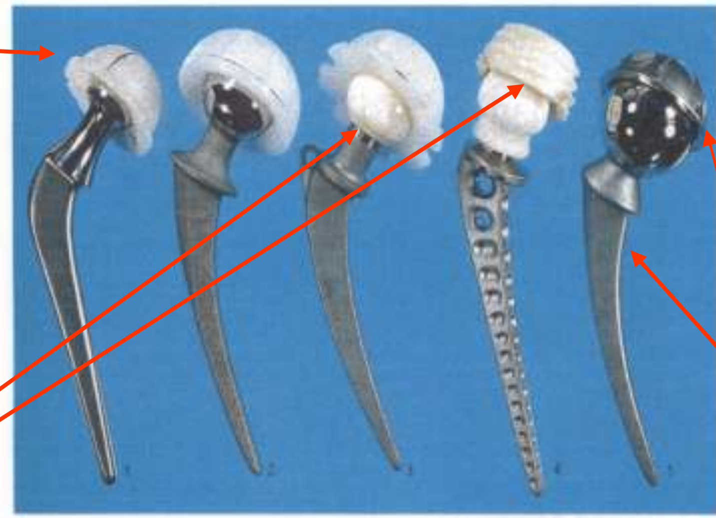
What are Biomaterials?

- Materials suitable for implantation into (or contact with) living tissue
- Biocompatible – non toxic
- Non-degradable for permanent applications – e.g. joint replacements
- Degradable for temporary applications – e.g. internal sutures

Structural Biomaterials

Polymer (UHMWPE)



Ceramic (Alumina, zirconia ZrO_2)

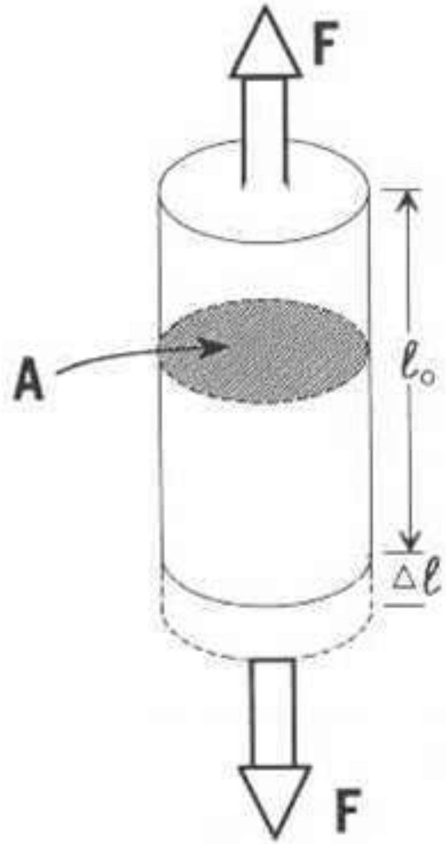
Metal Alloys (316L stainless steel, CoCrMo, Ti6Al4V)

Metal, ceramic and polymer combinations can be used in TJR

Orthopaedic Applications

- Usually load bearing
- Mechanical properties and biocompatibility dominate material choices
- *Structural biomaterials*

Axial Stress and Axial Strain



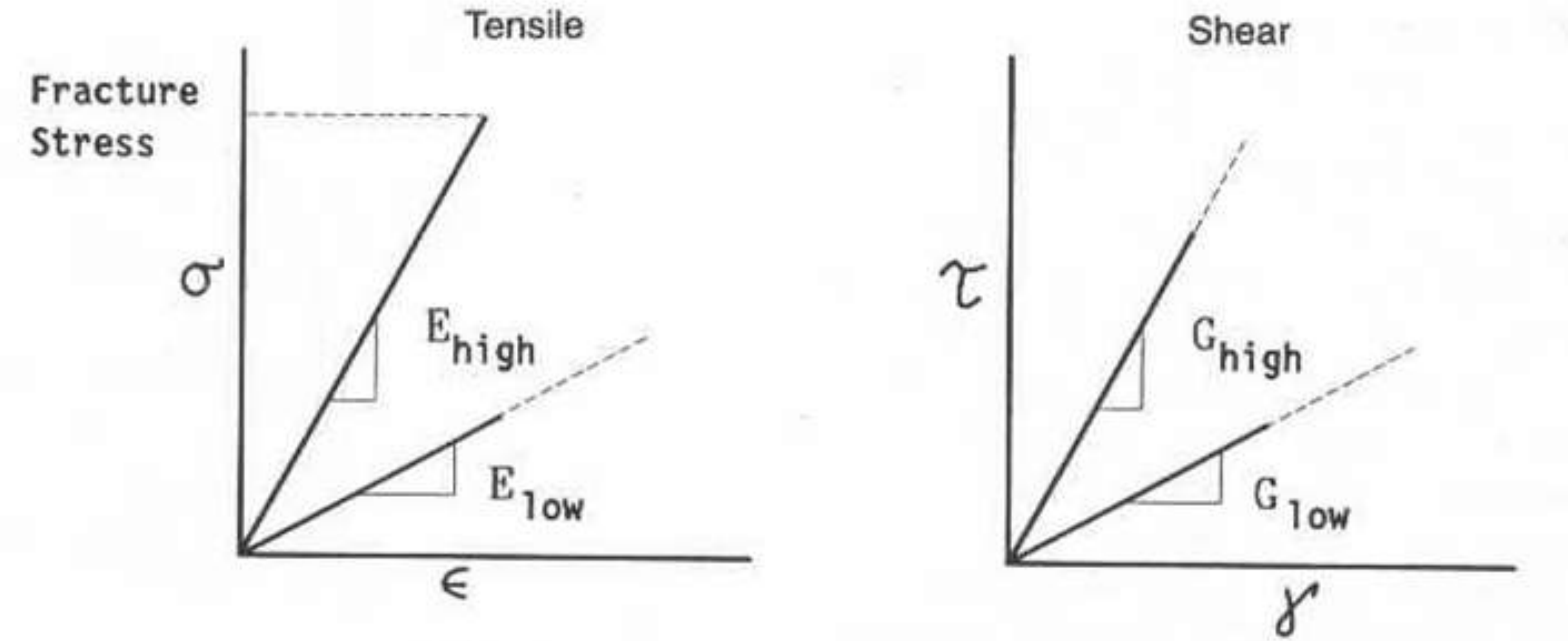
$$\sigma = \frac{F}{A_{\perp}}$$ TENSILE STRESS

$$\epsilon = \frac{\Delta \ell}{\ell_{o\parallel}}$$ TENSILE STRAIN

Intensity of load

Dimensional response to load

Stress-strain behaviour

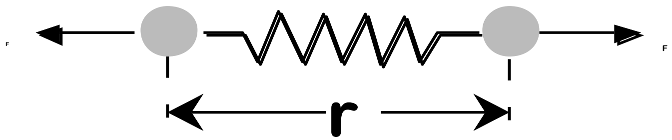


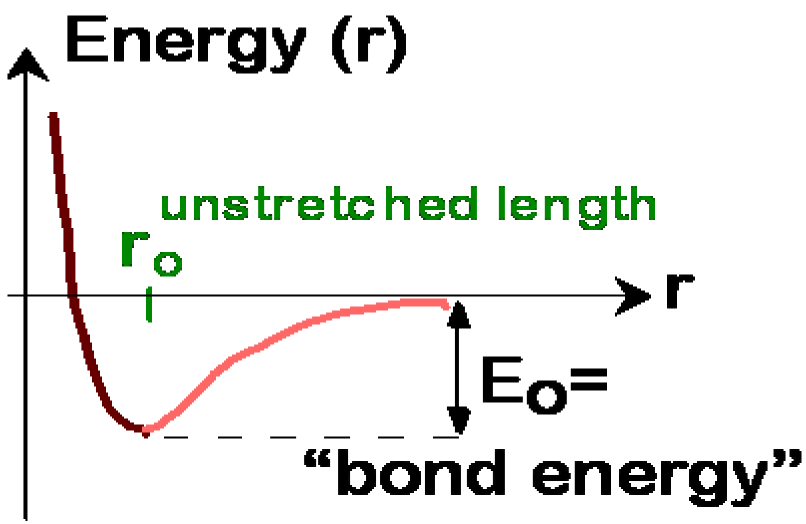
Elastic and Shear Moduli reflect the inter-atomic bond strength

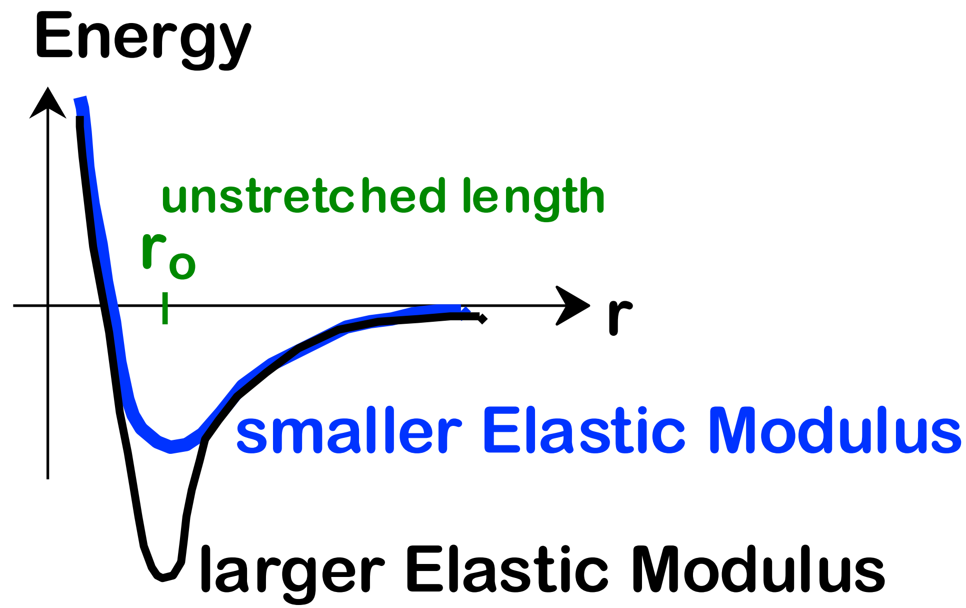
Bond Strength

(How easily can the atoms be separated)

- Bond length, r







E is larger if E_o is larger

Bonding Summary

Ceramics

(Ionic & covalent bonding)

Large bond energy

large T_m

large E

Metals

(Metallic bonding)

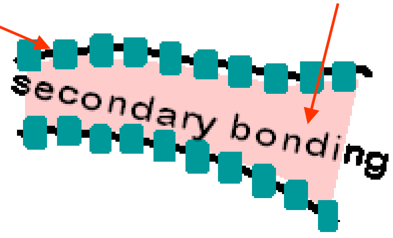
Variable bond energy

moderate T_m

moderate E

Polymers

(Covalent & Secondary)



Directional Properties

Secondary bonding dominates

small T_m

small E

Interatomic bonding types

Bonding type	**Bond energy**	**Example**	**Elastic modulus/GPa**	**Melting Temp /^oC**
Covalent	High	C (diamond)	1000	3500
Ionic	High	Alumina (Al_2O_3)	380	2500
Metallic	Intermediate	Stainless Steel	200	1500
Van der Waals	Low	UHMWPE	1	110
Hydrogen	Low	H_2O	n/a	0

BOND STRENGTH

Mechanical properties of interest for orthopaedic applications

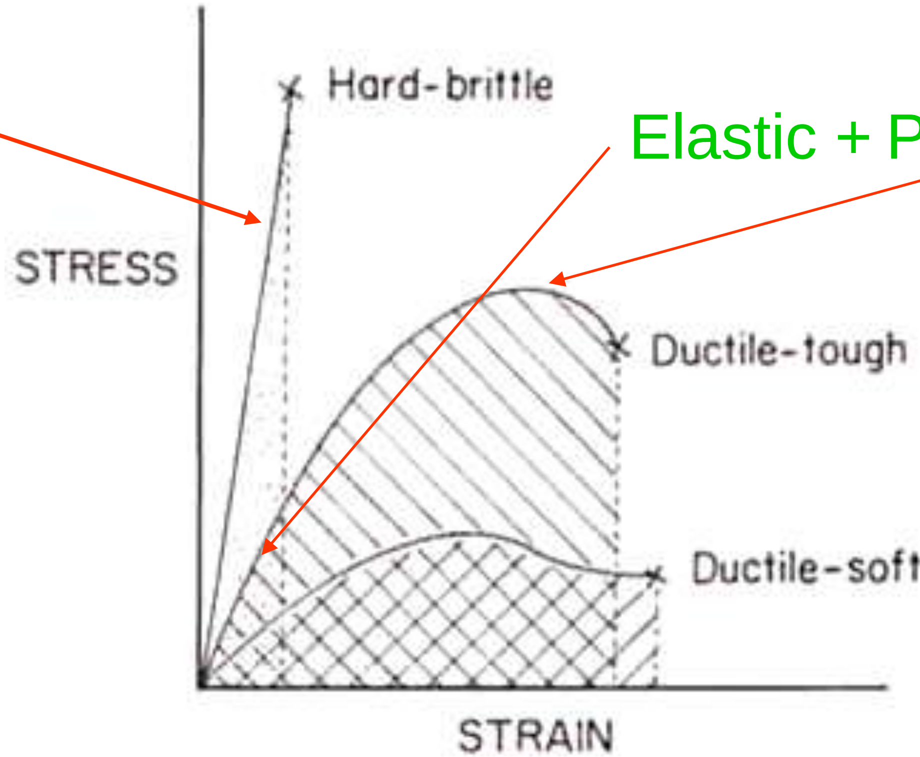
- Tensile strength
- Compressive strength
- Elongation
- Fracture toughness (crack propagation and growth)
- Fatigue behaviour (endurance limit)

All are microstructure dependent

Area under the stress-strain curve is the work of fracture

Purely elastic deformation

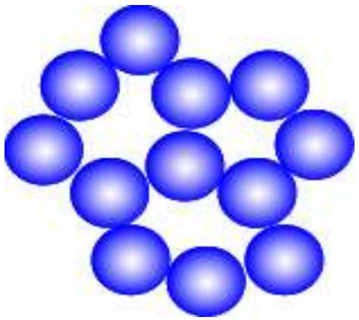
Elastic + Plastic deformation

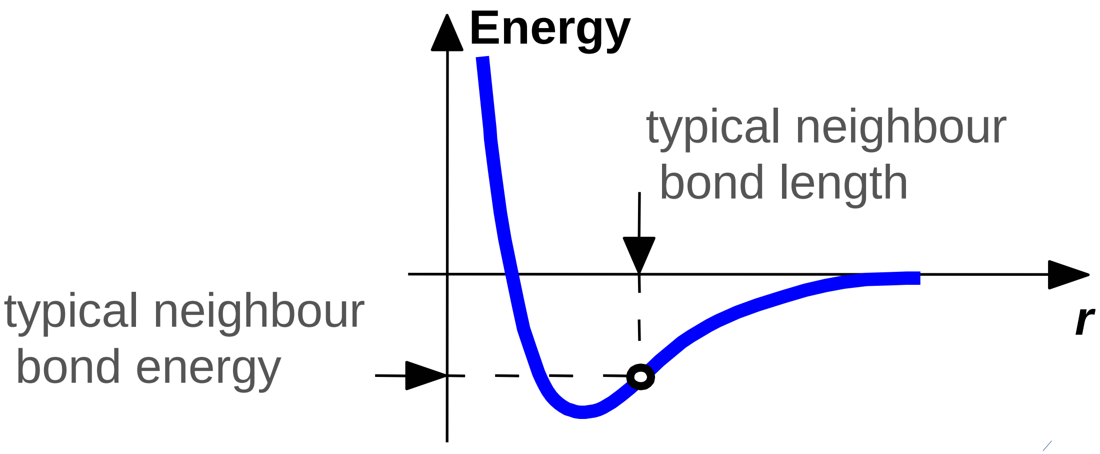


Ductility is determined by both atomic bonding and microstructural form

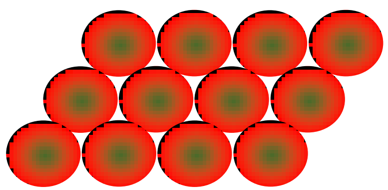
Energy and Packing

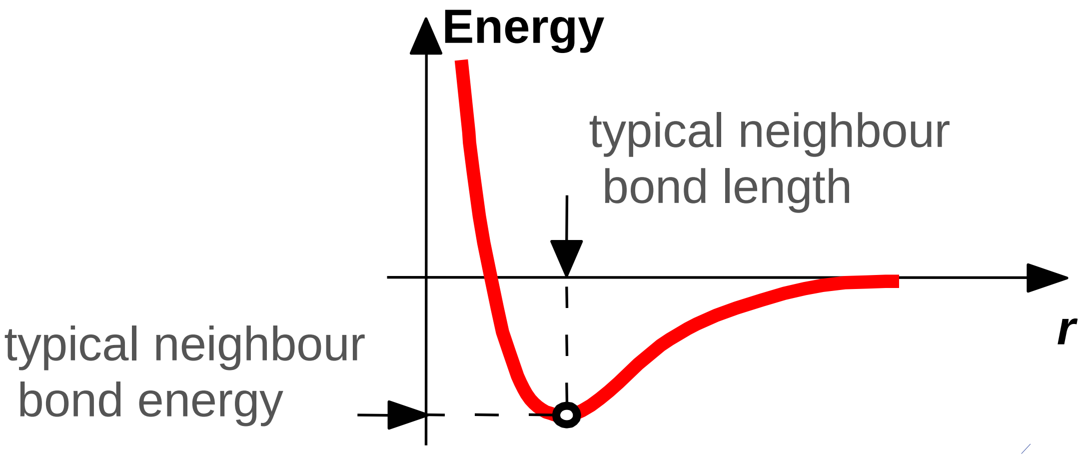
random





ordered



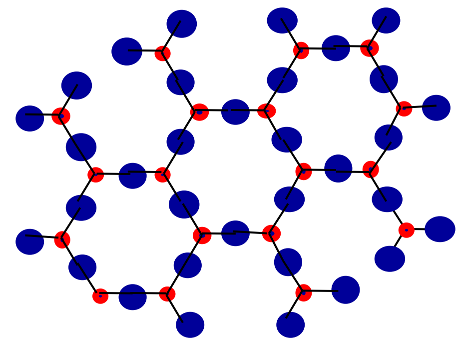


Dense, ordered packed structures tend to have lower energies.

Materials and Packing

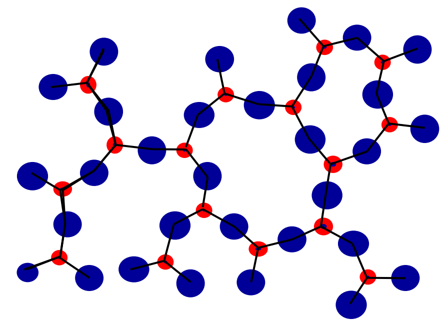
Crystalline materials...

- atoms pack in periodic, 3D arrays
- typical of: -metals
  -many ceramics
  -some polymers



Noncrystalline materials...

- atoms have no periodic packing
- occurs for: -complex structures
  -rapid cooling

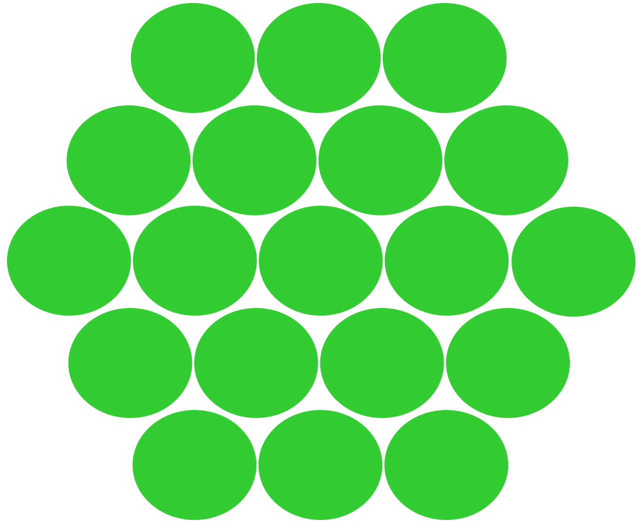


"Amorphous" = Noncrystalline

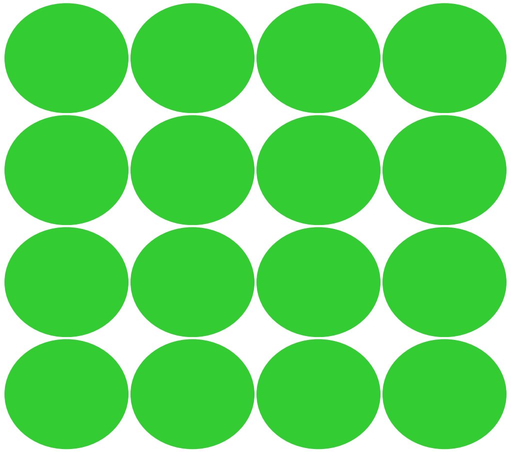
Metallic Crystal Structures

- How can we stack metal atoms to minimize empty space?

2-dimensions

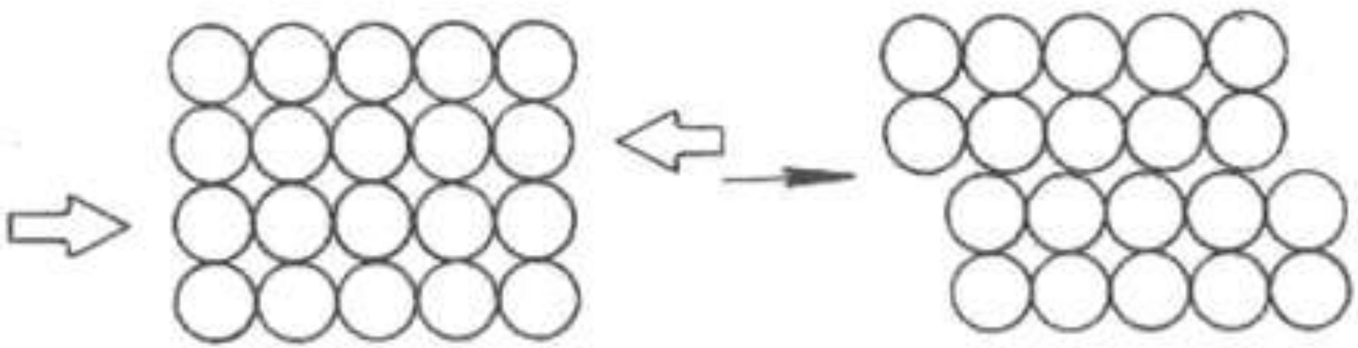


vs.



Now stack these 2-D layers to make 3-D structures

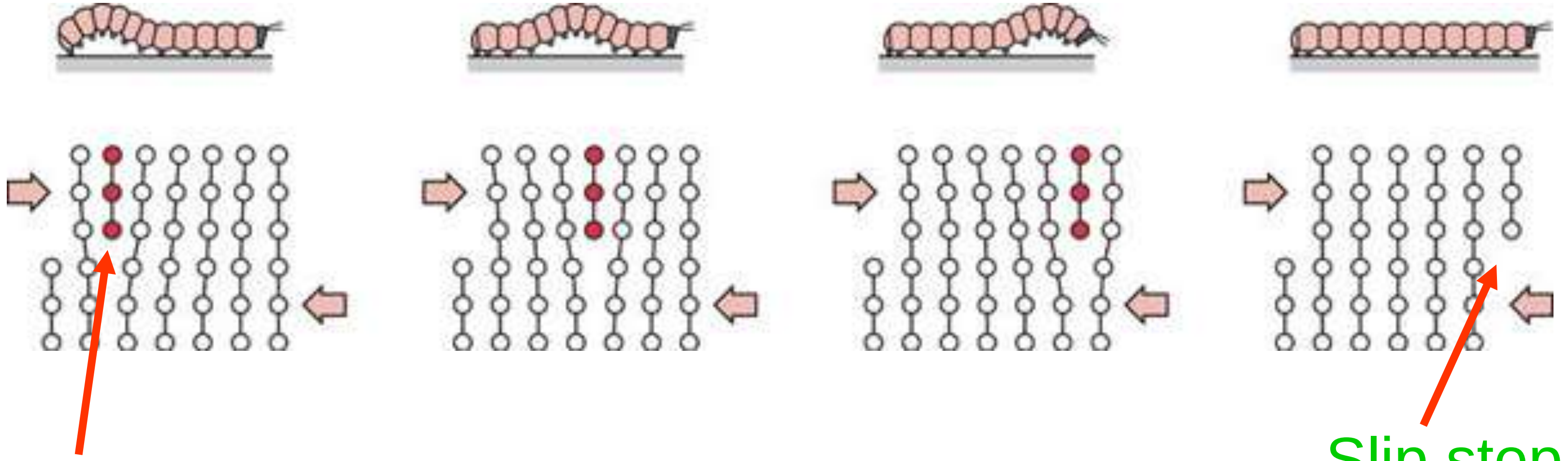
Plastic Deformation occurs via SLIP



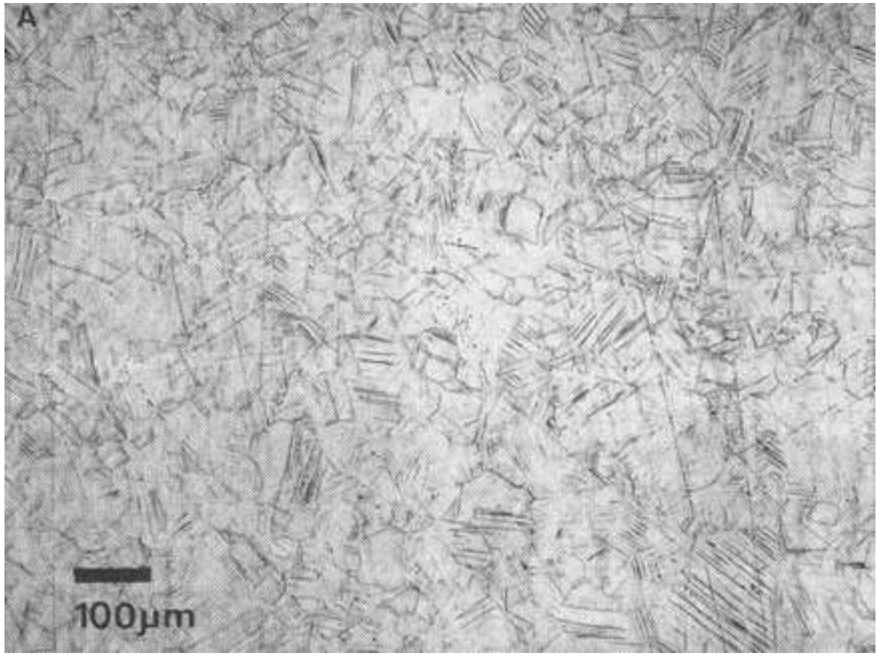
Easy slip = ductility

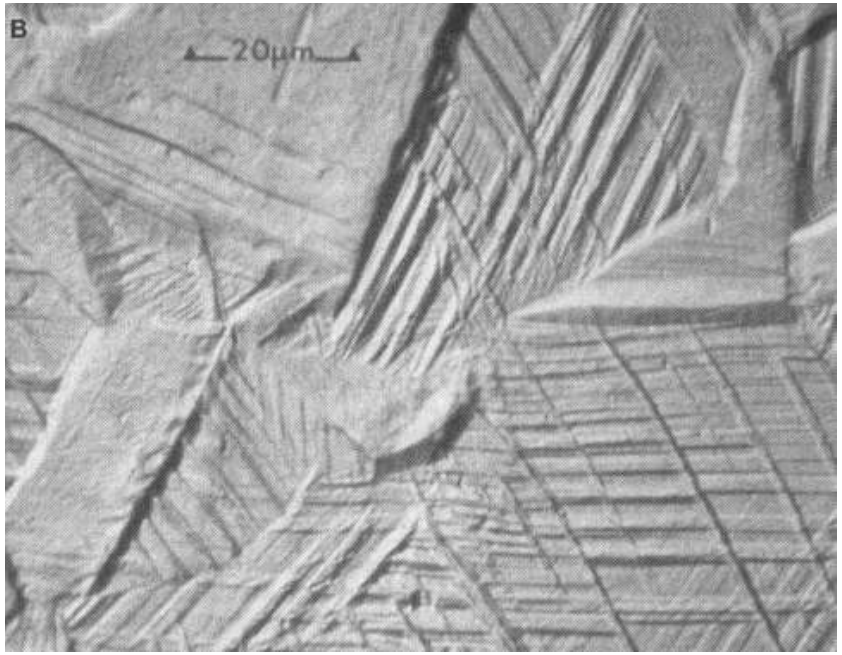
Dislocations

Enable plastic/permanent deformation in crystalline materials



Plastic deformation of metals





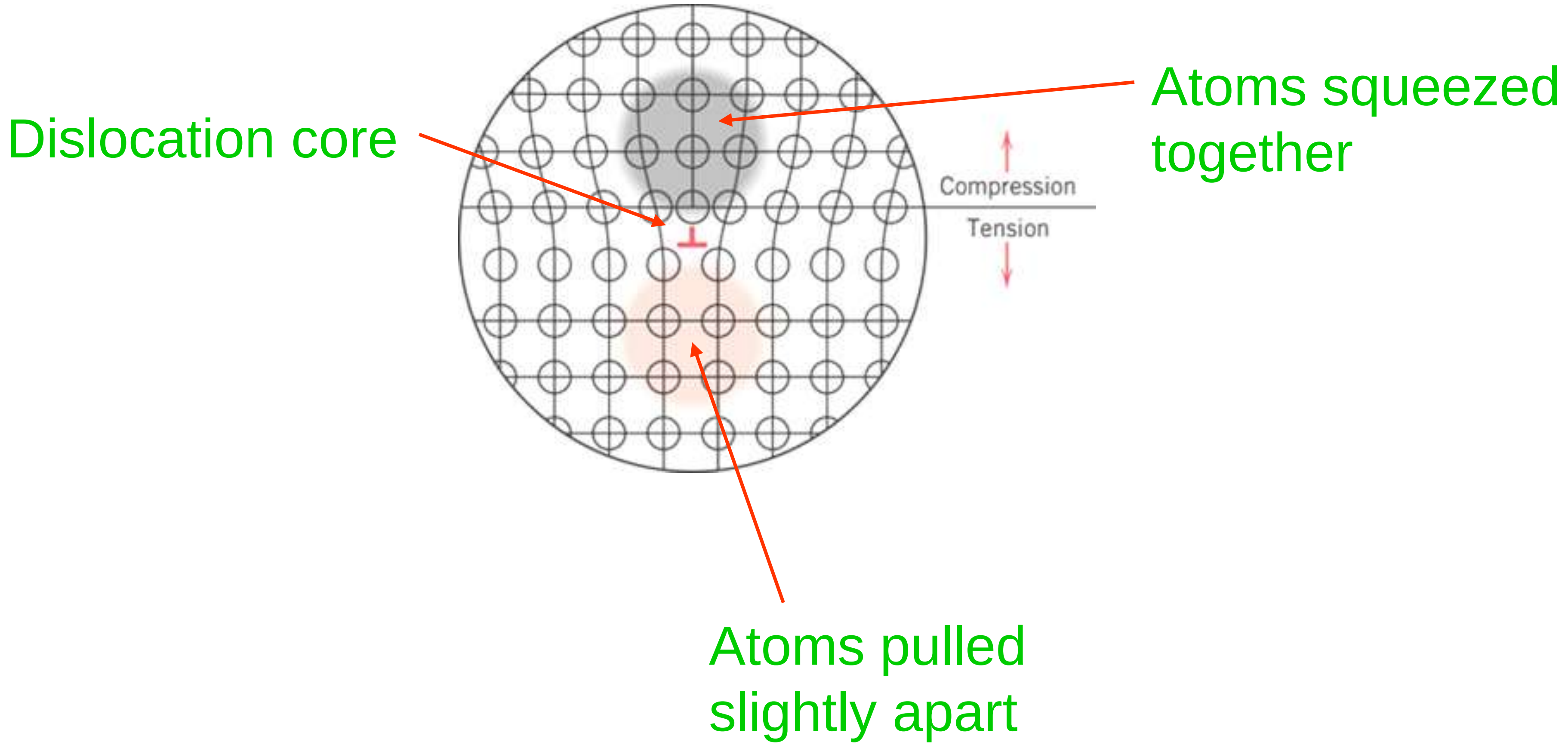
Surface slip steps are visible on heavily cold worked 316L alloy

Dislocations

In METALS, dislocations are MOBILE and facilitate plastic deformation at low shear stresses

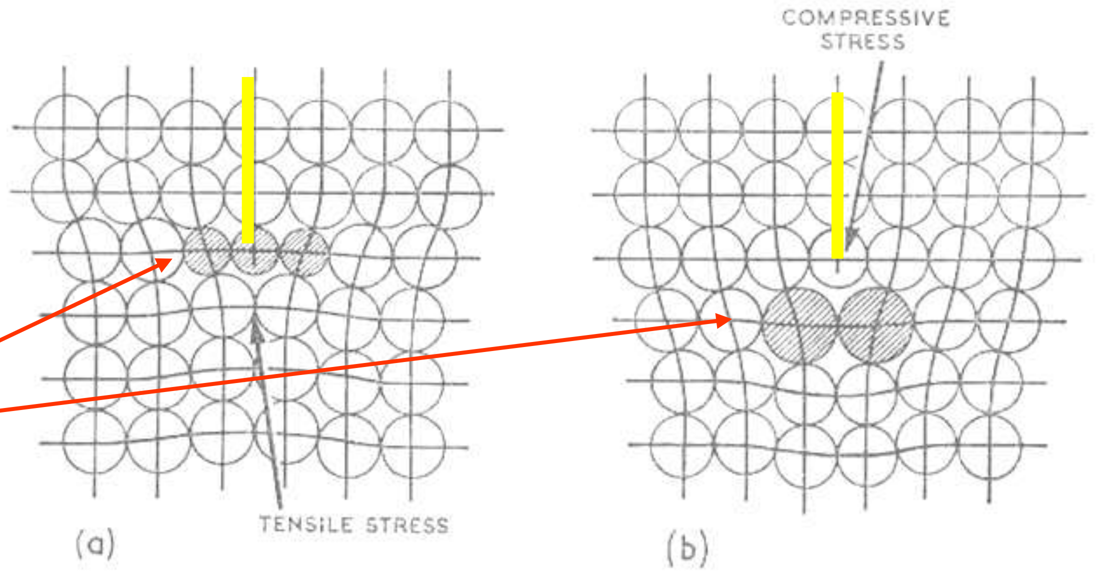
In CERAMICS, dislocations are IMMOBILE and hence ductilities are minimal

Dislocations introduce atomic-scale strains



Alloying Impedes Dislocation Motion

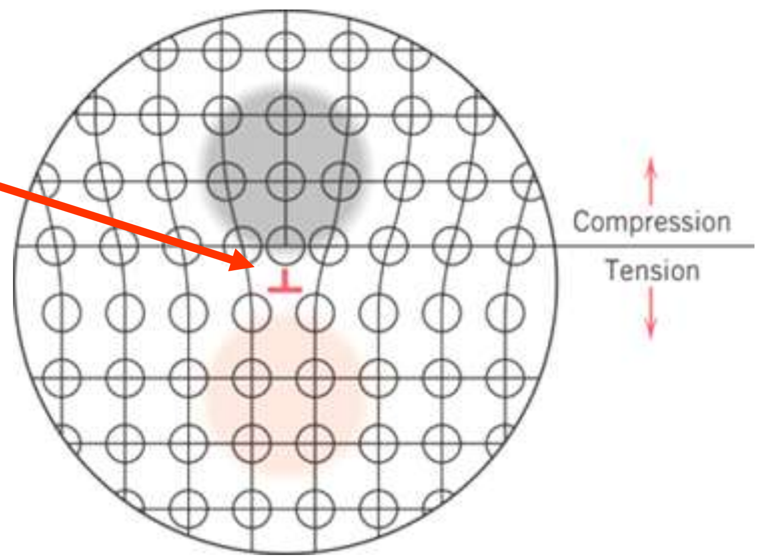
Alloying
elements



Alloying a metal introduces atomic mismatch and
lattice strains that 'pin' dislocations

Dislocations Introduce Atomic-scale Strains

Dislocation core

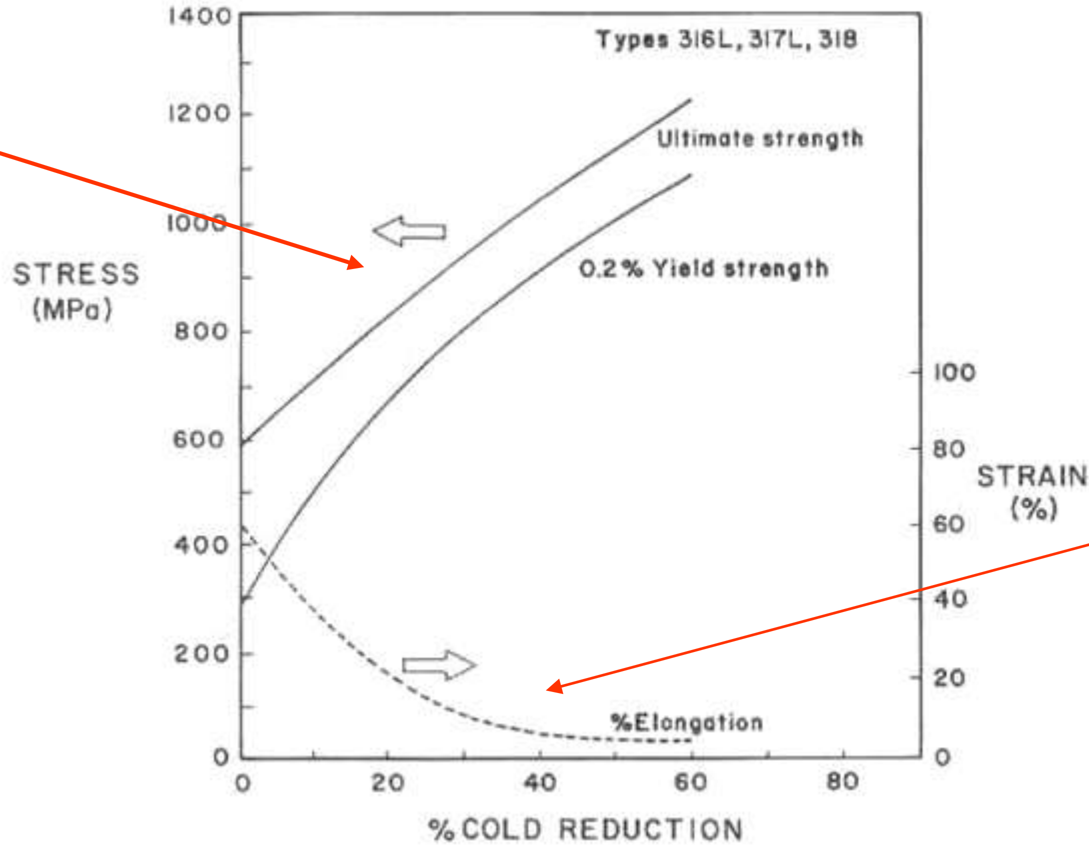


For a metal, more dislocations = higher yield stress

This is achieved by COLD WORKING

Effect of cold work on a stainless steel

Strength rises

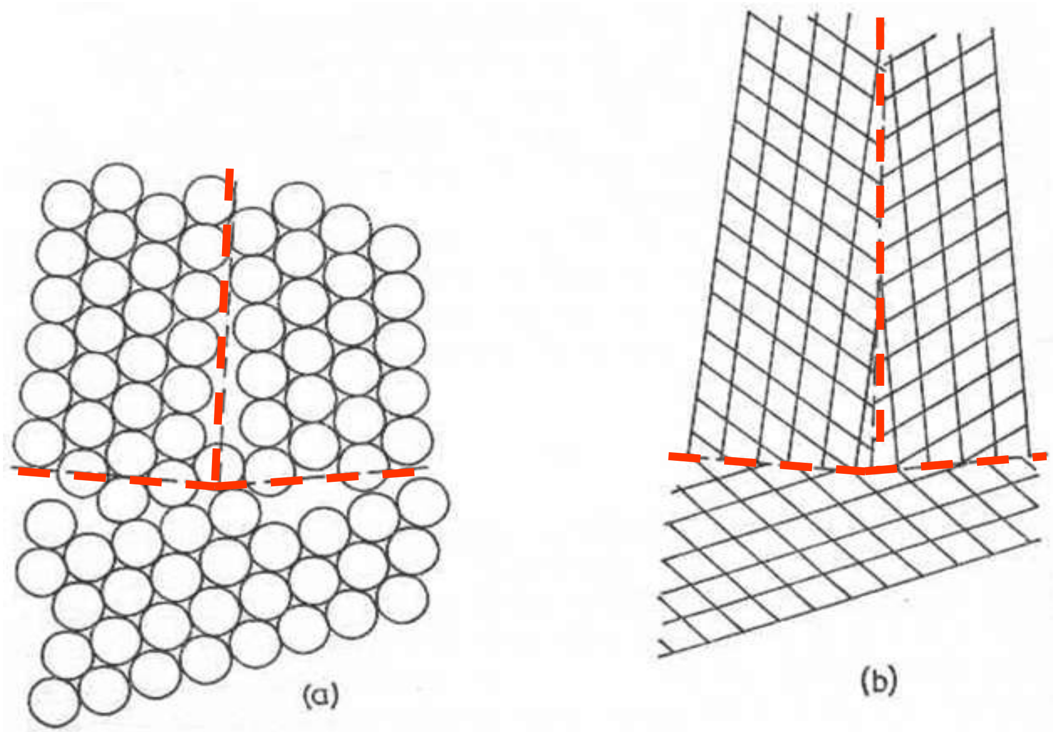


Ductility falls

Increasing dislocation density

GRAIN BOUNDARIES impede the motion of dislocations

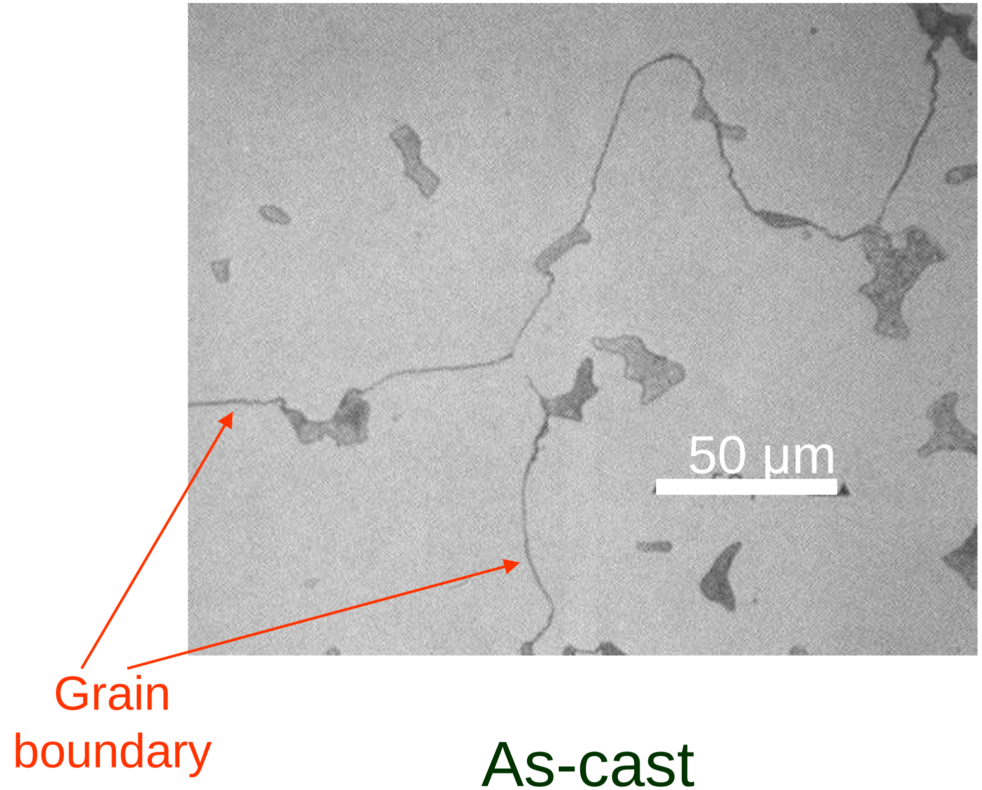
Grain boundary



GRAIN SIZE affects tensile strength and ductility

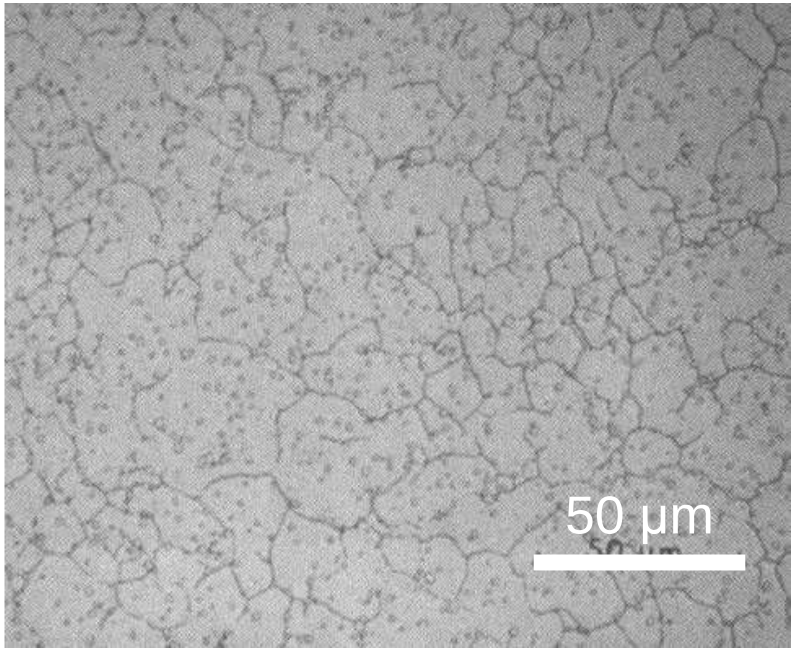
Smaller grains = higher number of grain boundaries per unit area

Co-Cr-Mo alloy (F75) samples



As-cast

750 MPa UTS



Hot-isostatically pressed

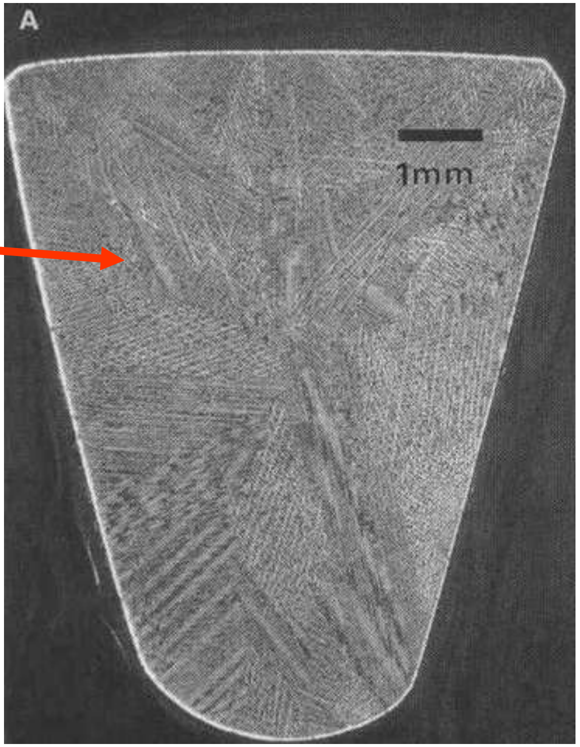
1250 MPa UTS

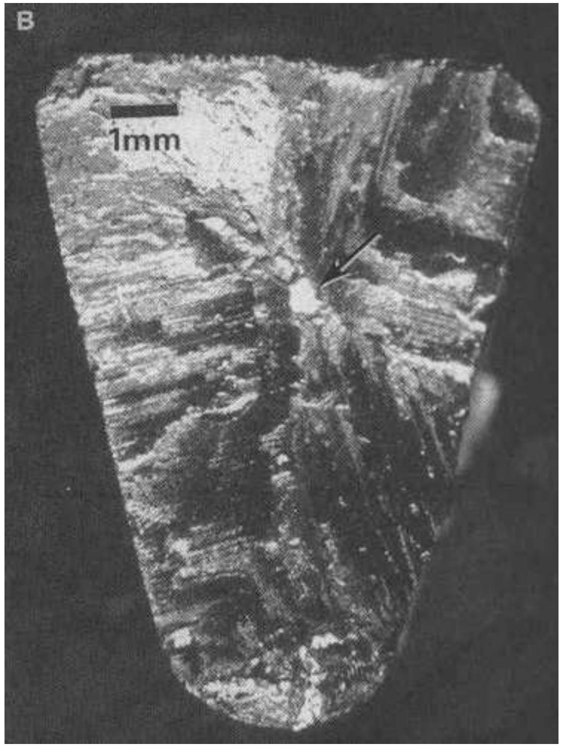
Influence of finished form on the mechanical properties for some common orthopaedic alloys

Material	ASTM designation	Condition	Young's modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)
Stainless steel	F745	Annealed	190	221	483
	F55, F56, F138, F139	Annealed	190	331	586
		30% Cold worked	190	792	930
		Cold forged	190	1213	1351
Co–Cr alloys	F75	As-cast/annealed	210	448–517	655–889
		P/M HIP[b]	253	841	1277
	F799	Hot forged	210	896–1200	1399–1586
	F90	Annealed	210	448–648	951–1220
		44% Cold worked	210	1606	1896
	F562	Hot forged	232	965–1000	1206
		Cold worked, aged	232	1500	1795
Ti alloys	F67	30% Cold-worked Grade 4	110	485	760
	F136	Forged annealed	116	896	965
		Forged, heat treated	116	1034	1103

Fatigue Resistance

Large grain structure, poor fatigue resistance

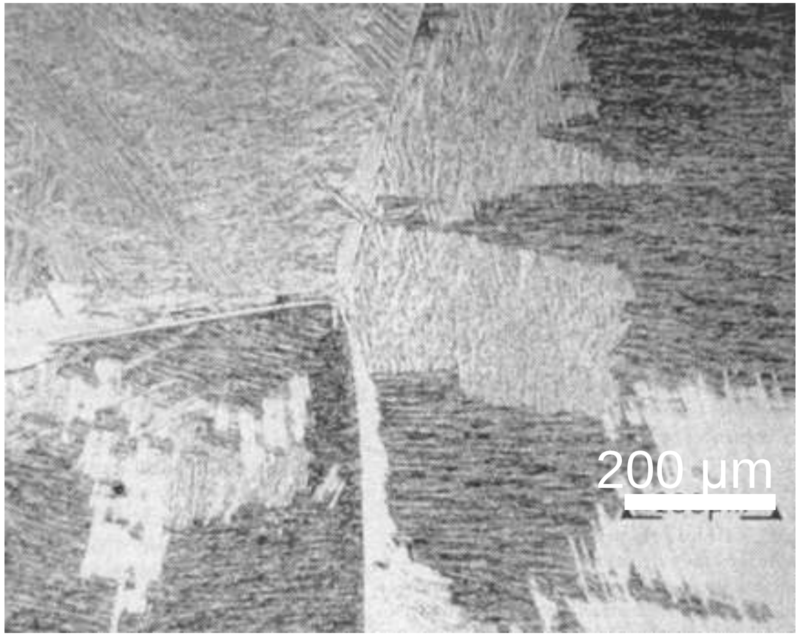




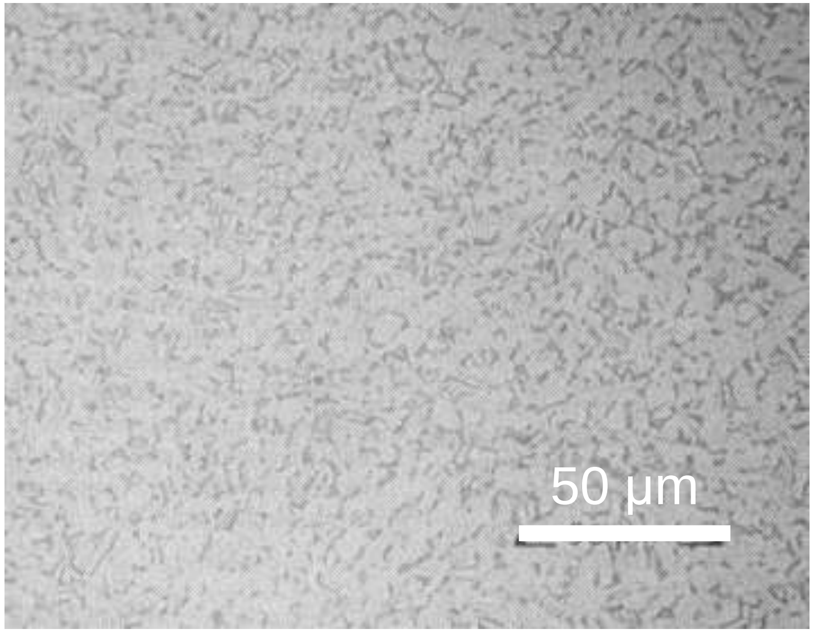
Co-Cr-Mo (F75) as-cast femoral component, failed in vivo

Fracture surface

Ti6Al4V Alloy



Typical as-cast microstructure

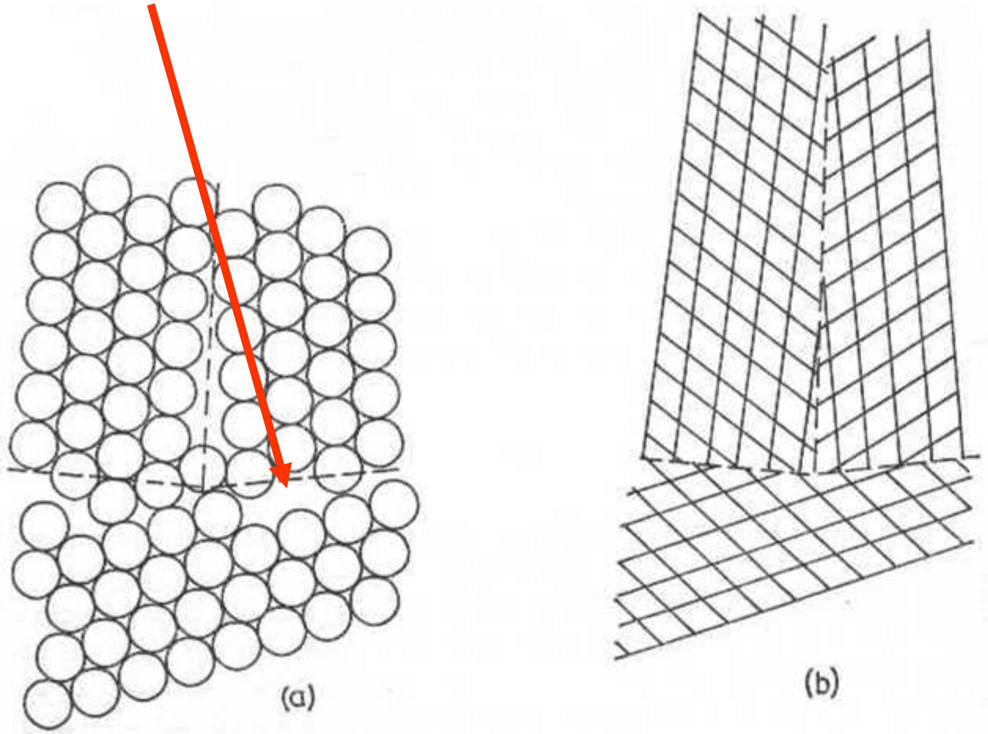


Hot-isostatically pressed

Large grains, low ductility and poor fatigue resistance

Grain boundaries

Grain boundaries are areas of atomic disorder

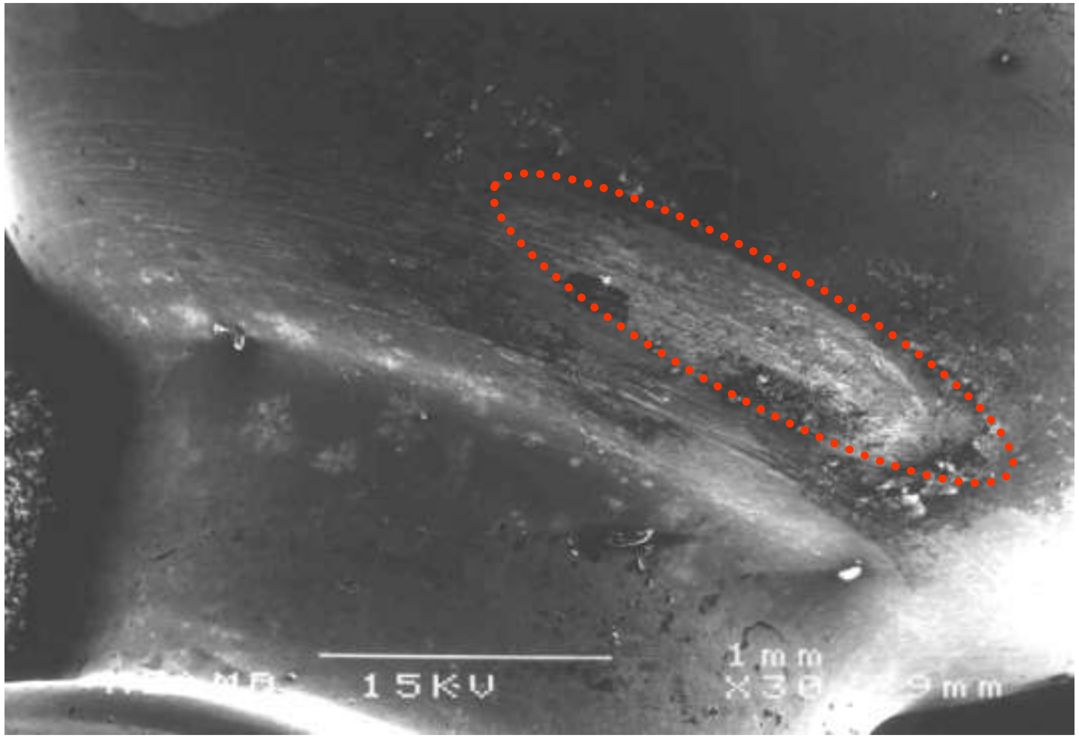


Disorder = Increased susceptibility to corrosion

Corrosion

Biocompatibility is often due to a stable oxide surface
Mechanical action may remove stable oxide film, leading to corrosion (fretting)

Fretting corrosion of 316L bone plate (2 months in vivo)



Environmental degradation

Oxide stability depends upon residual stress and alloy composition

Stainless steel intramedullary nails

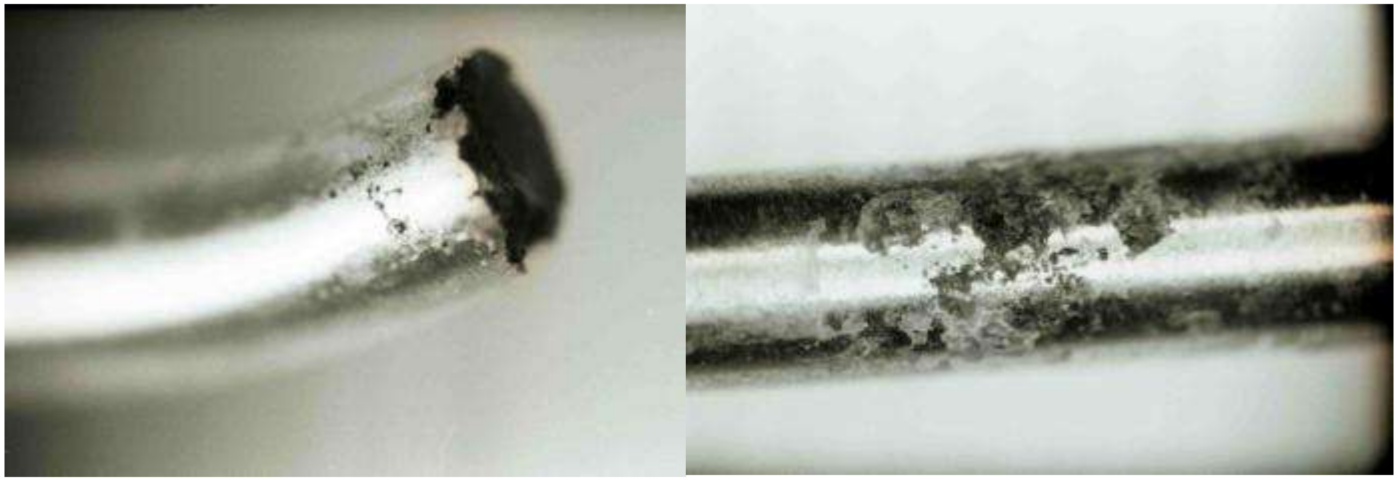
Batch failed in vivo after short time period

Failed intramedullary nail (top)

‘Stock’ intramedullary nail (bottom)

Environmental degradation

Metallographic examination of failed, retrieved nails

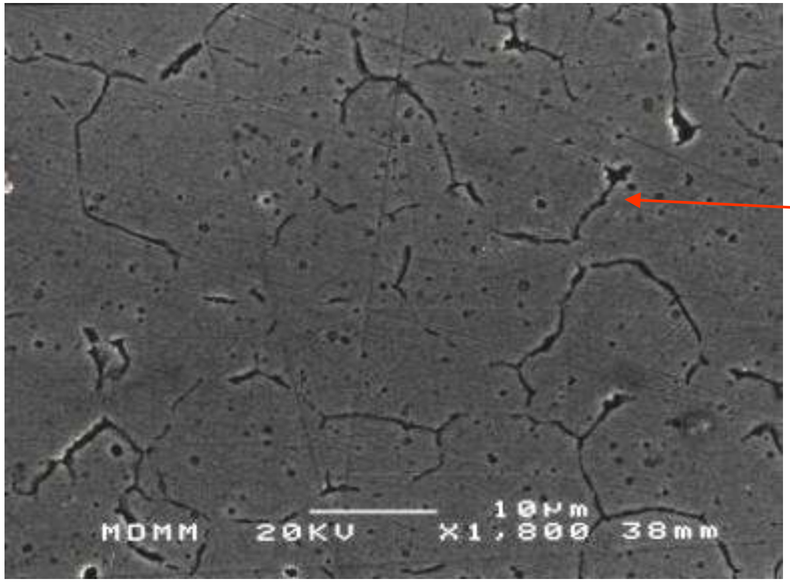


Extensive corrosion evident on retrievals

Metallographic examination

Grain decohesion evident on nail surface,
concentrated around bend area

Metallographic examination



Scanning electron microscopy:
Grain boundary de-cohesion

Nails manufactured from an inappropriate grade of stainless steel for in vivo use (440 C)

Chosen for primarily for high strength but corrosion resistance compromised due to residual stress and and high Cl^- environment.

Ceramic Biomaterials

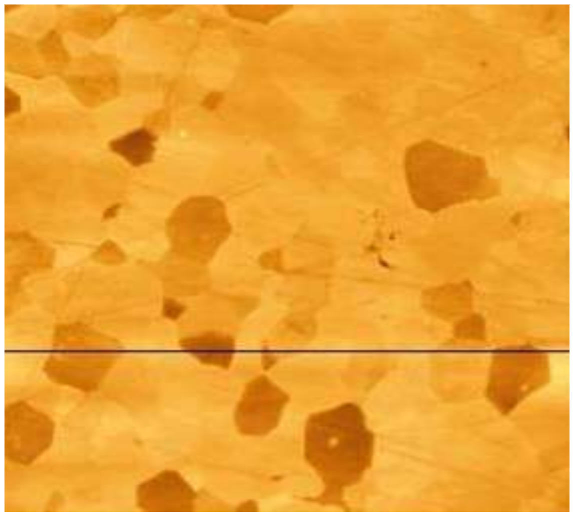
For ceramics, strength is critically dependent upon microstructure

- Pores/surface flaws act as stress-raisers and control the tensile (brittle) behaviour

- Small grain size produces strongest ceramics (highest fracture toughness)

	High alumina ceramics	ISO standard 6474
Alumina content (% by weight)	>99.8	≥99.50
Density (g/cm^3)	>3.93	≥3.90
Average grain size (μm)	3–6	<7
Ra (μm)[a]	0.02	
Hardness (Vickers hardness number, VHN)	2300	>2000
Compressive strength (MPa)	4500	
Bending strength (MPa) (after testing in Ringer's solution)	550	400
Young's modulus (GPa)	380	

Ceramic Biomaterials



20 μm

Microstructure and topographic profile typical of an alumina femoral head for TJR

SUMMARY MECHANICAL PROPERTIES OF SOME ORTHOPAEDIC BIOMATERIALS

Material	Elastic modulus (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Strain to failure (%)
Metals				
316L ss (annealed)	193	170	480	40
316L ss (cold worked)	193	1200	1300	12
CoCr Mo (as cast)	210	450	655	8
CoCrMo (Hot forged)	210	890	1400	28
Ti6Al4V	120	795	860	10
Ceramics				
Alumina (>99.5% dense)	380	n/a	$350^{comp.}$	-
Hydroxyapatite	50	n/a	$400^{comp.}$	-
Polymers				
PMMA bone cement	2	n/a	35	7
UHMWPE	1	25	39	450
Bone				
Cortical bone	15	n/a	150	3
Cancellous bone	0.3	n/a	15	6

Data from Black,1998 (Orthopaedic Biomaterials in research and practice)

Conclusions

- Specific compositions of metals, ceramics and polymers are used in structural orthopaedic applications
- Biocompatibility is a function of surface chemistry
- Microstructure has a key influence upon mechanical and chemical properties
- Microstructure is controlled by thermo-mechancial processing during component manufacture

Collaborative Research Opportunities:

- Orthopaedic (structural) biomaterials
- Biomechanics studies
- Design, build and test rigs and experimental studies
- Retrieval/forensic bioengineering

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