M. Sc. Bionics Engineering

Università di Pisa

Sant'Anna Scuola Universitaria Superiore Pisa

IMT Scuola Alti Studi Lucca

Advanced Materials for Bionics

Lecture 5: METALS

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AY 2024-25

L5 - 11.10.2024

METALS TOPICS

In a complete, standard Materials Science & Engineering course the topics regarding METALS are many

They include **several Chapters** in typical textbooks, such as:

- Defects, dislocations, mechanisms of plastic deformations
- Grain structure (polycrystalline), alteration of microstructure
- Fracture
- Phase diagrams: binary isomorphous or eutectic systems
- Phase Transformations
- Iron/Iron carbide - Fe/FeC3 phase diagrams →Steels!
- Ferrous/Non Ferrous alloys
- Microstructure
- Metals forming/strengthening
- Metals applications
- …

SELECTED HIGHLIGHTS/TOPICS ON METALS

- general classification of metals
- Fe/Fe_3C phase diagrams
- ferrous alloys
- non-ferrous alloys
- shape memory alloys
- metal in implants
- «Strange» Alloys?
- short notes on fabrication

L5.1

INTRO AND CLASSIFICATION OF METALS

RECAP: BONDING IN METALS

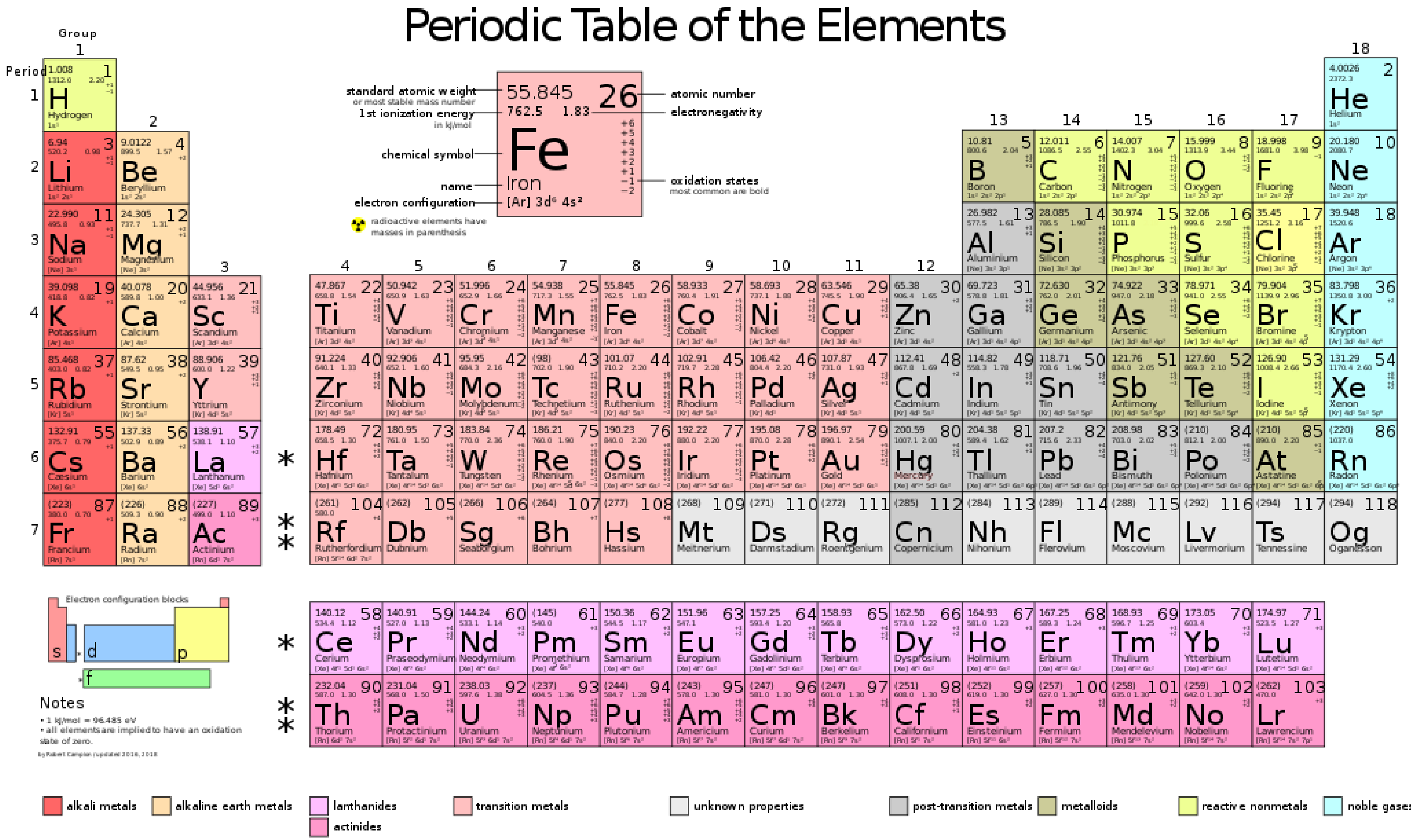
see LECTURE 2

Jove Core: Bonding in metals

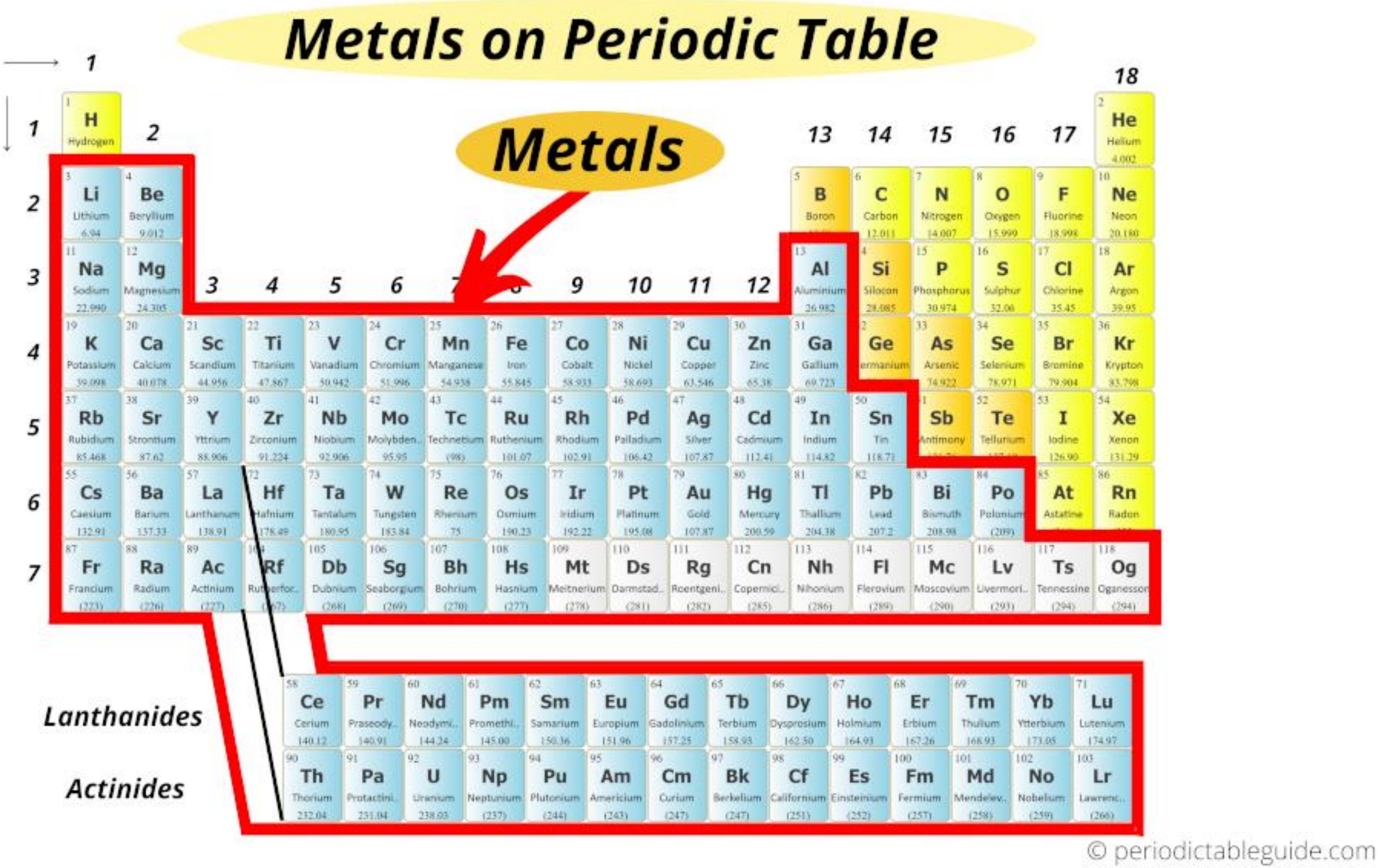
JOVE VIDEO

https://www.jove.com/science-education/11330/bonding-in-metals

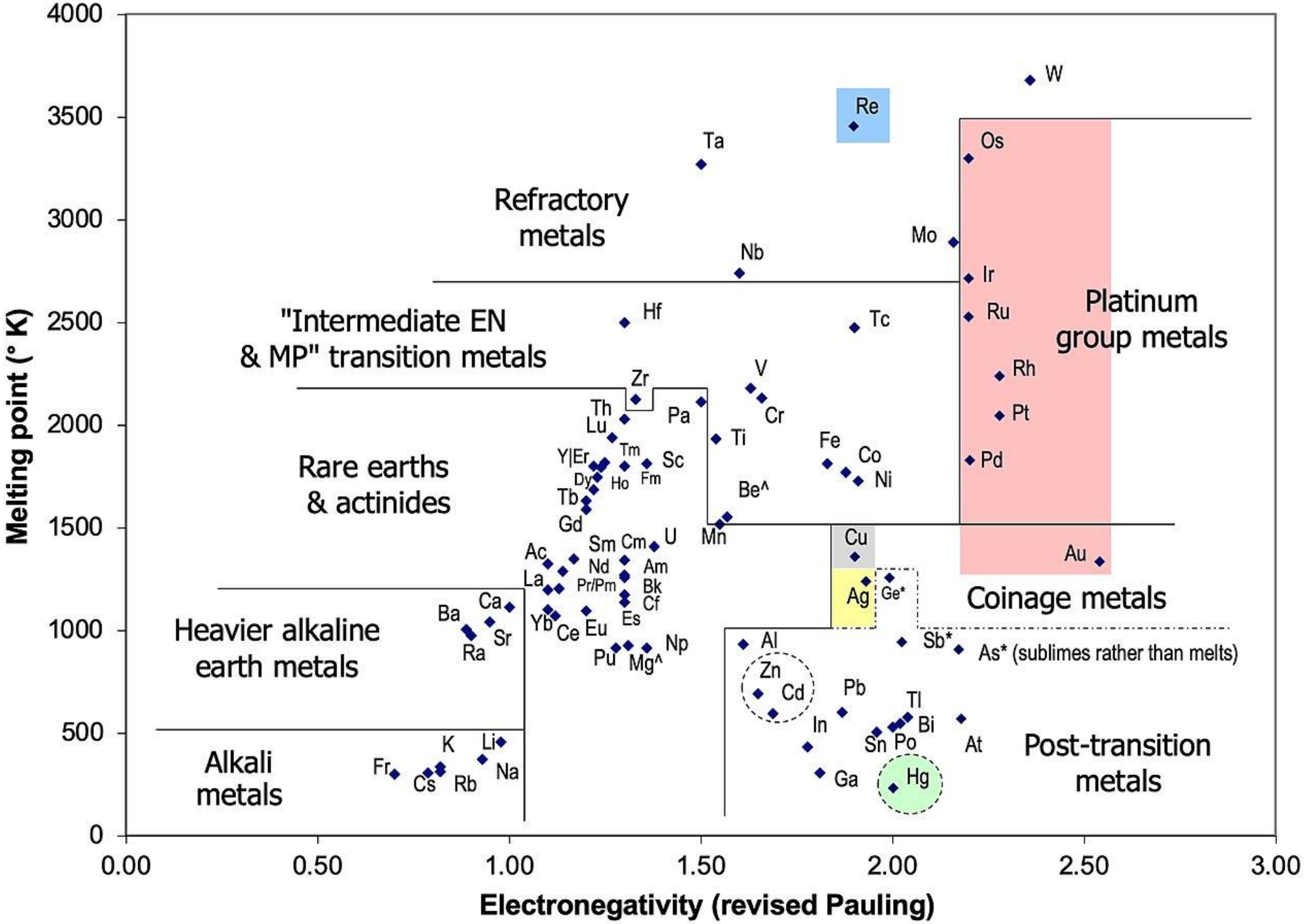
METALS IN PERIODIC TABLE



METALS IN PERIODIC TABLE



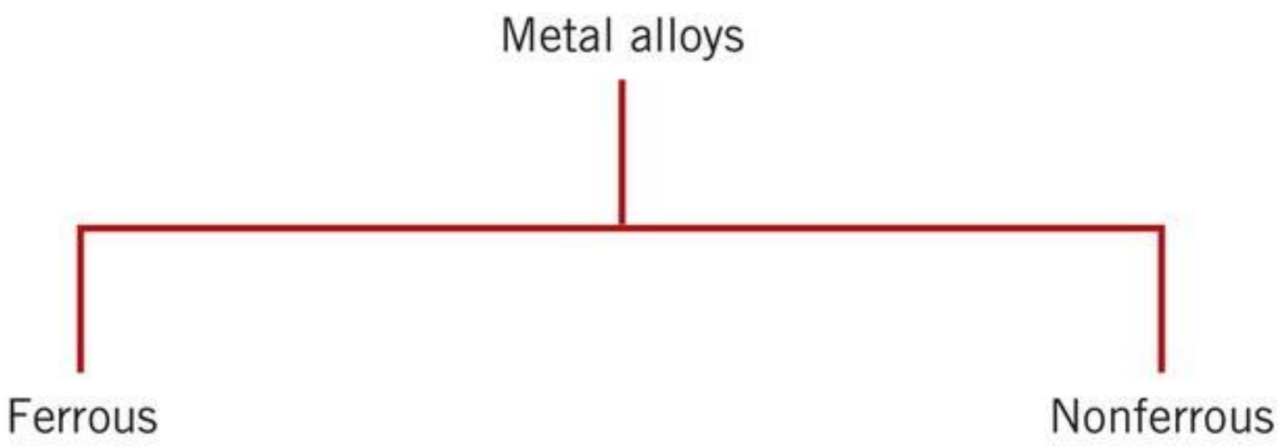
METALS (SCIENCE)



^Light alkaline earth metals (Be, Mg) Group 12 metals *commonly recognised as metalloids (Ge, As, Sb)

Classification of Metal Alloys (Engineering)

- in ENG mostly considered for STRUCTURAL properties!
- some nonferrous important for FUNCTIONAL properties



L5.2

SHORT RECAP ON PHASE DIAGRAMS

Phase Diagrams

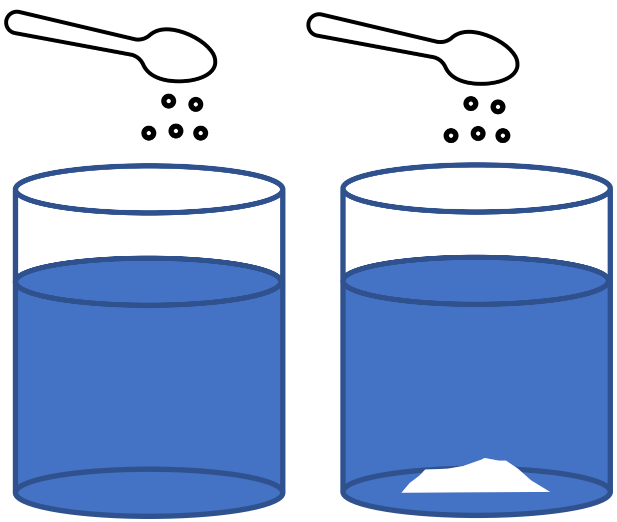
- phase: a homogeneous portion of a system that has uniform physical and chemical characteristics
- a single-phase system is termed homogeneous
- systems composed of two or more phases: mixtures or heterogeneous systems
- most metallic alloys (but also ceramic, polymeric, and composites) are heterogeneous
- understanding of phase diagrams for alloy systems is extremely important
- phase diagrams provide valuable information about melting, casting, crystallization…

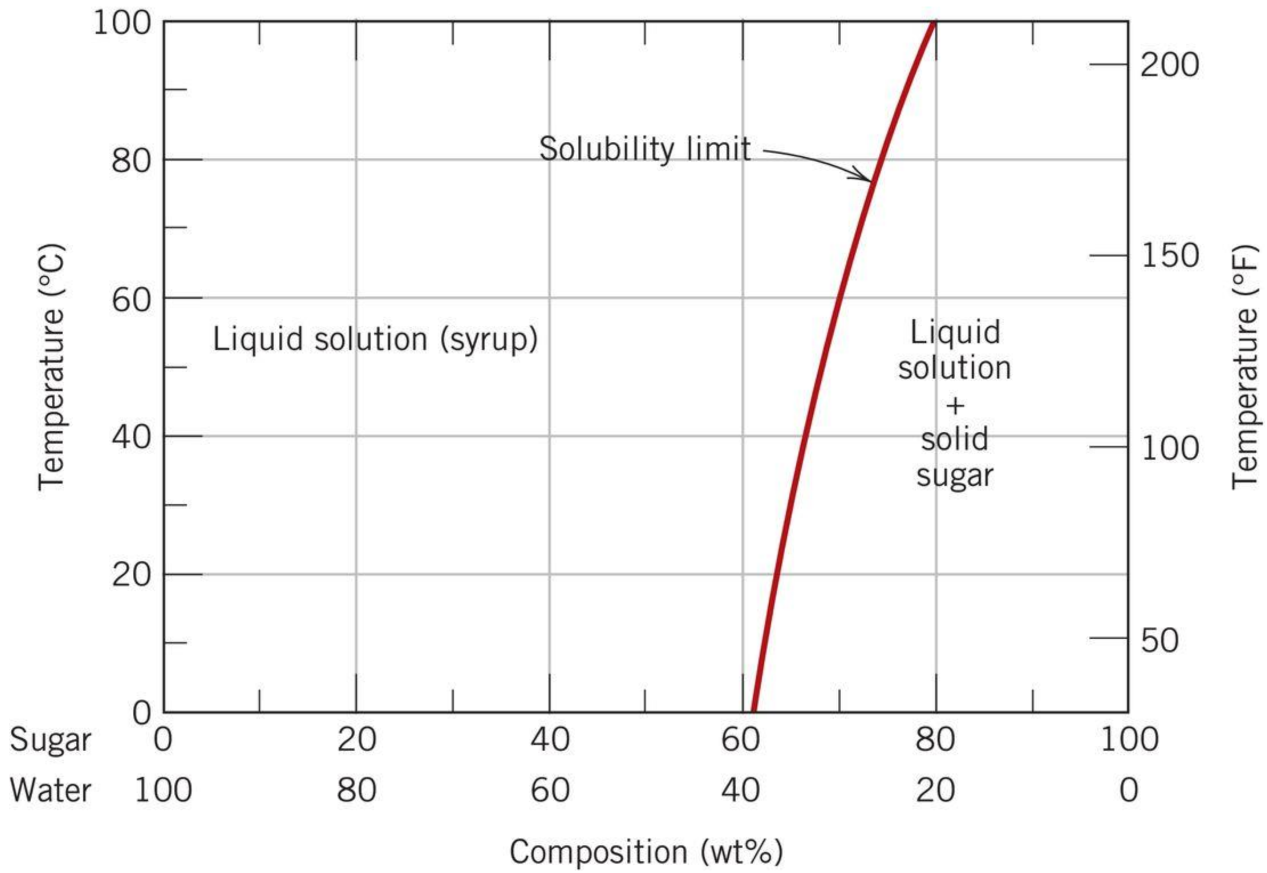
PHASE EQUILIBRIUM

- from thermodynamics: Equilibrium → minimum of free energy G
  @specified combination of T, P, composition
- characteristics of the system do not change with time, the system is stable
- Change in T, P and/or composition → increase in G: possible spontaneous change to another state by which G is lowered
- For many alloy systems and at some specific temperature, there is a maximum concentration of solute atoms that may dissolve in the solvent to form a solid solution: solubility limit

SOLUBILITY LIMIT

- ex.: sugar–water ($C_{12}H_{22}O_{11}$–H_2O) system

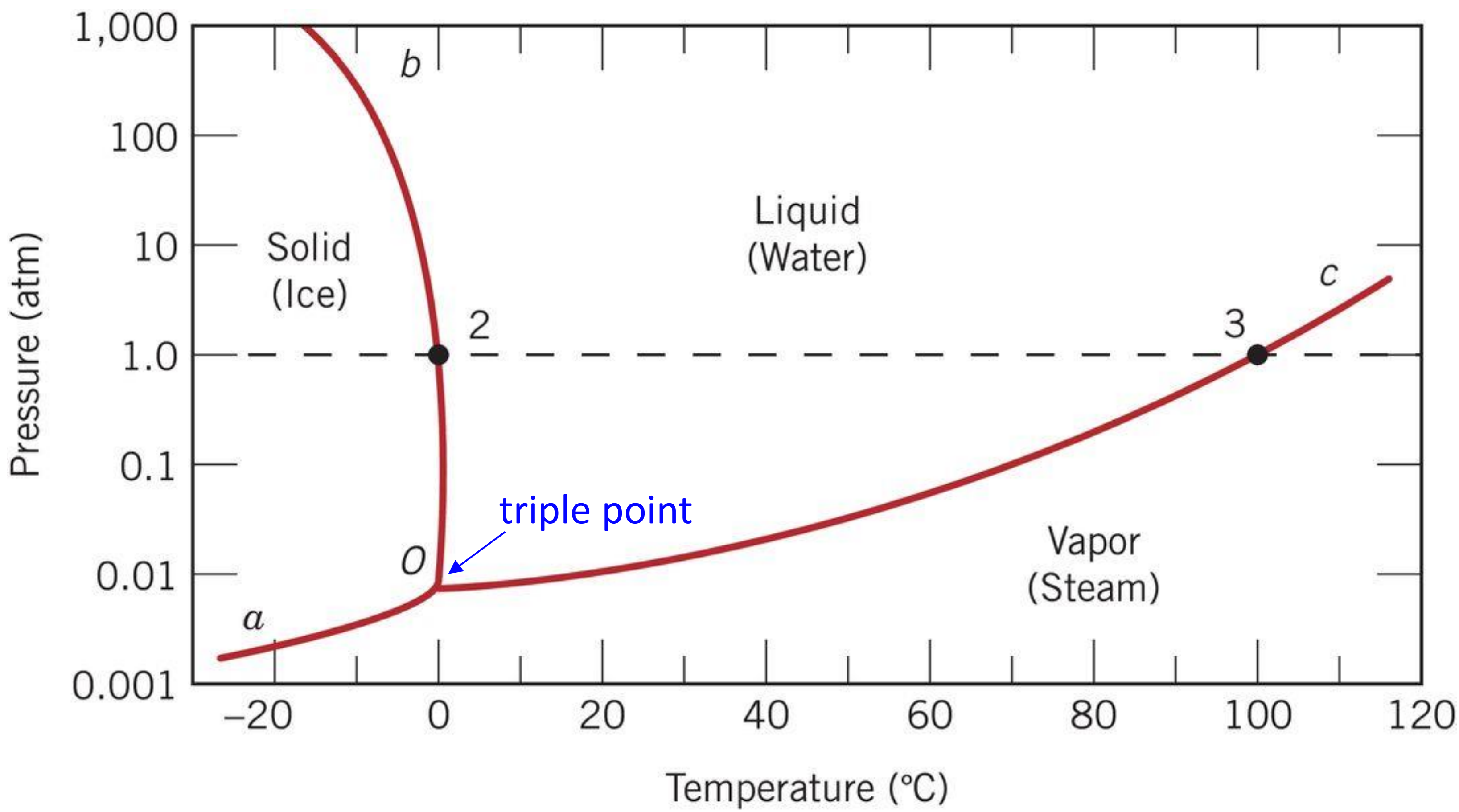




[Animated Graph chap 9]

1 COMPONENT PHASE DIAGRAM

- phase diagram with 1 component (composition costant = phase diagram of a pure substance)
- ex.: T – P phase diagram of water



Binary Phase Diagrams

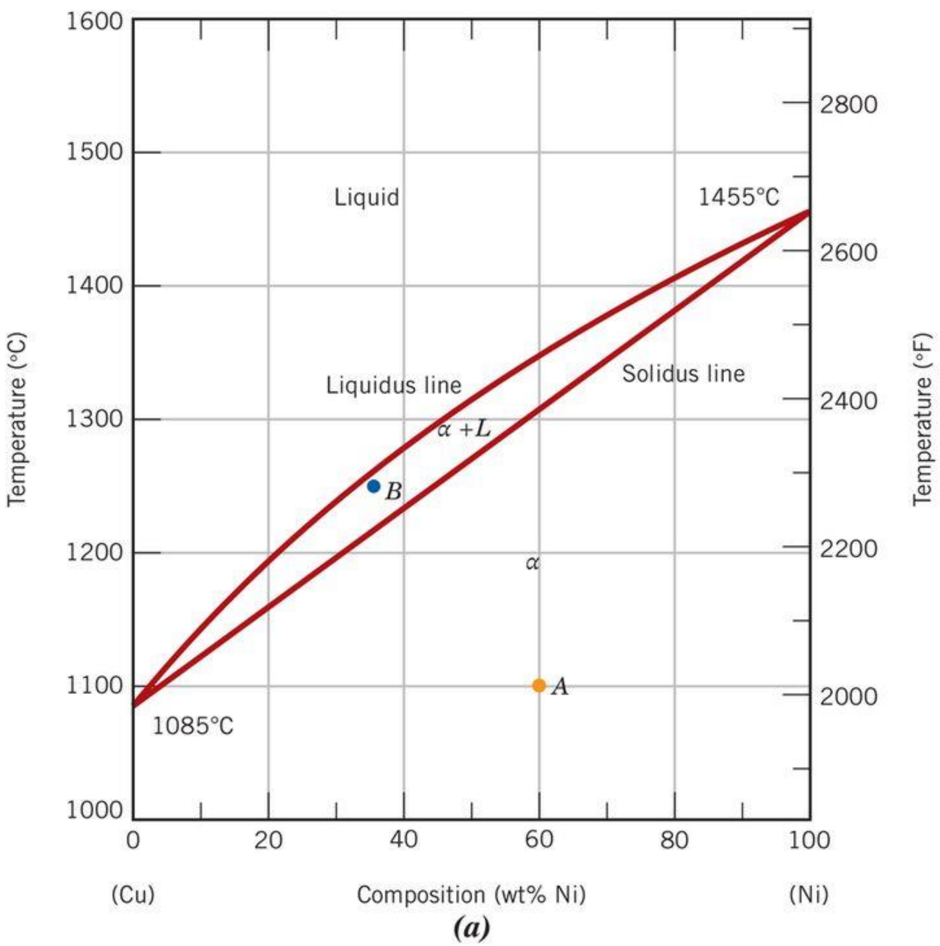
- phase diagram with 2 components
- T and composition: variable parameters, P constant (normally 1 atm)
- binary alloys: various behaviours

binary isomorphous
eutectic
eutectoid
intermediate solid solutions (intermediate phases)

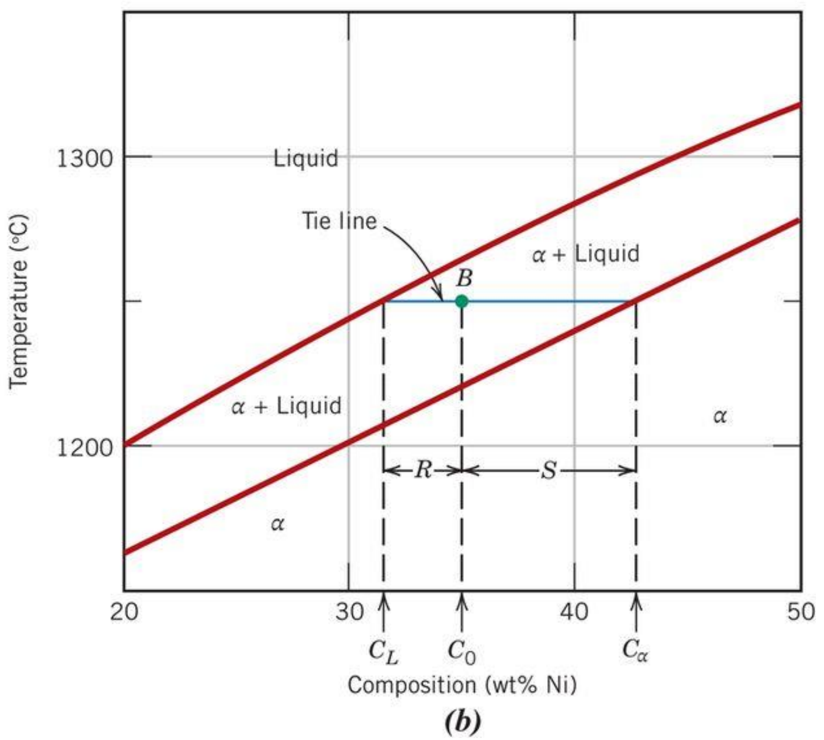
- > 2 components: phase diagrams extremely complicated and difficult to represent

BINARY ISOMORPHOUS SYSTEMS

- complete solubility of two components in both liquid and solid

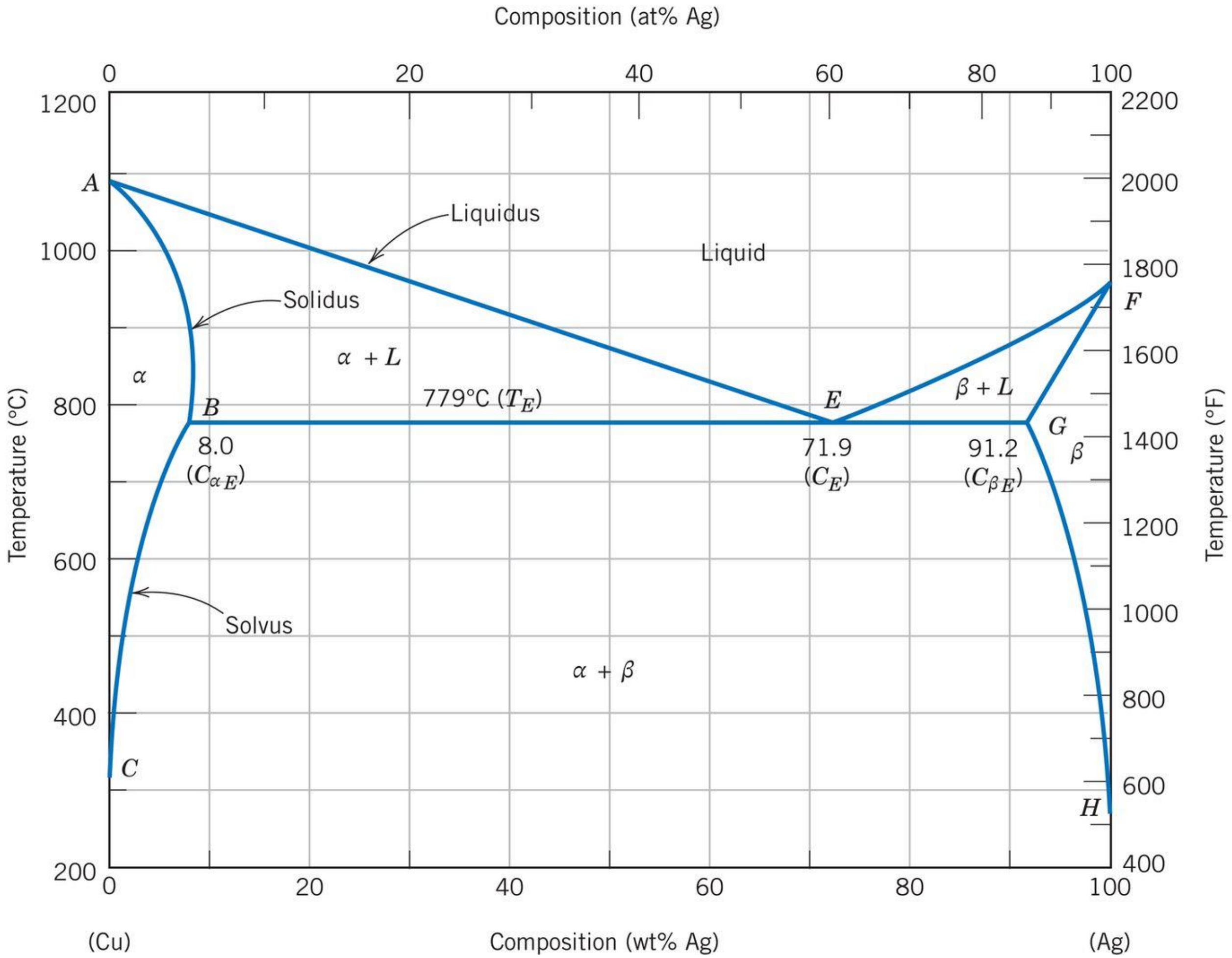


Example: Cu-Ni



BINARY EUTECTIC SYSTEMS

- incomplete solubility of two components



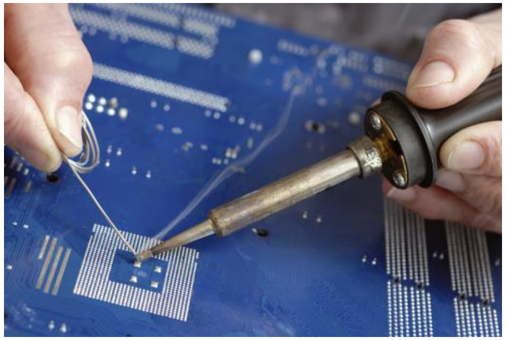
Example: Cu-Ag

- 3 monophase regions: α, β, Liquid

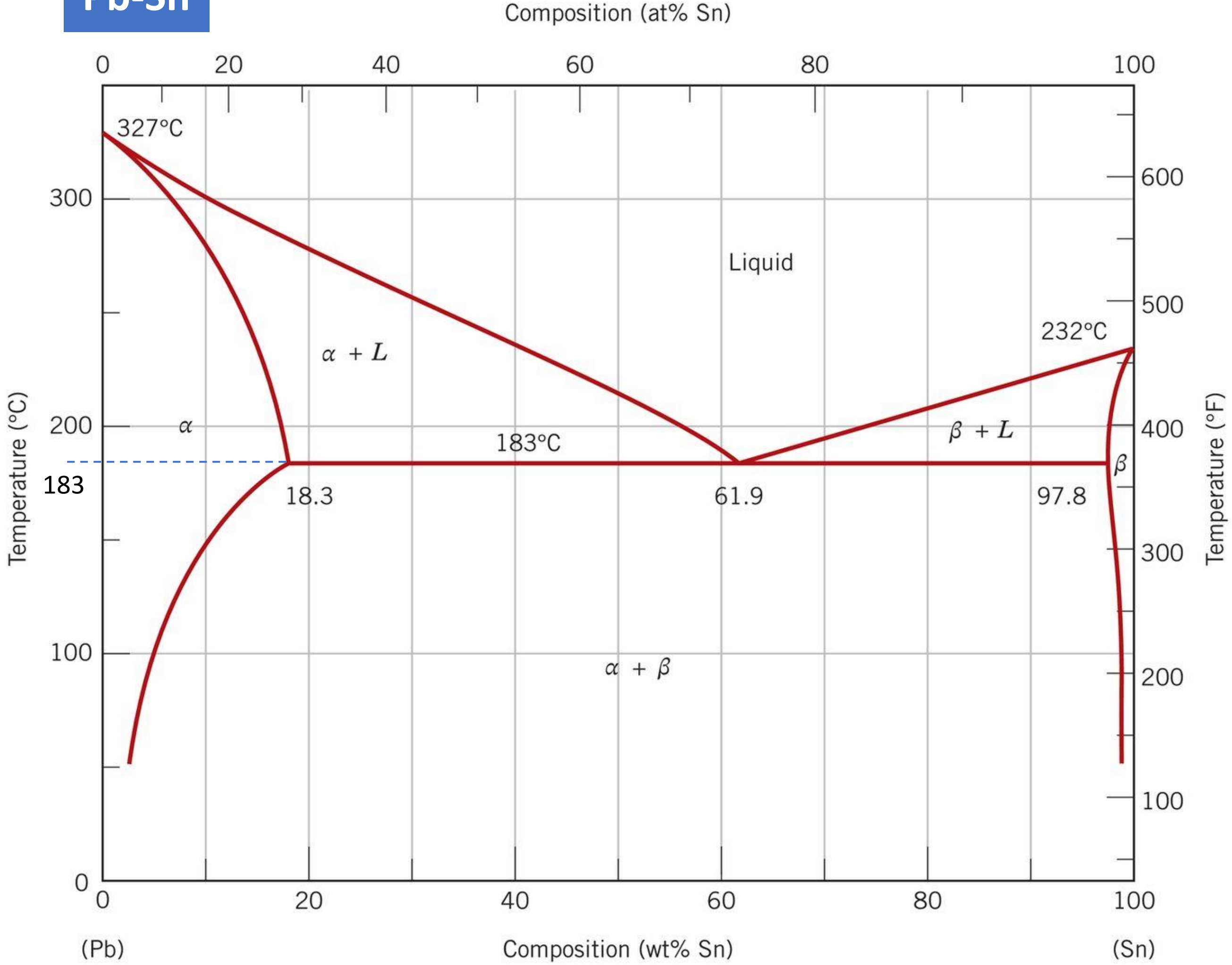
eutectic reaction

$$L\left(C_E\right) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha\left(C_{\alpha E}\right) + \beta\left(C_{\beta E}\right)$$

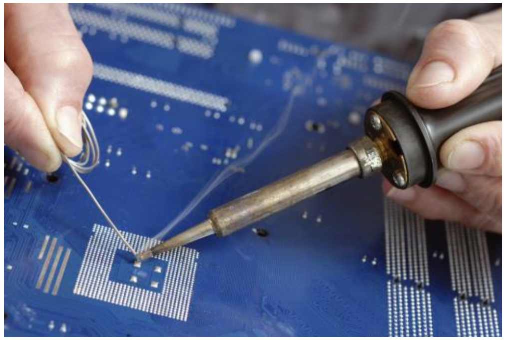
«60-40 SOLDER»



Pb-Sn

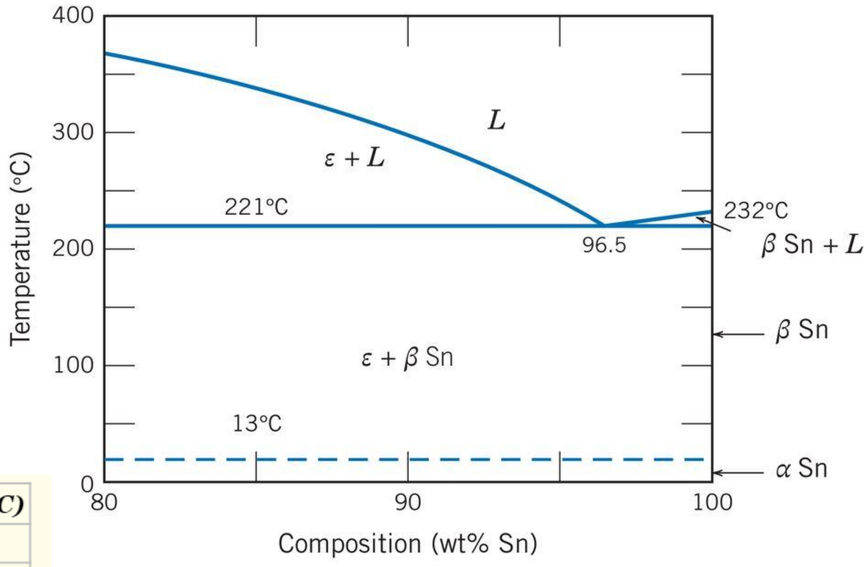


LEAD-FREE SOLDER



- Pb toxic!
- environmental concerns (e-waste)
- lead-free solders

Example: Ag-Sn



Composition (wt%)	*Solidus Temperature (°C)*	*Liquidus Temperature (°C)*
	Solders Containing Lead	
63 Sn–37 Pb[a]	183	183
50 Sn–50 Pb	183	214
	Lead-Free Solders	
99.3 Sn–0.7 Cu[a]	227	227
96.5 Sn–3.5 Ag[a]	221	221
95.5 Sn–3.8 Ag–0.7 Cu	217	220
91.8 Sn–3.4 Ag–4.8 Bi	211	213
97.0 Sn–2.0 Cu–0.85 Sb–0.2 Ag	219	235

L5.3

FERROUS ALLOYS

Classification of Metal Alloys (Engineering)

- in ENG mostly considered for STRUCTURAL properties!

Metal alloys
- Ferrous
- Nonferrous

Fe-containing: especially important as engineering construction materials

3 main aspects/advantages

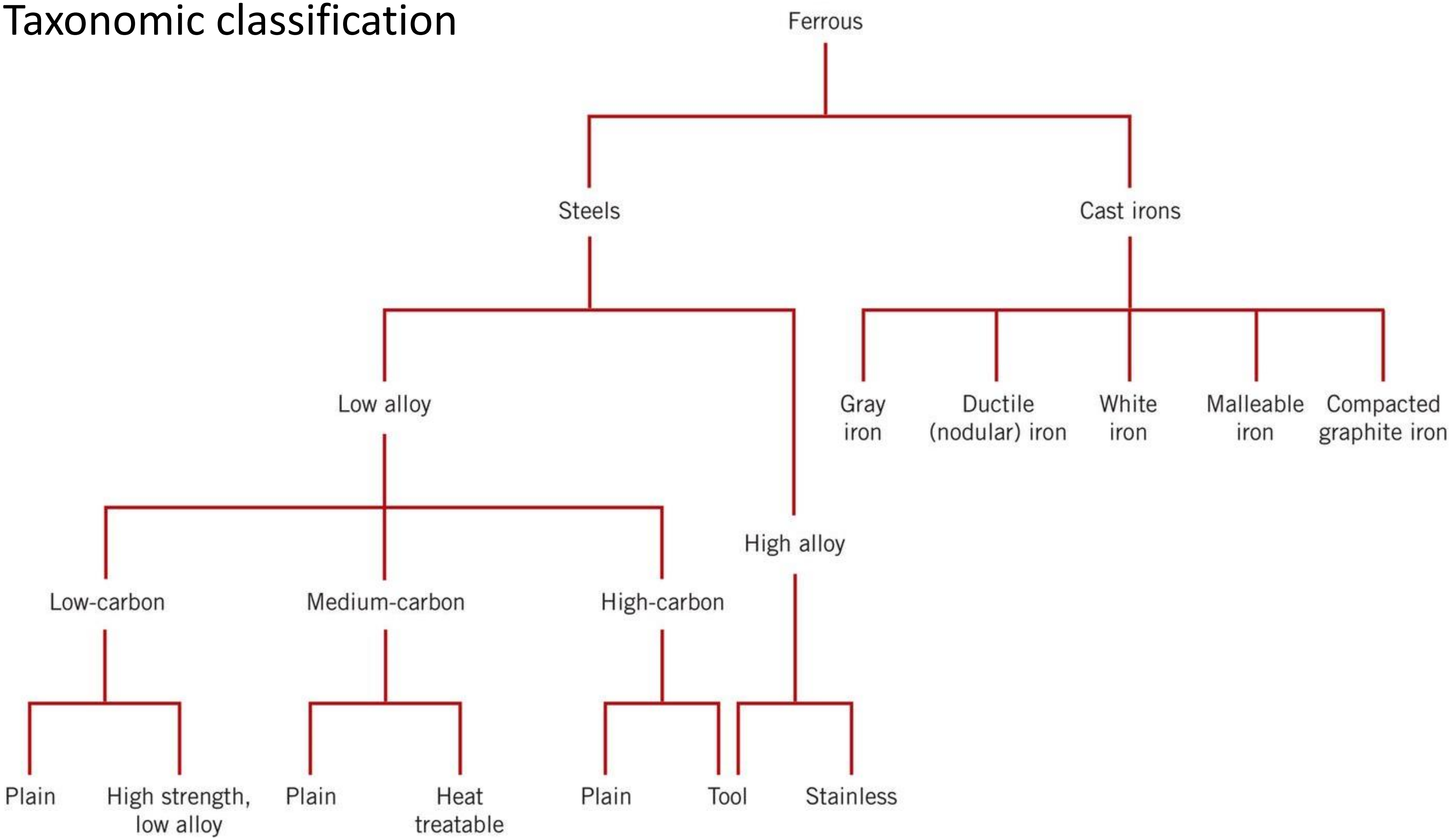
1. Fe-containing compounds abundant
2. relativ. economical extraction, refining, alloying, and fabrication techniques
3. extremely versatile: a wide range of mechanical properties.

3 disadvantages

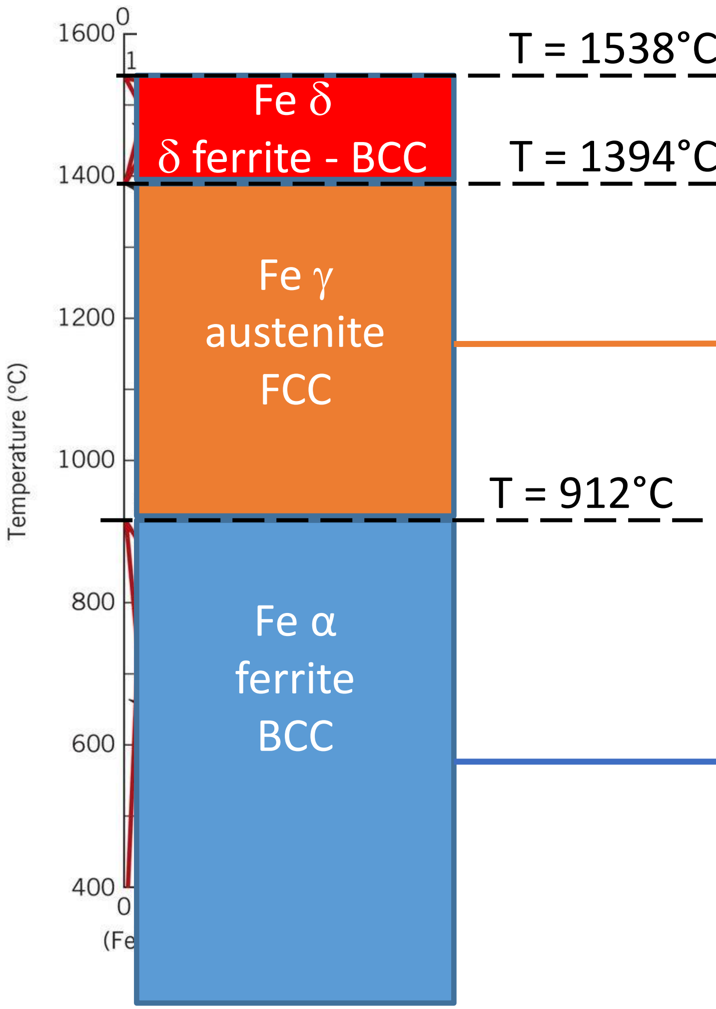
1. relatively high density,
2. low electrical conductivity,
3. susceptibility to corrosion in some common environments

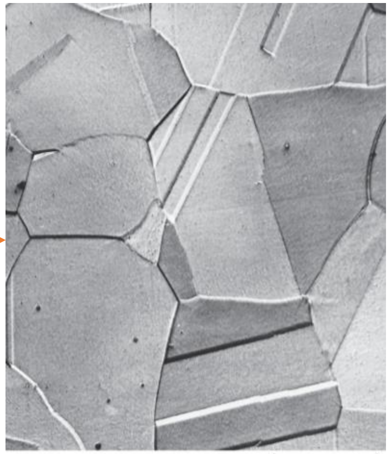
Ferrous alloys

Taxonomic classification



Iron - Fe




(b) 50 µm


(a) 200 µm

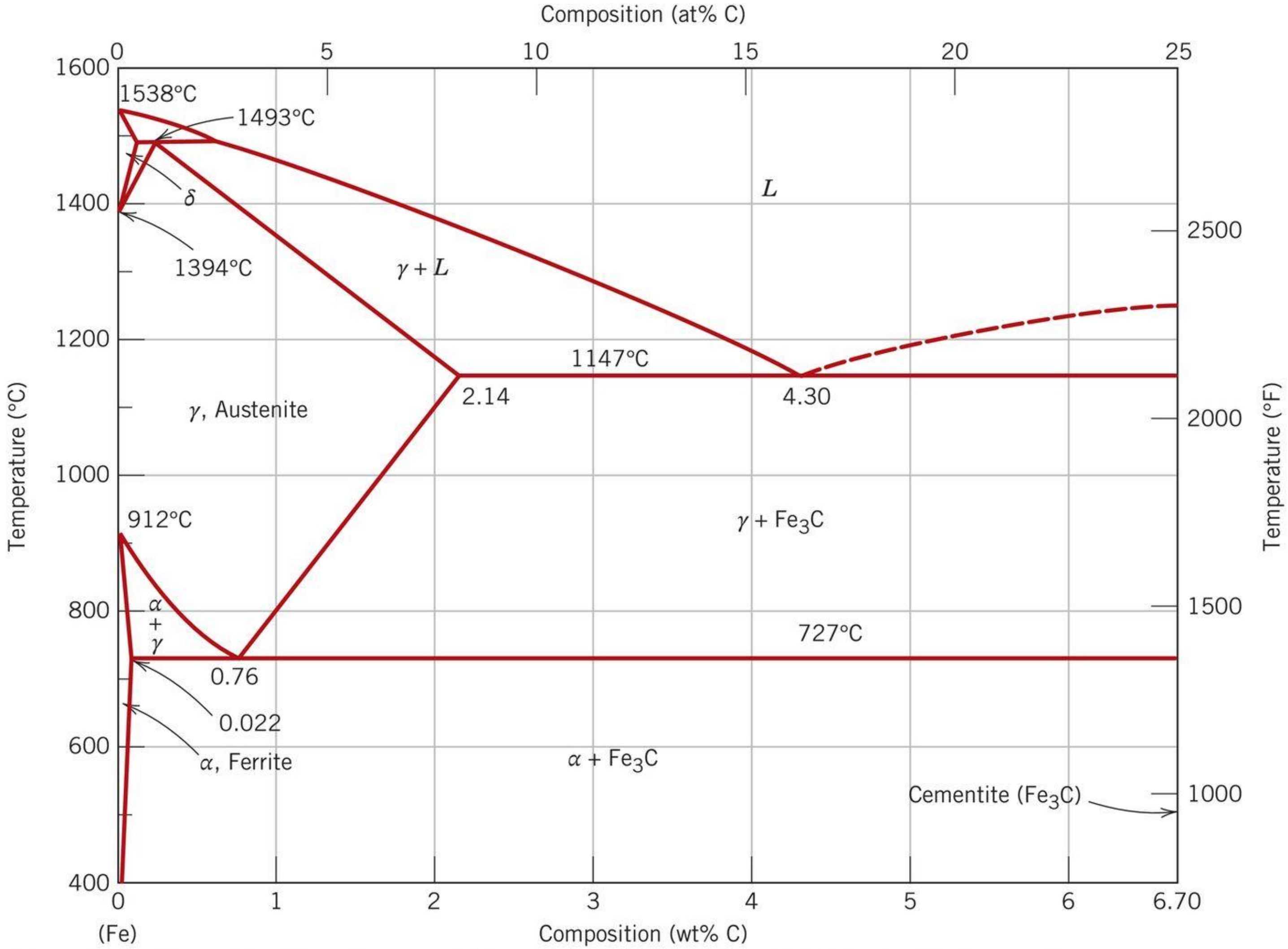
Binary System Fe-C

- of all binary alloy systems, the most important is Fe-C

The Fe-C phase diagram can be divided in 2 parts

$0 < C < 6.7$ wt.%	$C > 6.7$ wt.%
• steels and cast irons: primary structural materials	

Fe – Fe_3C phase diagram

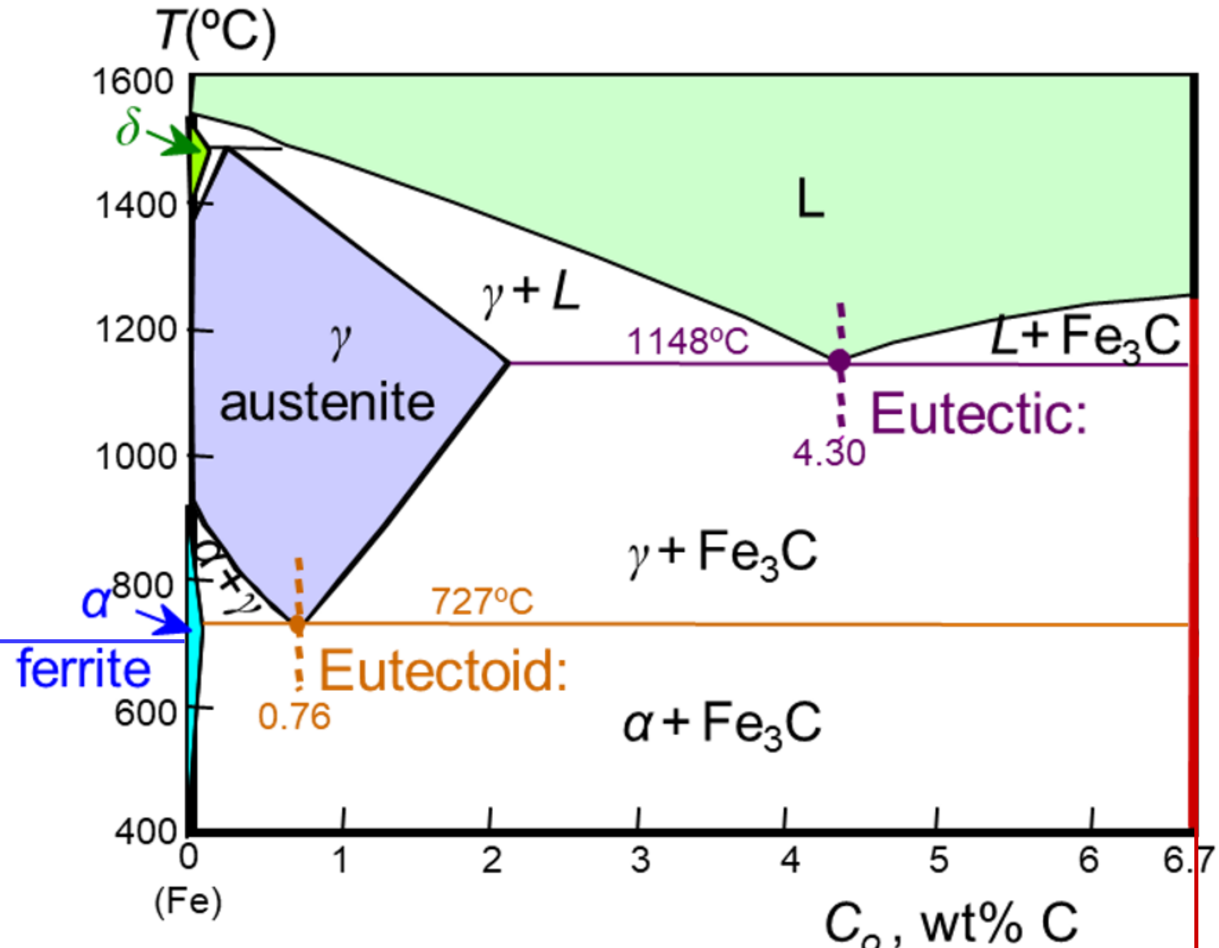


C (wt.%)> 6.7
cementite Fe_3C

Fe – Fe_3C phase diagram

colored:
monophasic regions

C: impurity in Fe
it forms solid solutions



α ferrite: low solubility of C
(max 0.0022% @727°C)
small interstitial sites in BCC
relatively soft, may be made
magnetic at T<768°C

γ austenite: improved C solubility
(max 2.14% @1148°C)
because of larger octahedral interstitial
sites in FCC; non magnetic
unstable at T<727°C

Fe_3C cementite: very hard and brittle
actually metastable! transforms into Fe α + C
graphite after several years at 650< T<700°C
all C in steels is in Fe_3C form

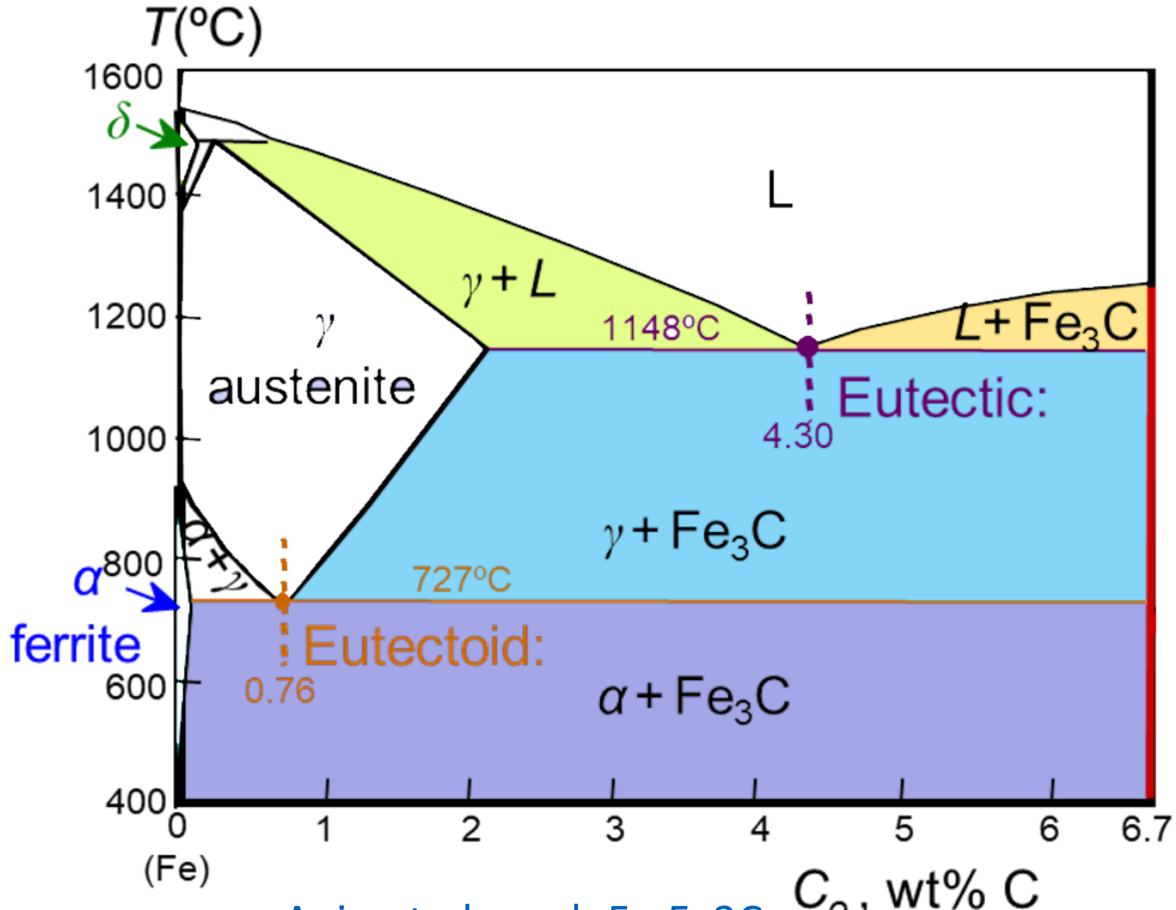
$Fe - Fe_3C$ phase diagram

colored:
biphasic regions

Eutectic reaction

$$L \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \gamma + Fe_3C$$

upon cooling, liquid solidifies forming:
austenite and cementite



Animated graph Fe-Fe3C

Eutectoid reaction

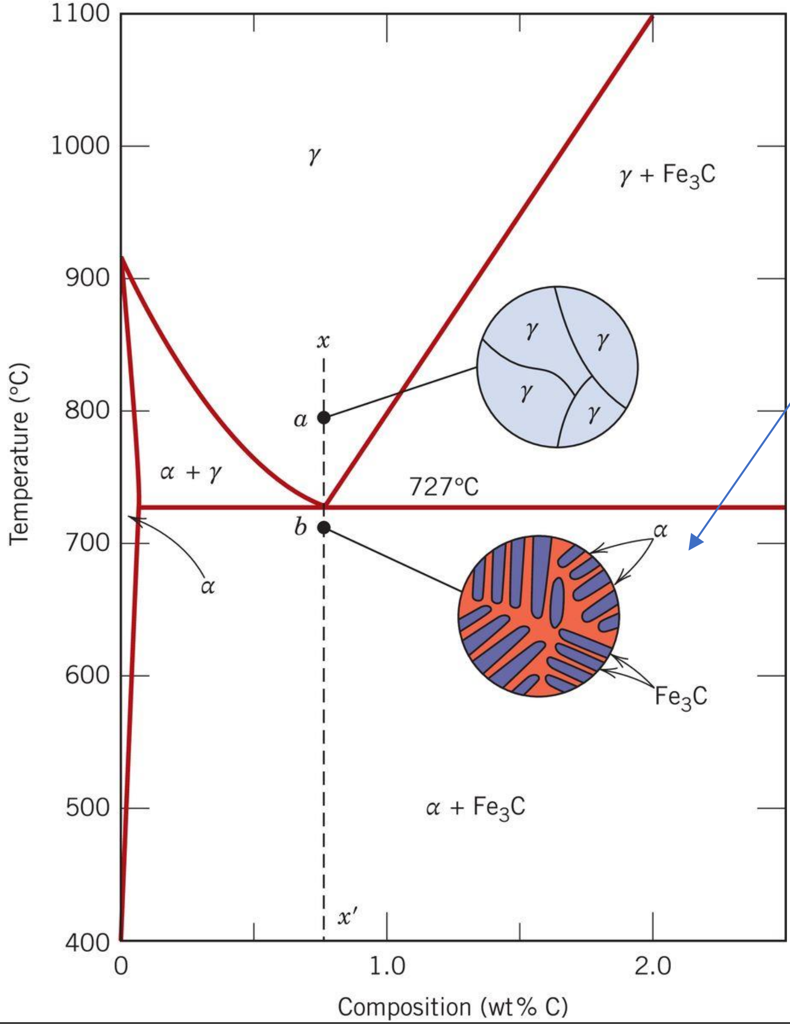
$$\gamma\,(0.76\ \text{wt}\,\%\ \text{C}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha\,(0.022\ \text{wt}\,\%\ \text{C}) + Fe_3C\,(6.7\ \text{wt}\,\%\ \text{C})$$

upon cooling, the solid γ phase is transformed into: α-iron and cementite.

MICROSTRUCTURE EVOLUTION Fe-C

eutectoid
@C = 0.76%

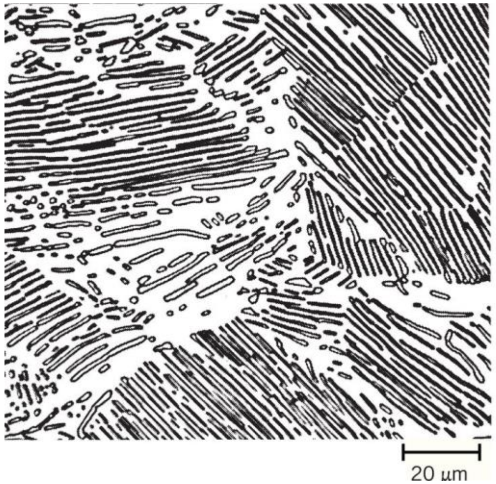
- **Eutectoid transformation**: from 1 solid phase to 2 solid phases

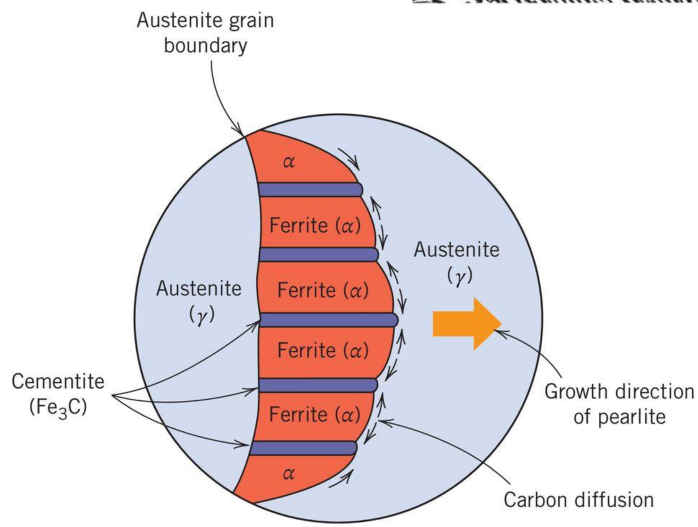


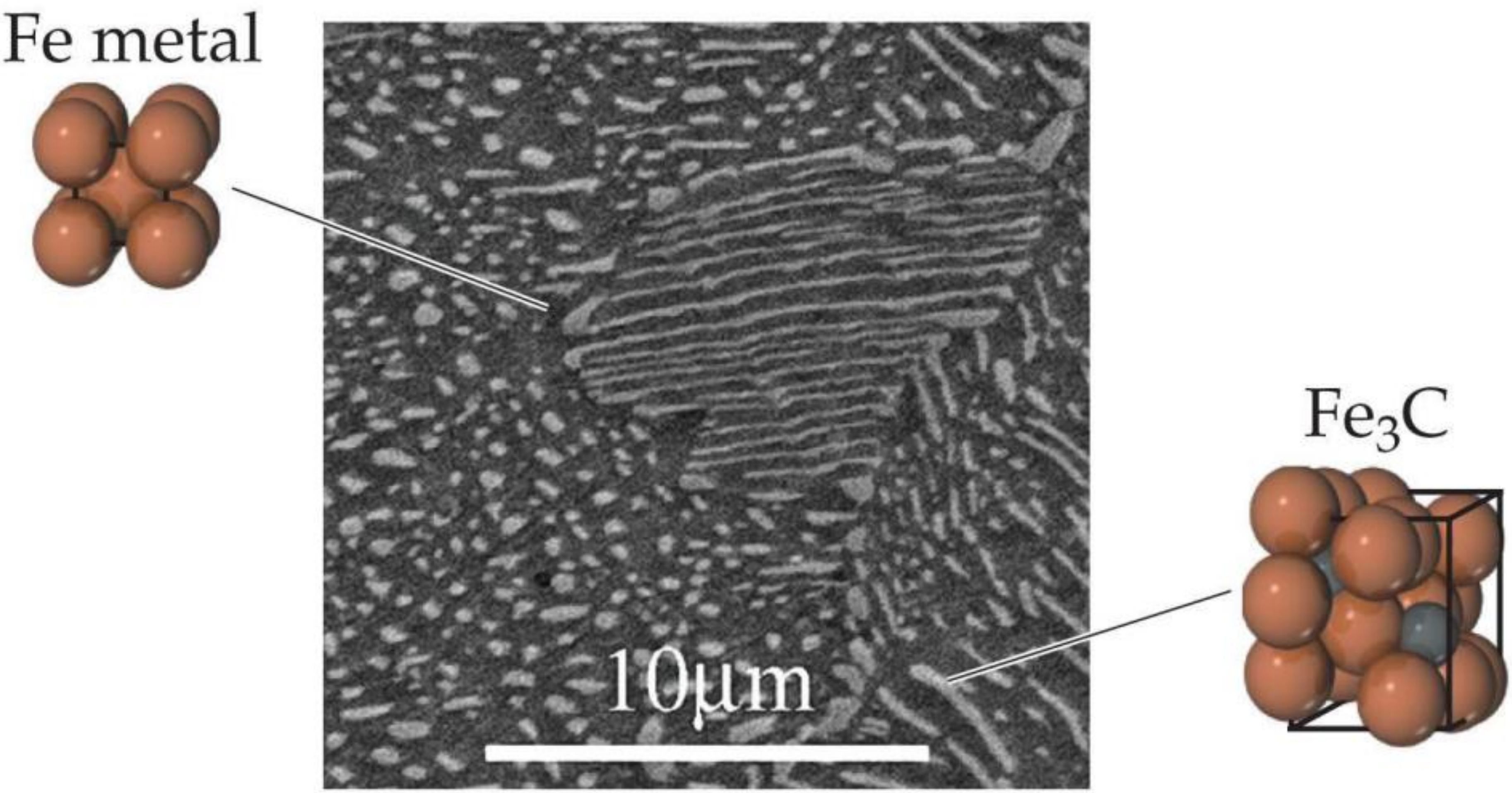
$$\gamma \Rightarrow \alpha + Fe_3C$$

Pearlite

alternating layers of α and Fe_3C

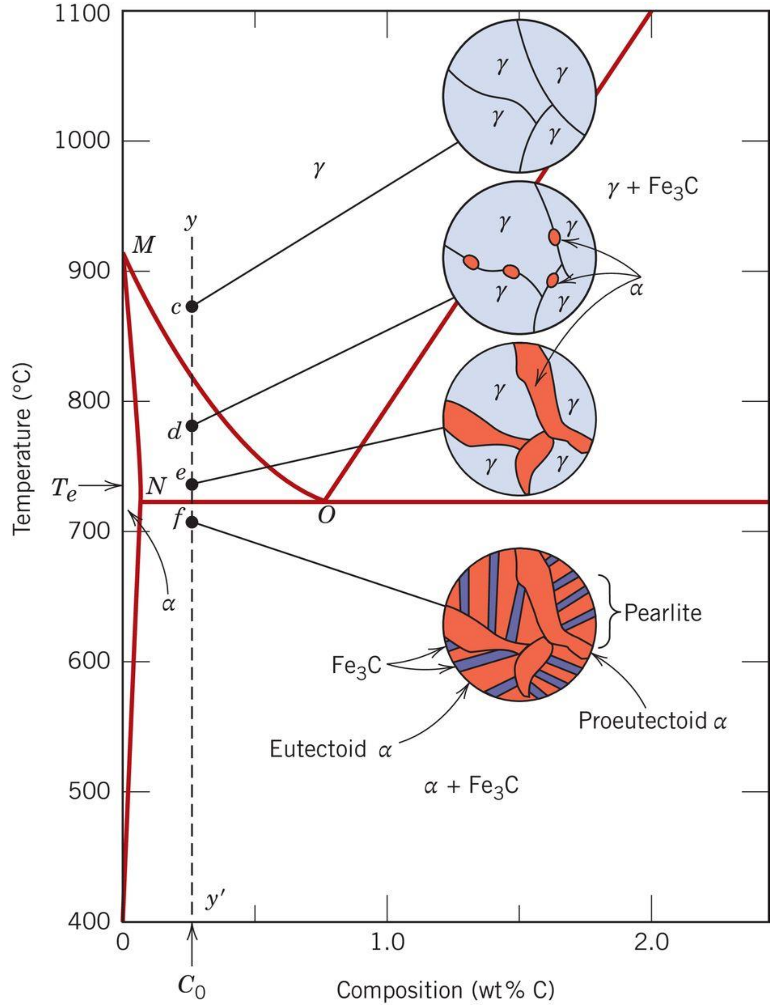




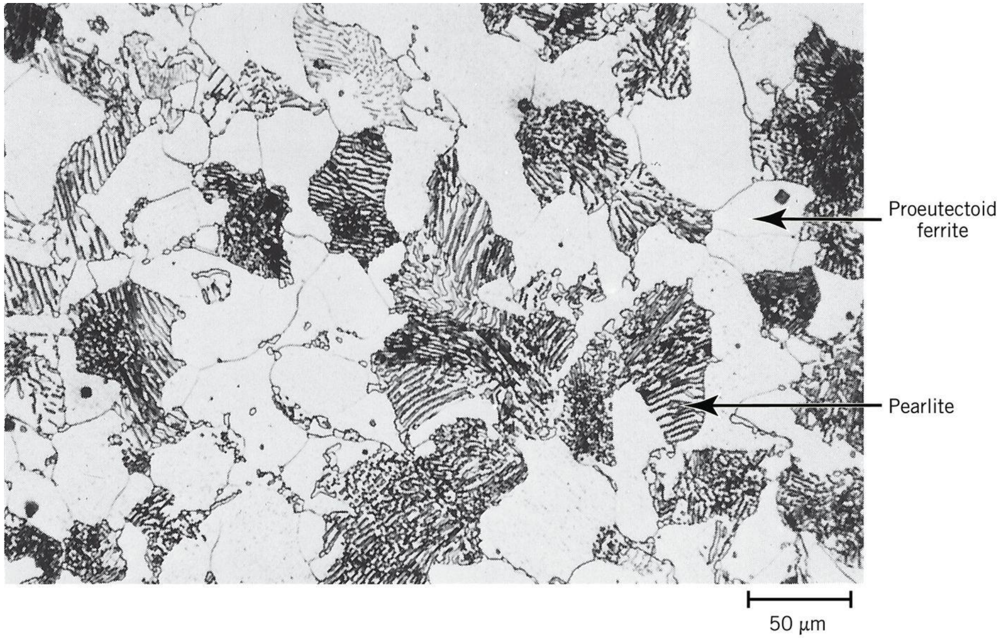

Fe metal
10μm
Fe_3C

Microstructure evolution Fe-C

- Hypoeutectoid alloys $0.022 < C_0 < 0.76$ wt.% C



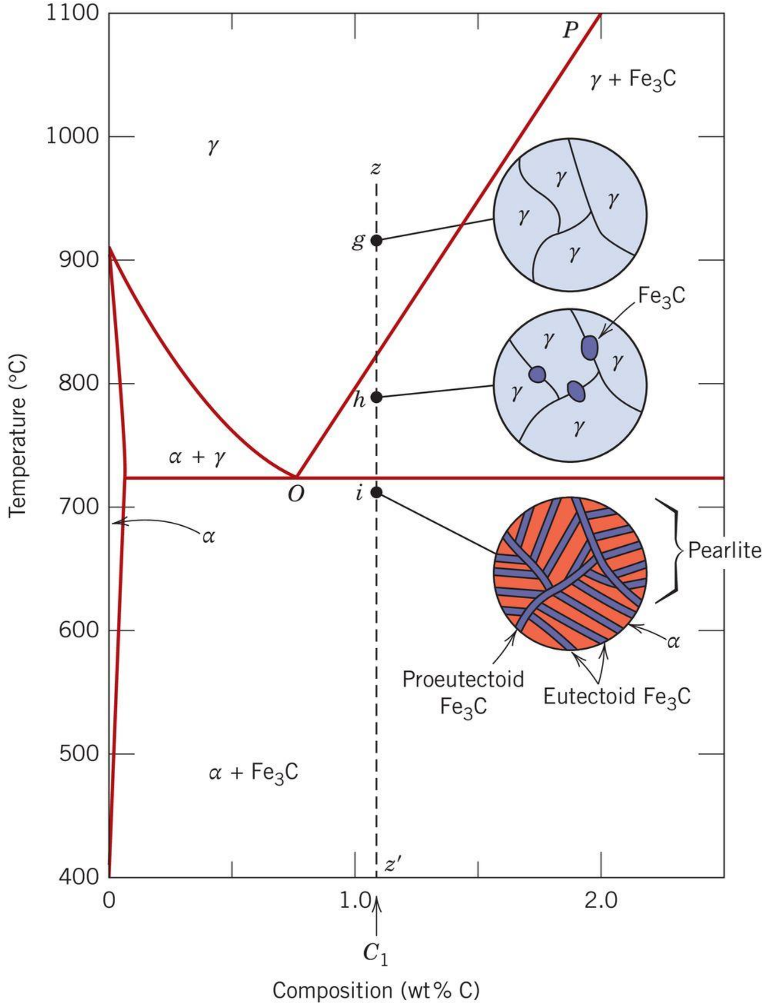
steel w 0.38wt.% C



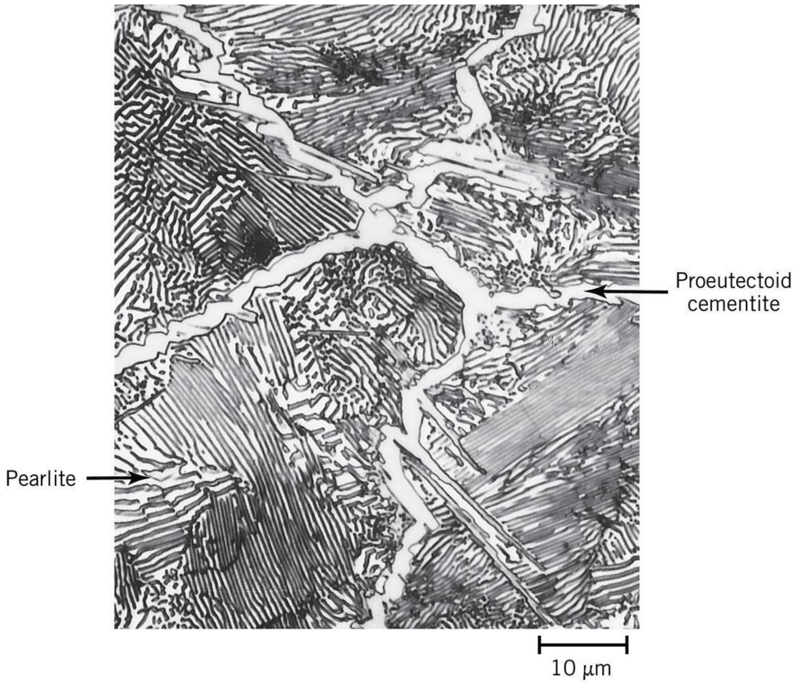
Photomicrograph courtesy of Republic Steel Corporation.

MICROSTRUCTURE EVOLUTION Fe-C

- Hypereutectoid alloys $0.76 < C_0 < 2.14$ wt.% C



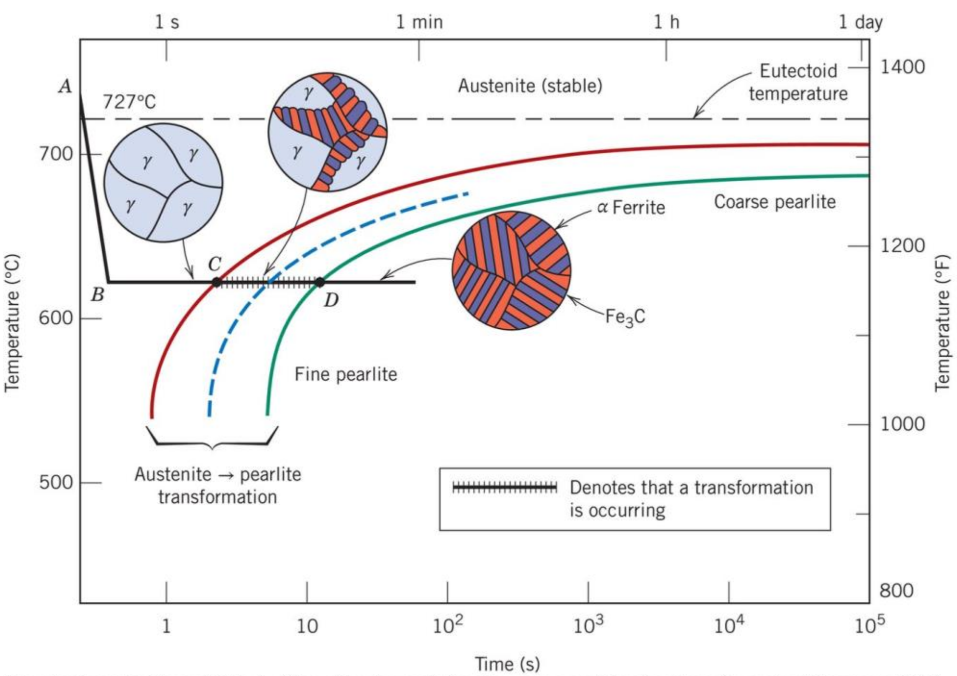
steel w 1.4wt.% C



PHASE TRANSFORMATIONS

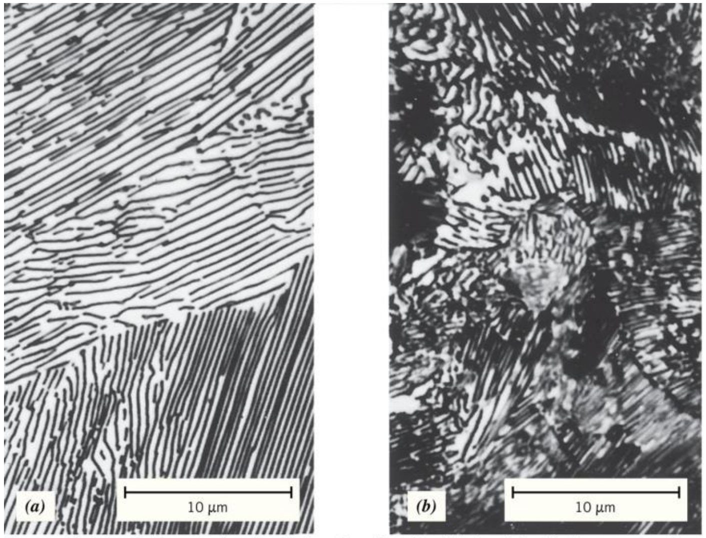
upon various heat treatments microstructure can evolve with phase transformations

Examples



Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, 1977. Reproduced by permission of ASM International, Materials Park, OH.]

coarse pearlite | fine pearlite



From K. M. Ralls et al., *An Introduction to Materials Science and Engineering*, p. 361. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

PHASE TRANSFORMATIONS

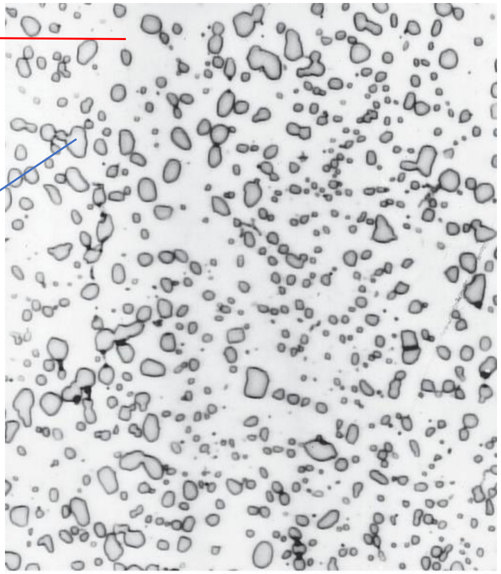
upon various heat treatments microstructure can evolve with phase transformations

Example

steel with pearlite structure maintained at T =700°C for 18-24 h
pearlite → sferoidite

matrix: α Fe ferrite

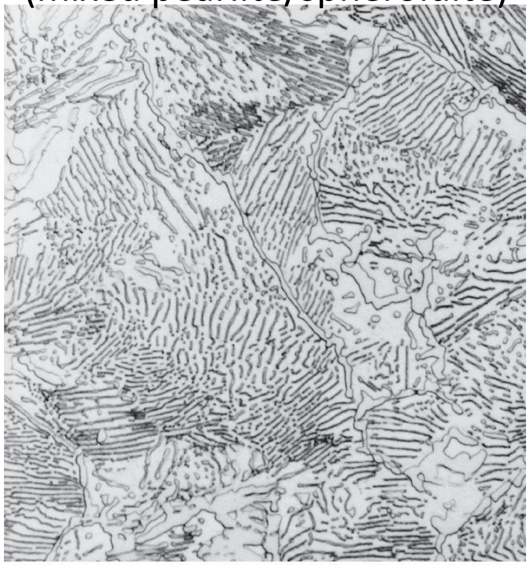
particles: Fe_3C cementite



10 μm

Copyright 1971 by United States Steel Corporation.

partial conversion
(mixed pearlite/spheroidite)



10 μm

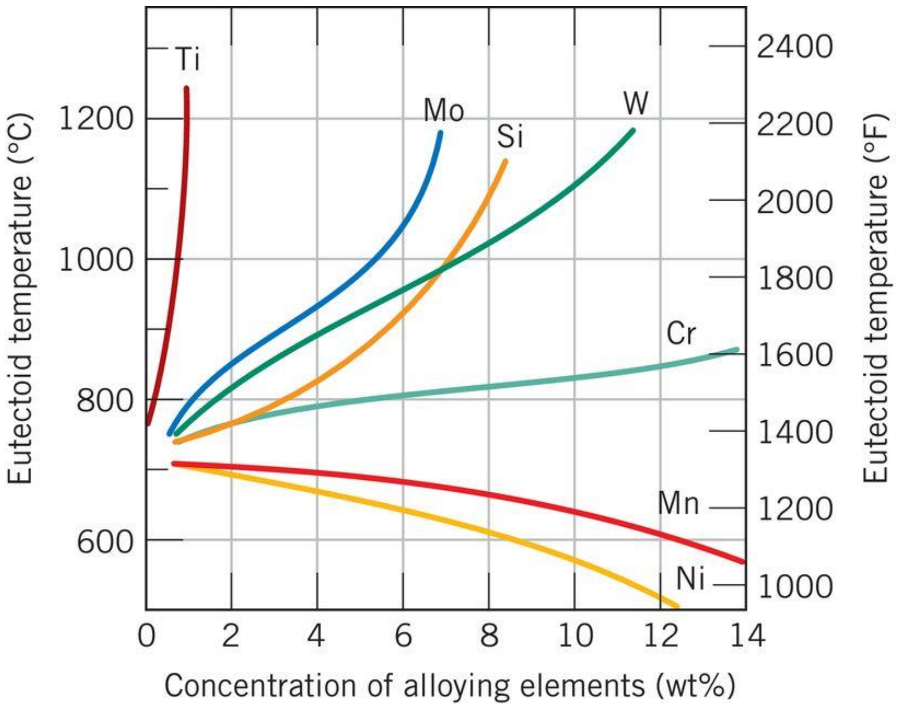
Courtesy of United States Steel Corporation.

INFLUENCE OF OTHER ELEMENTS

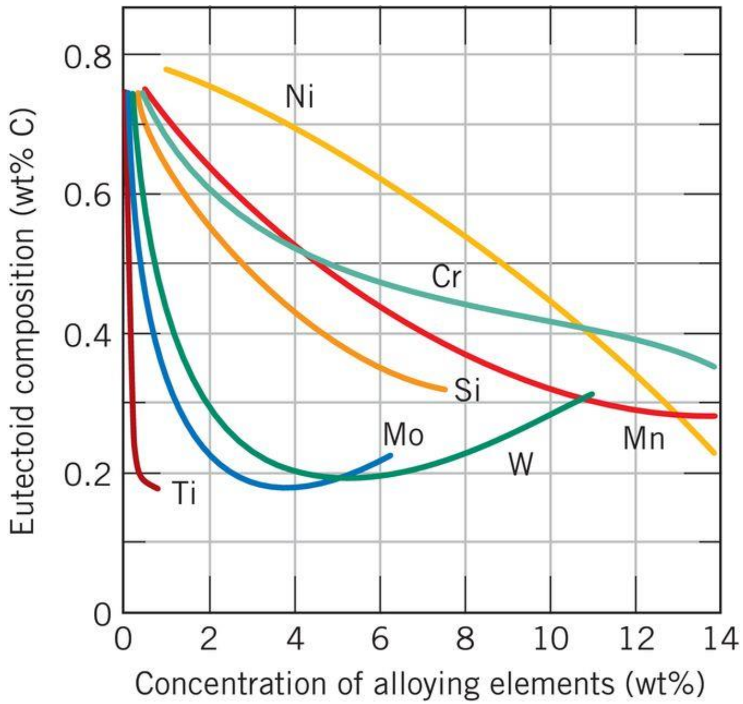
Additions of other alloying elements (Cr, Ni, Ti, etc.) → dramatic changes in the binary Fe–Fe_3C phase diagram

Example: shift of eutectoid

Eutectoid temperature

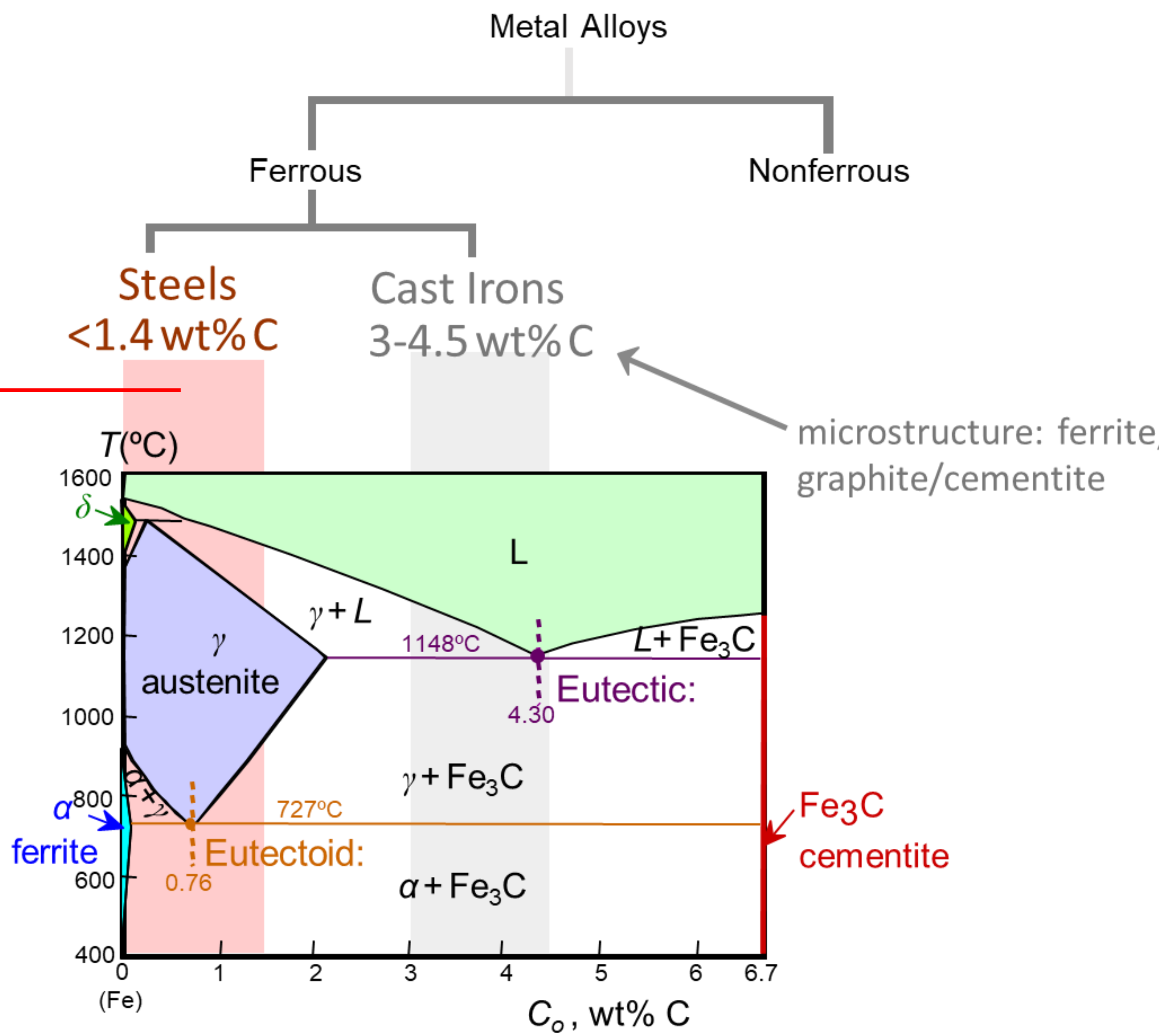


Eutectoid composition (wt. % of C)



Classification of Iron Alloys

Pure Fe:
<0.008% C impurity



NB!
in this range upon cooling the steel necessarily enters the γ phase
this gives rise to the various characteristic microstructures

Ferrous Alloys

Iron-based alloys

- Steels
- Cast Irons

Nomenclature for steels (AISI/SAE)

10xx	Plain Carbon Steels
11xx	Plain Carbon Steels (resulfurized for machinability)
15xx	Mn (1.00 - 1.65%)
40xx	Mo (0.20 ~ 0.30%)
43xx	Ni (1.65 - 2.00%), Cr (0.40 - 0.90%), Mo (0.20 - 0.30%)
44xx	Mo (0.5%)

xx: wt% C x 100

example: 1060 steel – plain carbon steel with 0.60 wt% C

Stainless Steel >11% Cr

STEELS

HSLA: High strength low alloy

Low Alloy

High Alloy

low carbon <0.25 wt%C

Med carbon 0.25-0.6 wt%C

high carbon 0.6-1.4 wt%C

Name	plain	HSLA	plain	heat treatable	plain	tool	stainless
Additions	none	Cr, V Ni, Mo	none	Cr, Ni Mo	none	Cr, V, Mo, W	Cr, Ni, Mo
Example	1010	4310	1040	43 40	1095	4190	304, 409
Hardenability	0	+	+	++	++	+++	varies
TS	-	0	+	++	+	++	varies
EL	+	+	0	-	-	--	++
Uses	auto struc. sheet	bridges towers press. vessels	crank shafts bolts hammers blades	pistons gears wear applic.	wear applic.	drills saws dies	high T applic. turbines furnaces Very corros. resistant

increasing strength, cost, decreasing ductility

Stainless steel (for implants?)

- early step: 1920s development of 304 stainless steel - also known as **18/8**

  improving corrosion resistance
  mechanical strength
  extend useful lifetime of metallic implants
  reduce post-operative complications, metallosis

Cr Ni

Cr 18 wt.% - sufficient for alloy passivation

formation of a self-healing, chemically inert, protective **Cr oxide layer** prevents the diffusion of O_2 to the underlying material

↓

corrosion resistance in reducing acids and against pitting attack in solutions containing Cl^- ions, *e.g.* biofluids

Ni 8 wt% - modifies microstructure

allows the alloy to take on an austenitic **fcc** crystal microstructure

↓

increasing the density, hardness, and abrasive resistance

↓

improving its resistance to oxidation, corrosion and heat

NB 304 steel is still susceptible to pitting corrosion:
fluids rich in Cl− ions +O_2 (i.e. conditions commonly encountered by an implant)

Table 11.4 Designations, Compositions, Mechanical Properties, and Typical Applications for Austenitic, Ferritic, Martensitic, and Precipitation-Hardenable Stainless Steels

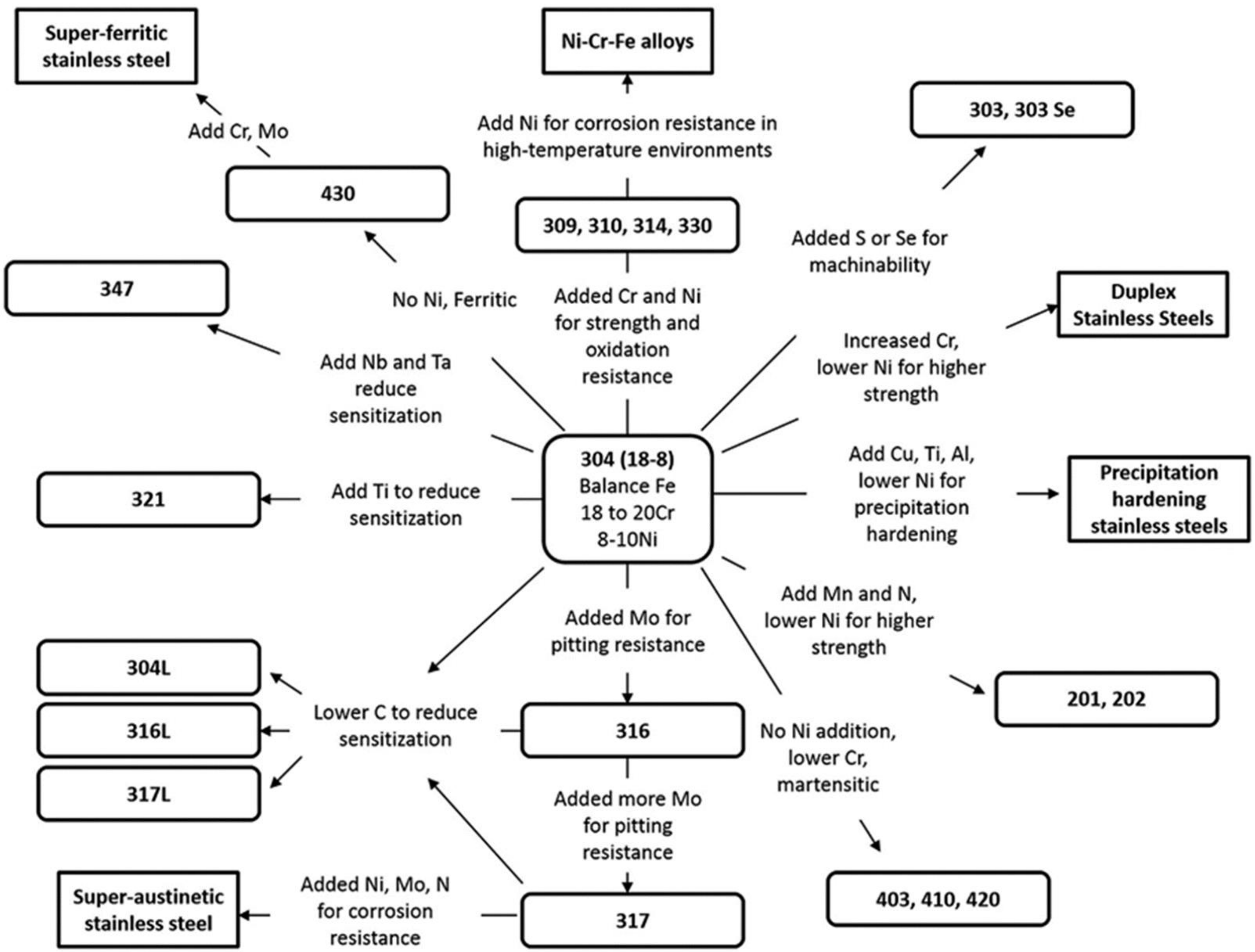
				Mechanical Properties			
AISI Number	***UNS Number***	***Composition (wt%)[a]***	***Condition[b]***	***Tensile Strength [MPa (ksi)]***	***Yield Strength [MPa (ksi)]***	***Ductility [%EL in 50 mm (2 in.)]***	***Typical Applications***
Ferritic							
409	S40900	0.08 C, 11.0 Cr, 1.0 Mn, 0.50 Ni, 0.75 Ti	Annealed	380 (55)	205 (30)	20	Automotive exhaust components, tanks for agricultural sprays
446	S44600	0.20 C, 25 Cr, 1.5 Mn	Annealed	515 (75)	275 (40)	20	Valves (high temperature), glass molds, combustion chambers
Austenitic							
304	S30400	0.08 C, 19 Cr, 9 Ni, 2.0 Mn	Annealed	515 (75)	205 (30)	40	Chemical and food processing equipment, cryogenic vessels
316L	S31603	0.03 C, 17 Cr, 12 Ni, 2.5 Mo, 2.0 Mn	Annealed	485 (70)	170 (25)	40	Welding construction, temporary biomedical orthopedic devices
Martensitic							
410	S41000	0.15 C, 12.5 Cr, 1.0 Mn	Annealed Q & T	485 (70) 825 (120)	275 (40) 620 (90)	20 12	Rifle barrels, cutlery, jet engine parts
440A	S44002	0.70 C, 17 Cr, 0.75 Mo, 1.0 Mn	Annealed Q & T	725 (105) 1790 (260)	415 (60) 1650 (240)	20 5	Cutlery, bearings, surgical tools
Precipitation Hardenable							
17-4PH	S17400	0.07 C, 16.25 Cr, 4 Ni, 4 Cu, 0.3 (Nb + Ta), 1.0 Mn, 1.0 Si	Precipitation hardened	1310 (190)	1172 (170)	10	Chemical, petrochemical, and foodprocessing equipment, aerospace parts

[a] The balance of the composition is iron.

[b] Q & T denotes quenched and tempered.

Source: Adapted from *ASM Handbook*, Vol. 1, *Properties and Selection: Irons, Steels, and High-Performance Alloys*, 1990. Reprinted by permission of ASM International, Materials Park, OH.

Relationships between the composition and properties in stainless steel alloys

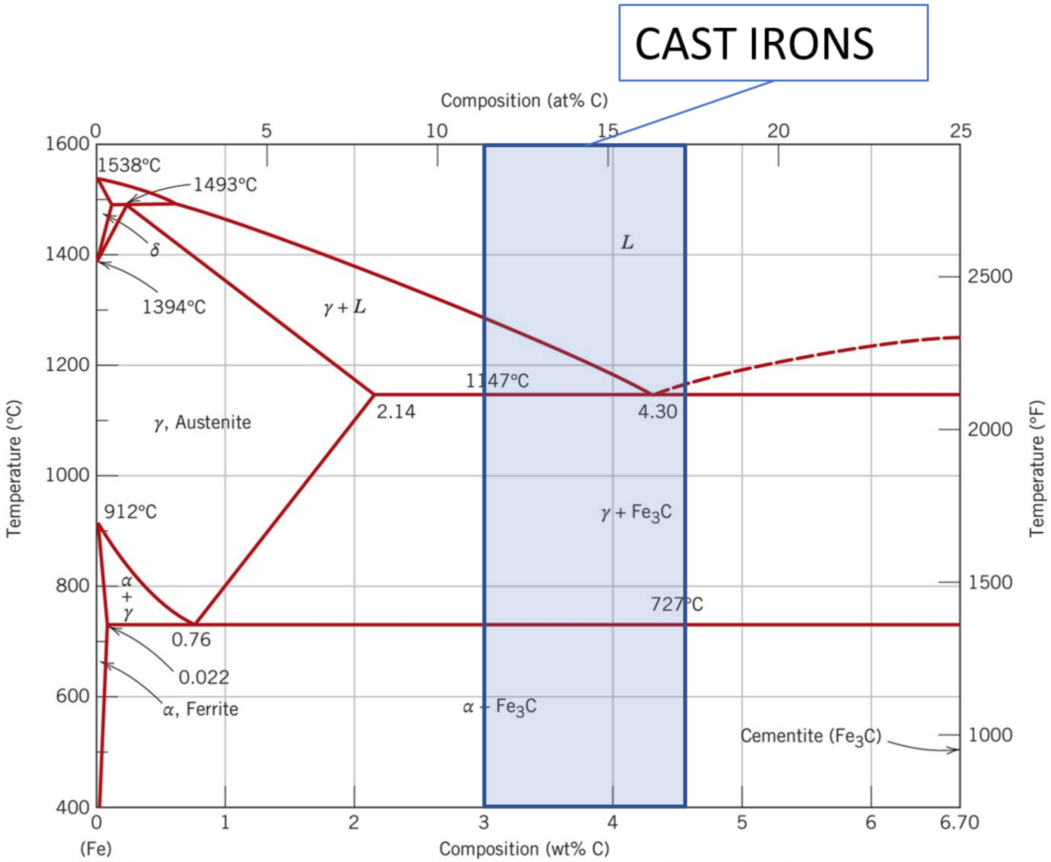


Cast Irons

Ferrous alloys with > 2.1 wt% C

- more commonly 3 - 4.5 wt% C

italian: «ghise»



Adapted from *Binary Alloy Phase Diagrams*, Vol. 1, 2nd edition, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.

SEE DETAILS OF

TYPES OF CAST IRON

in ADDITIONAL SLIDES TO THIS LECTURE

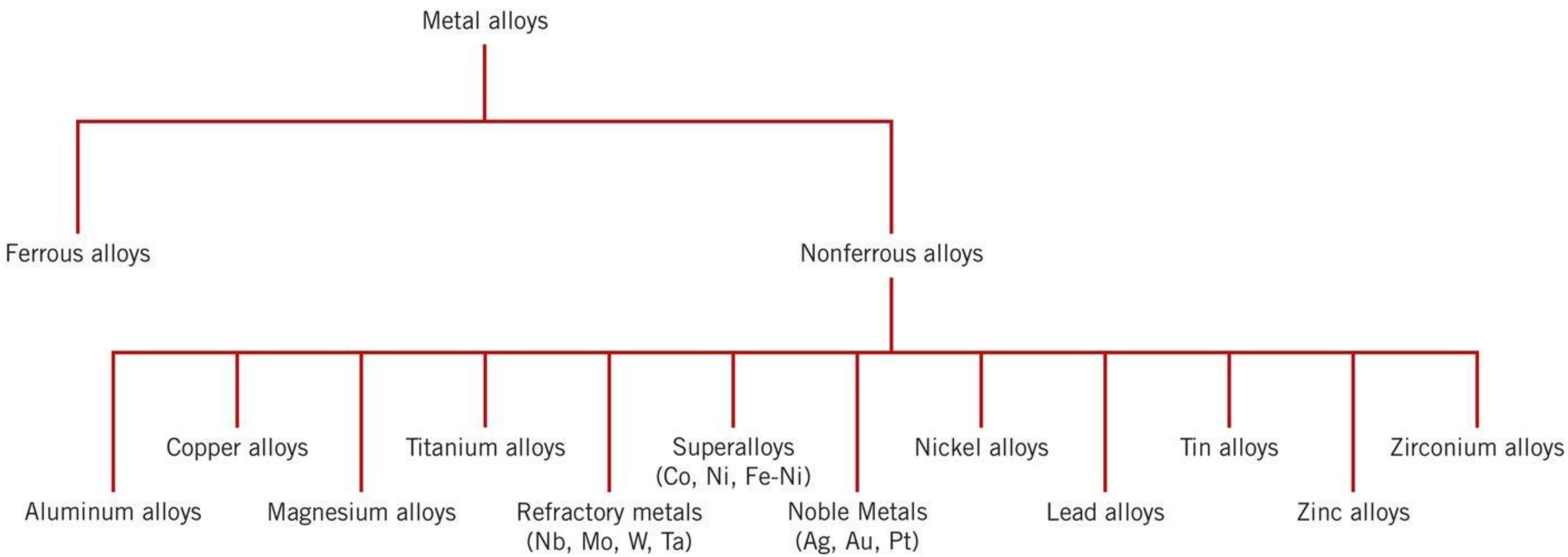
Limitations of Ferrous Alloys

- Relatively high densities
- Relatively low electrical conductivities
- Generally poor corrosion resistance

L5.4

NON FERROUS ALLOYS

NON-FERROUS ALLOYS



MANUFACTURING MATTERS!

CAST AND WROUGHT ALLOYS

CAST ALLOYS

it. «leghe da fonderia»
melted in a furnace and poured into a mold

WROUGHT ALLOYS

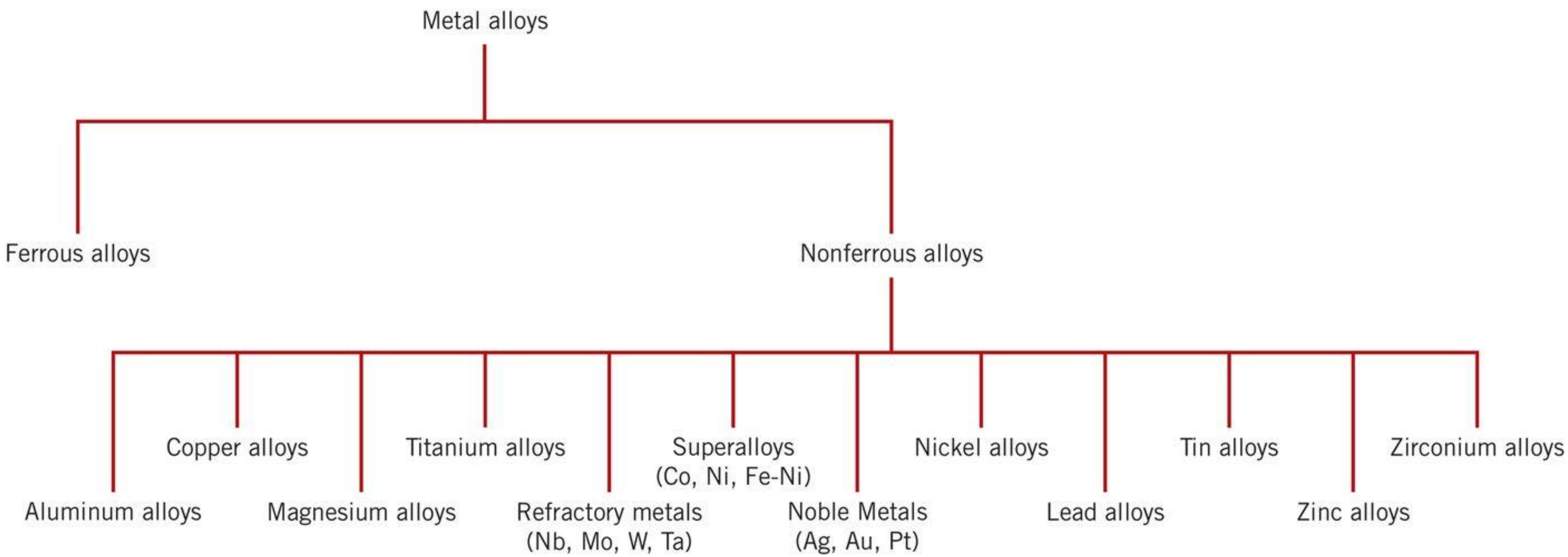
it. «leghe da lavorazione plastica»
alloy is worked in the solid form with the help of specific tools + heat
(stamping, bending, rolling, extrusion, etc.)

The two manufacturing processes will yield two materials with very different properties.

CAST Al parts

WROUGHT Al parts

NON-FERROUS ALLOYS



Cu ALLOYS

wikimedia commons

native copper

Cu

fcc

Tm= 1084,4°C

σ = 59.6 10^6 S/m

k_T = 390 W·m^{-1}·K^{-1}

BRASSES Cu-Zn

Tm = 915-960°C

σ = 16 10^6 S/m

k_T = 150 W·m^{-1}·K^{-1}

«α» phase Zn < 36%

fcc

«α-β'» 36< Zn< 45%

β' phase bcc

BRONZES

Cu – Sn, Al, Si, Ni

Tm= 880-1020°C

σ = 16 10^6 S/m

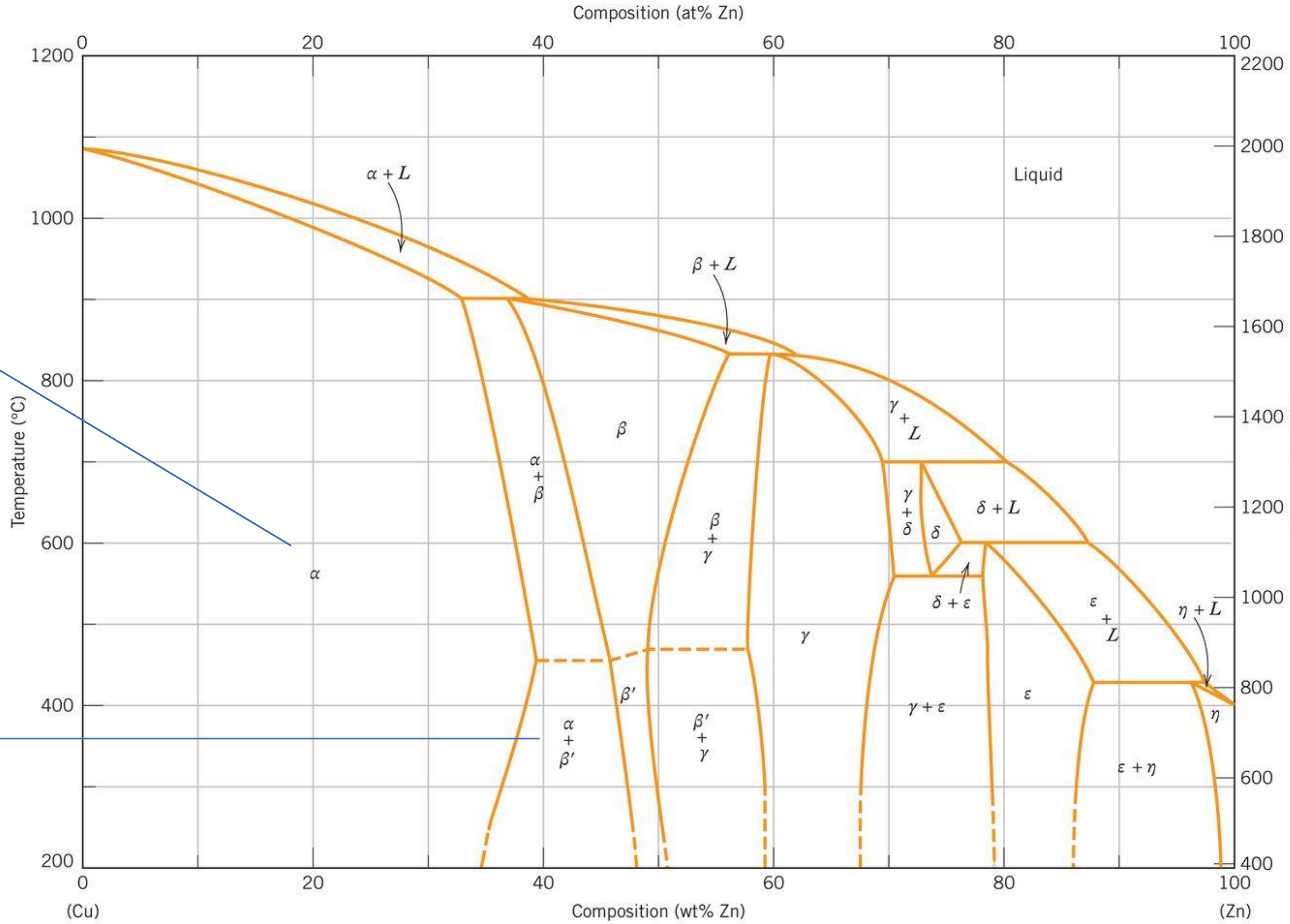
k_T = 62 W·m^{-1}·K^{-1}

Cu-Zn PHASE DIAGRAM

BRASS

«α» phase
Zn < 36%
fcc
soft, ductile

«α-β'»
36< Zn< 45%
β' phase bcc
more strong
resistant



Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 2, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.

Cu ALLOYS

Table 11.6 **Compositions, Mechanical Properties, and Typical Applications for Eight Copper Alloys**

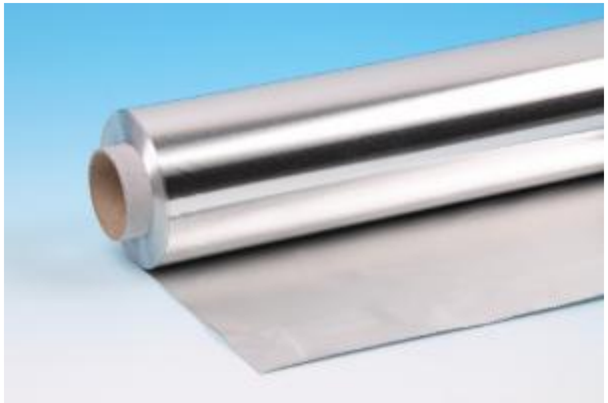
				Mechanical Properties			
Alloy Name	***UNS Number***	***Composition (wt%)a***	***Condition***	***Tensile Strength [MPa (ksi)]***	***Yield Strength [MPa (ksi)]***	***Ductility [%EL in 50 mm (2 in.)]***	***Typical Applications***
				Wrought Alloys			
Electrolytic tough pitch	C11000	0.04 O	Annealed	220 (32)	69 (10)	45	Electrical wire, rivets, screening, gaskets, pans, nails, roofing
Beryllium copper	C17200	1.9 Be, 0.20 Co	Precipitation hardened	1140–1310 (165–190)	965–1205 (140–175)	4–10	Springs, bellows, firing pins, bushings, valves, diaphragms
Cartridge brass	C26000	30 Zn	Annealed Cold-worked (H04 hard)	300 (44) 525 (76)	75 (11) 435 (63)	68 8	Automotive radiator cores, ammunition components, lamp fixtures, flashlight shells, kickplates
Phosphor bronze, 5% A	C51000	5 Sn, 0.2 P	Annealed Cold-worked (H04 hard)	325 (47) 560 (81)	130 (19) 515 (75)	64 10	Bellows, clutch disks, diaphragms, fuse clips, springs, welding rods
Copper–nickel, 30%	C71500	30 Ni	Annealed Cold-worked (H02 hard)	380 (55) 515 (75)	125 (18) 485 (70)	36 15	Condenser and heat-exchanger components, saltwater piping
				Cast Alloys			
Leaded yellow brass	C85400	29 Zn, 3 Pb, 1 Sn	As cast	234 (34)	83 (12)	35	Furniture hardware, radiator fittings, light fixtures, battery clamps
Tin bronze	C90500	10 Sn, 2 Zn	As cast	310 (45)	152 (22)	25	Bearings, bushings, piston rings, steam fittings, gears
Aluminum bronze	C95400	4 Fe, 11 Al	As cast	586 (85)	241 (35)	18	Bearings, gears, worms, bushings, valve seats and guards, pickling hooks

[a] The balance of the composition is copper.

Source: Adapted from *ASM Handbook*, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, 1990. Reprinted by permission of ASM International, Materials Park, OH.

from Callister & Retwisch *Materials Science and Engineering: An Introduction, Enhanced eText*. (10th Edition). Wiley Global Education US, 2018.

Al Alloys

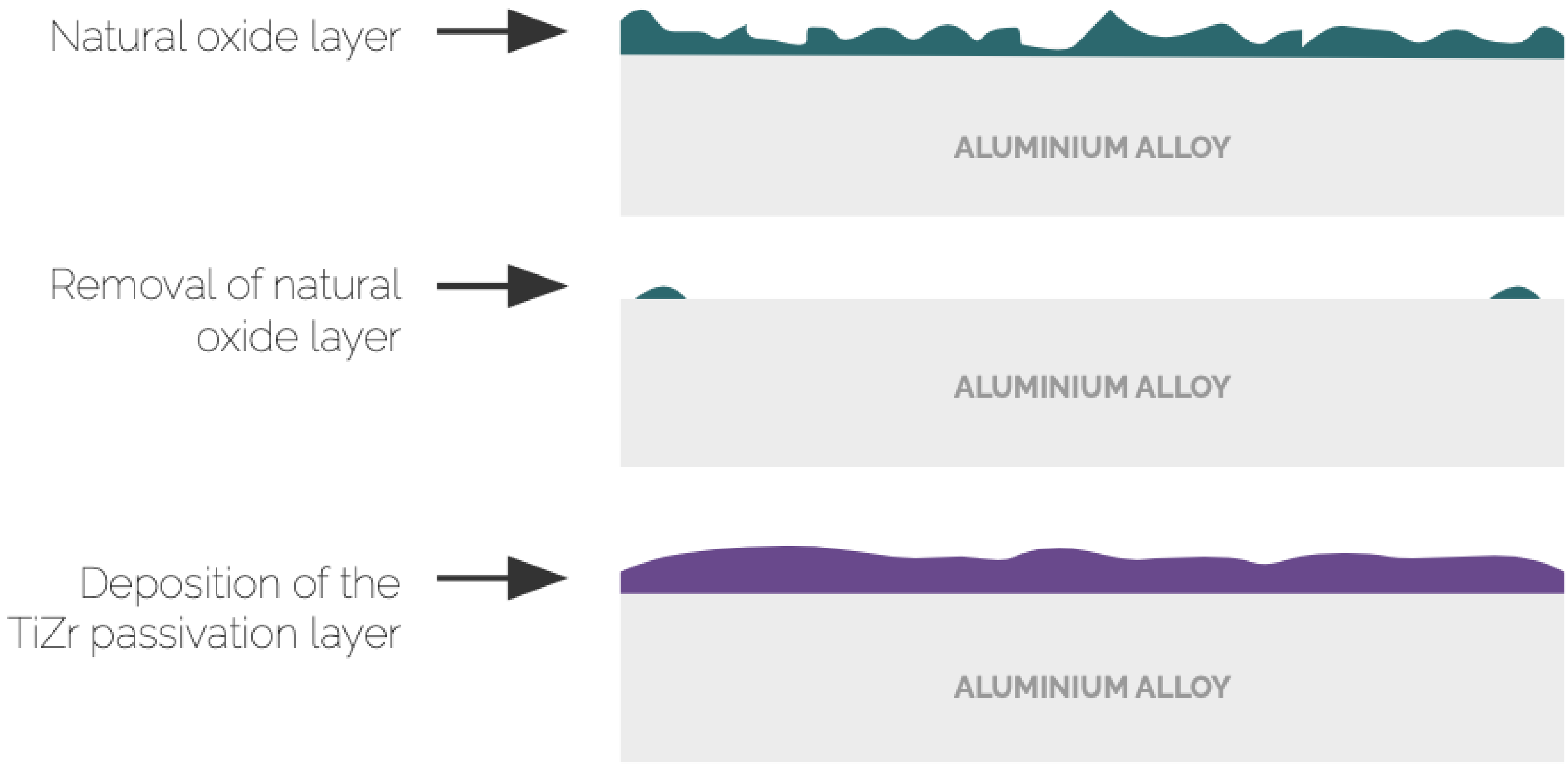


- Al: fcc cryst struct
- low density, d= 2.7 g/cm^3 (Steel: 7.9 g/cm^3)
- high ductility
- low melting temperature T_m = 660°C
- main alloying elements: Cu, Mg, Si, Mn, Zn
- good resistance to corrosion in ambient atmosphere:

Al_2O_3 passivation layer ≈4 nm

- Novel alloys
  - low density alloys Al-Mg, Al-Ti -> reductions in fuel consumption
  - Al-Li aircraft and aerospace industries. low d (2.5 g/cm^3), high moduli,excellent fatigue properties. BUT more costly to manufacture: special processing techniques because of Li chemical reactivity.

Cleaning the metal surface



Source: The importance of metal passivation | LinkedIn

Table 11.8 **Compositions, Mechanical Properties, and Typical Applications for Several Common Aluminum Alloys**

				Mechanical Properties			
Aluminum Association Number	*UNS Number*	*Composition (wt%)a*	*Condition (Temper Designation)*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*	*Typical Applications/Characteristics*
Wrought, Non-Heat-Treatable Alloys							
1100	A91100	0.12 Cu	Annealed (O)	90 (13)	35 (5)	35–45	Food/chemical handling and storage equipment, heat exchangers, light reflectors
3003	A93003	0.12 Cu, 1.2 Mn, 0.1 Zn	Annealed (O)	110 (16)	40 (6)	30–40	Cooking utensils, pressure vessels and piping
5052	A95052	2.5 Mg, 0.25 Cr	Strain hardened (H32)	230 (33)	195 (28)	12–18	Aircraft fuel and oil lines, fuel tanks, appliances, rivets, and wire
Wrought, Heat-Treatable Alloys							
2024	A92024	4.4 Cu, 1.5 Mg, 0.6 Mn	Heat-treated (T4)	470 (68)	325 (47)	20	Aircraft structures, rivets, truck wheels, screw machine products
6061	A96061	1.0 Mg, 0.6 Si, 0.30 Cu, 0.20 Cr	Heat-treated (T4)	240 (35)	145 (21)	22–25	Trucks, canoes, railroad cars, furniture, pipelines
7075	A97075	5.6 Zn, 2.5 Mg, 1.6 Cu, 0.23 Cr	Heat-treated (T6)	570 (83)	505 (73)	11	Aircraft structural parts and other highly stressed applications
Cast, Heat-Treatable Alloys							
295.0	A02950	4.5 Cu, 1.1 Si	Heat-treated (T4)	221 (32)	110 (16)	8.5	Flywheel and rear-axle housings, bus and aircraft wheels, crankcases
356.0	A03560	7.0 Si, 0.3 Mg	Heat-treated (T6)	228 (33)	164 (24)	3.5	Aircraft pump parts, automotive transmission cases, water-cooled cylinder blocks
Aluminum–Lithium Alloys							
2090	—	2.7 Cu, 0.25 Mg, 2.25 Li, 0.12 Zr	Heat-treated, cold-worked (T83)	455 (66)	455 (66)	5	Aircraft structures and cryogenic tankage structures
8090	—	1.3 Cu, 0.95 Mg, 2.0 Li, 0.1 Zr	Heat-treated, cold-worked (T651)	465 (67)	360 (52)	—	Aircraft structures that must be highly damage tolerant

[a] The balance of the composition is aluminum.

Source: Adapted from *ASM Handbook*, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, 1990. Reprinted by permission of ASM International, Materials Park, OH.

from Callister & Retwisch *Materials Science and Engineering: An Introduction, Enhanced eText*. (10th Edition). Wiley Global Education US, 2018.

Mg Alloys

- Mg, d = 1.7 g/cm^3, lowest of all the structural metals
- hcp structure
- low melting Tm = 651°C
- relatively soft, ductile; low modulus E = 45 GPa
- Mg alloys relatively unstable, susceptible to corrosion in marine environments
- lightweight applications: aircraft, missiles, luggage,…

  automobiles

  (e.g., steering wheels and columns, seat frames, transmission cases),

  audio, video, computer, and communications equipment

  (e.g., laptops, mobile phones, etc.)
- transient and bioresorbable electronics?

Table 11.9 **Compositions, Mechanical Properties, and Typical Applications for Six Common Magnesium Alloys**

				Mechanical Properties			
ASTM Number	***UNS Number***	***Composition (wt%)a***	***Condition***	***Tensile Strength [MPa (ksi)]***	***Yield Strength [MPa (ksi)]***	***Ductility [%EL in 50 mm (2 in.)]***	***Typical Applications***
				Wrought Alloys			
AZ31B	M11311	3.0 Al, 1.0 Zn, 0.2 Mn	As extruded	262 (38)	200 (29)	15	Structures and tubing, cathodic protection
HK31A	M13310	3.0 Th, 0.6 Zr	Strain hardened, partially annealed	255 (37)	200 (29)	9	High strength to 315°C (600°F)
ZK60A	M16600	5.5 Zn, 0.45 Zr	Artificially aged	350 (51)	285 (41)	11	Forgings of maximum strength for aircraft
				Cast Alloys			
AZ91D	M11916	9.0 Al, 0.15 Mn, 0.7 Zn	As cast	230 (33)	150 (22)	3	Die-cast parts for automobiles, luggage, and electronic devices
AM60A	M10600	6.0 Al, 0.13 Mn	As cast	220 (32)	130 (19)	6	Automotive wheels
AS41A	M10410	4.3 Al, 1.0 Si, 0.35 Mn	As cast	210 (31)	140 (20)	6	Die castings requiring good creep resistance

[a] The balance of the composition is magnesium.

Source: Adapted from *ASM Handbook*, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, 1990. Reprinted by permission of ASM International, Materials Park, OH.

Ti Alloys

- Ti: low density (4.5 g/cm^3), high Tm=1668°C, E = 107 GPa.
- Ti alloys, extremely strong: TS = 1400 MPa (@RT)
- highly ductile easily forged and machined.

- pure Ti: hcp structure (α phase)

Ti dental implant
www.matmatch.com

hcp structure (α phase) $\xrightarrow[T = 883°C]{}$ bcc structure (β phase)

influence of elements:
V, Nb, Mo β-phase stabilizers
Al, Sn α-phase stabilizers
→ different properties (s. Table)

Ti hip joint implant
www.matmatch.com

- major limitation of Ti: chemical reactivity at high T → quite expensive manufacturing
- BUT, @ normal T excellent corrosion resistance:
  virtually immune to air, marine, and a variety of industrial environments
- Implants into the human body: highly biocompatible, do not release toxic substances
- Used extensively for dental and orthopedic (hip and knee) implants

Table 11.10 **Compositions, Mechanical Properties, and Typical Applications for Several Common Titanium Alloys**

				Average Mechanical Properties			
Alloy Type	***Common Name (UNS Number)***	***Composition (wt%)***	***Condition***	***Tensile Strength [MPa (ksi)]***	***Yield Strength [MPa (ksi)]***	***Ductility [%EL in 50 mm (2 in.)]***	***Typical Applications***
Commercially pure	Unalloyed (R50250)	99.5 Ti	Annealed	240 (35)	170 (25)	24	Jet engine shrouds, cases and airframe skins, corrosion-resistant equipment for marine and chemical processing industries
α	Ti-5Al-2.5Sn (R54520)	5 Al, 2.5 Sn, balance Ti	Annealed	826 (120)	784 (114)	16	Gas turbine engine casings and rings; chemical processing equipment requiring strength to temperatures of 480°C (900°F)
Near α	Ti-8Al-1Mo-1V (R54810)	8 Al, 1 Mo, 1 V, balance Ti	Annealed (duplex)	950 (138)	890 (129)	15	Forgings for jet engine components (compressor disks, plates, and hubs)
$\alpha + \beta$	Ti-6Al-4V (R56400)	6 Al, 4 V, balance Ti	Annealed	947 (137)	877 (127)	14	High-strength prosthetic implants, chemical-processing equipment, airframe structural components
$\alpha + \beta$	Ti-6Al-6V-2Sn (R56620)	6 Al, 2 Sn, 6 V, 0.75 Cu, balance Ti	Annealed	1050 (153)	985 (143)	14	Rocket engine case airframe applications and high-strength airframe structures
β	Ti-10V-2Fe-3Al	10 V, 2 Fe, 3 Al, balance Ti	Solution + aging	1223 (178)	1150 (167)	10	Best combination of high strength and toughness of any commercial titanium alloy; used for applications requiring uniformity of tensile properties at surface and center locations; high-strength airframe components

Source: Adapted from *ASM Handbook*, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, 1990. Reprinted by permission of ASM International, Materials Park, OH.

METALS (ENGINEERING)

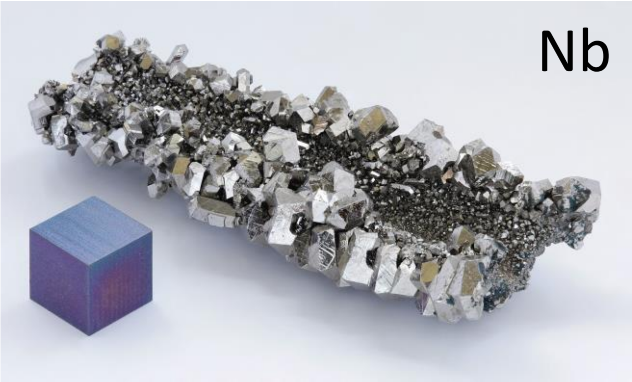
YOUTUBE VIDEO - «The efficient engineer»
"Understanding metals"

(17:00)

https://youtu.be/PaGJwOPg2kU

REFRACTORY MATERIALS

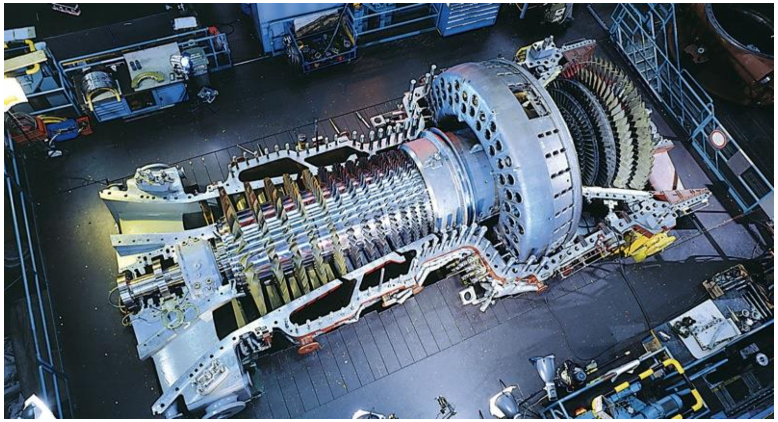
- Nb, Mo, W, Ta
- Interatomic bonding extremely strong:
  - extremely high melting temperatures:
    2468°C (Nb) < Tm < 3410°C (W)
  - large E, high strength, hardness

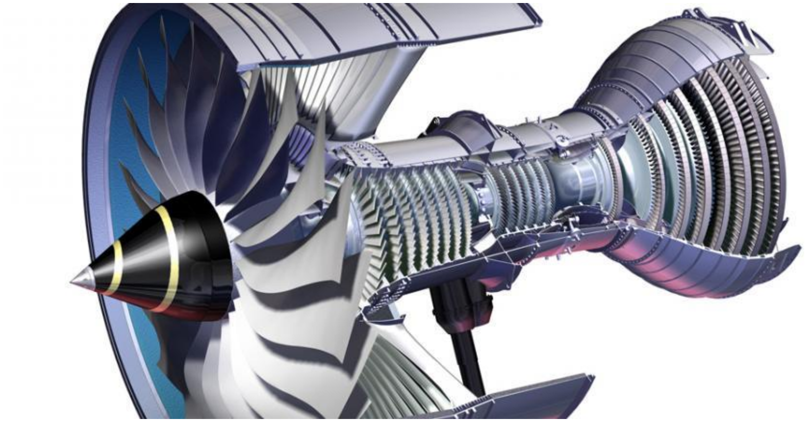


- Ta, Mo: improve corrosion resistance of stainless steel
- Mo alloys: extrusion dies, structural parts in space vehicles
- W: incandescent light filaments, x-ray tubes, and welding electrodes
- Ta: immune to chemical attack by virtually all environments @ T<150°C

SUPERALLOYS

- "superalloys" superlative combinations of properties
- Most are used in aircraft turbine components:
    - withstand exposure to oxidizing environments + high T + long time
    - relatively low density
- classified according to the predominant metal(s) in the alloy: Fe–Ni, Ni, Co
- Alloying elements: Nb, Mo, W, Ta, Cr, Ti





Univ. of Cambridge/Rolls Royce https://www.cam.ac.uk/

Table 11.11 Compositions for Several Superalloys

Composition (wt%)										
Alloy Name	***Ni***	***Fe***	***Co***	***Cr***	***Mo***	***W***	***Ti***	***Al***	***C***	***Other***
Iron–Nickel (Wrought)										
A-286	26	55.2	—	15	1.25	—	2.0	0.2	0.04	0.005 B, 0.3 V
Incoloy 925	44	29	—	20.5	2.8	—	2.1	0.2	0.01	1.8 Cu
Nickel (Wrought)										
Inconel-718	52.5	18.5	—	19	3.0	—	0.9	0.5	0.08	5.1 Nb, 0.15 max Cu
Waspaloy	57.0	2.0 max	13.5	19.5	4.3	—	3.0	1.4	0.07	0.006 B, 0.09 Zr
Nickel (Cast)										
Rene 80	60	—	9.5	14	4	4	5	3	0.17	0.015 B, 0.03 Zr
Mar-M-247	59	0.5	10	8.25	0.7	10	1	5.5	0.15	0.015 B, 3 Ta, 0.05 Zr, 1.5 Hf
Cobalt (Wrought)										
Haynes (L-605) 25	10	1	54	20	—	15	—	—	0.1	
Cobalt (Cast)										
X-40	10	1.5	57.5	22	—	7.5	—	—	0.50	0.5 Mn, 0.5 Si

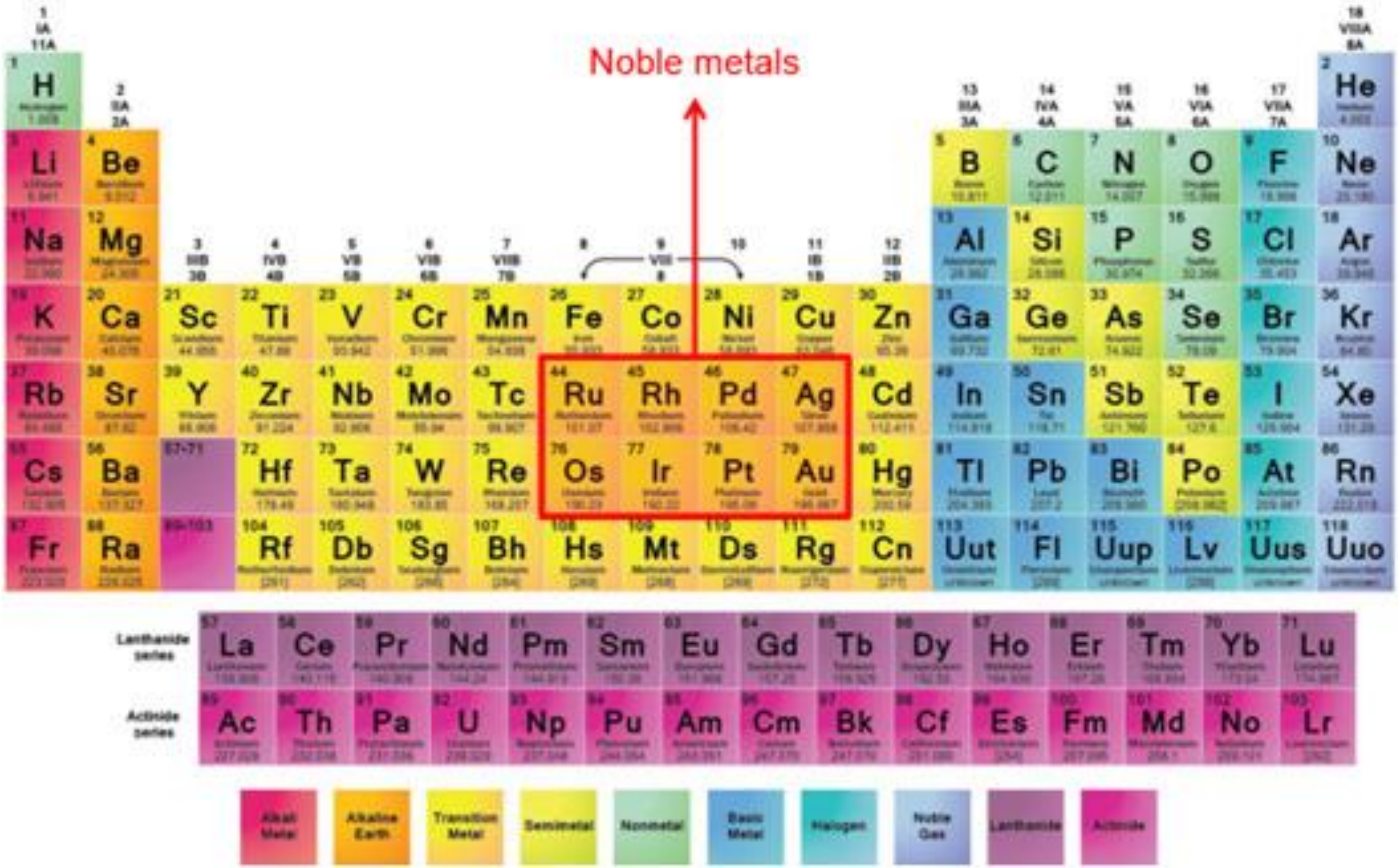
SUPERALLOYS

YOUTUBE VIDEO – channel «The MatSci guy»
“Ni superalloys”

(13:00)

https://youtu.be/k6m5iJOk24o

Noble metals



NOBLE METALS

- outstanding resistance to chemical attack even at high T
- soft, ductile. extremely expensive
- record thermal and electrical conductivity
- extreme importance in catalysis (enabling and speeding up chem reations)

- Ru: only dissolved in acqua regia, high conc HCl/HNO3, + O2,
- Rh: same but only if fine powder
- Pd, Ag: soluble in HNO3, Ag limited by AgCl precipitate
- Os, Ir: are chemically inert in ambient conditions
- Pt, Au: can be dissolved in aqua regia

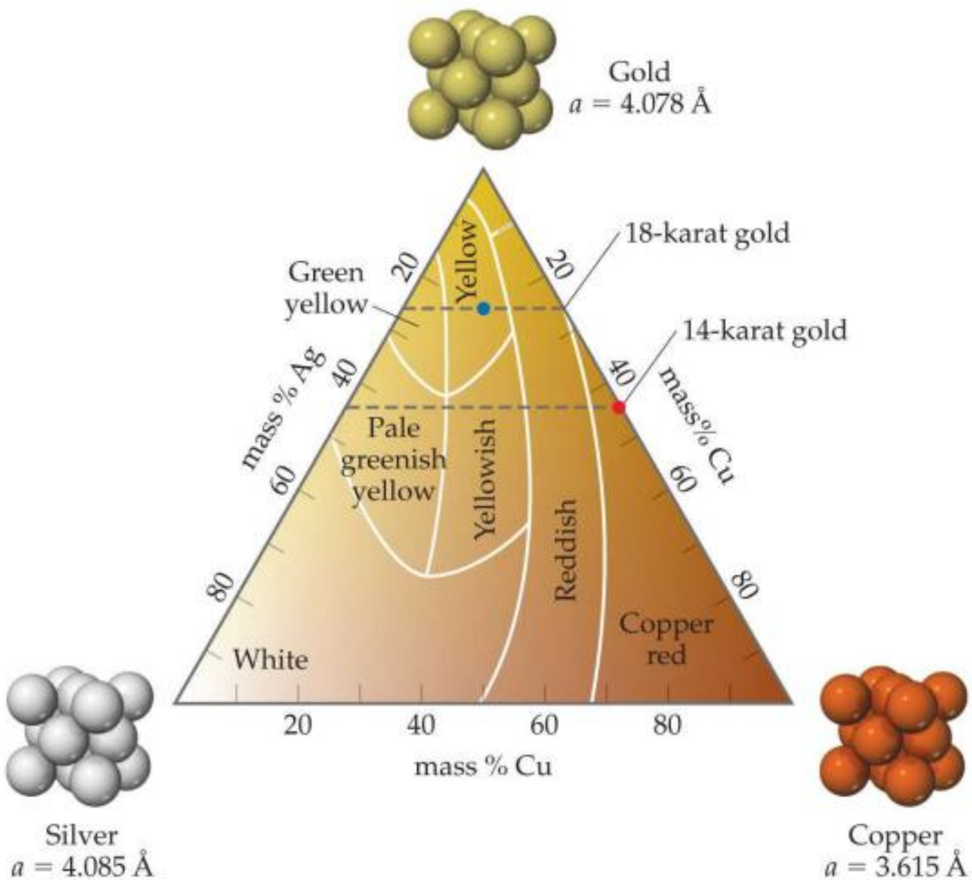
- extreme importance in electronics, biomedicine, bionics:

  integrated circuits contacts
  neural interfaces
  biosensors

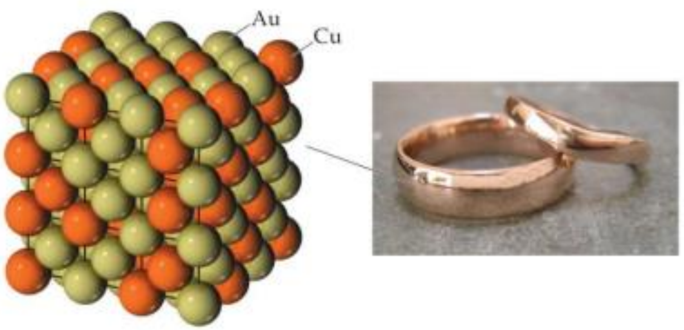
→ SEMINAR TOPIC: **Metal-based NEURAL INTERFACES**

GOLD

Pure gold is denoted 24 karat

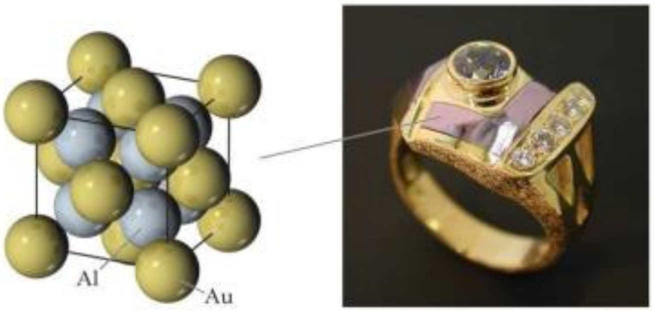


SUBSTITUTIONAL ALLOY



14-karat red gold, a substitutional alloy marked with a red dot in Figure 12.18

INTERMETALLIC COMPOUND



Purple gold, the intermetallic compound $AuAl_2$

taken from : Michael Lufaso, UNF (General Chemistry II (unf.edu))

NONFERROUS ALLOYS

NonFerrous Alloys

- Cu Alloys

Brass: Zn is subst. impurity

Bronze : Sn, Al, Si, Ni are subst. impurities

Cu-Be : precip. hardened for strength

- Al Alloys

-low ρ: 2.7 g/cm^3
-Cu, Mg, Si, Mn, Zn additions
-solid sol. or precip. strengthened

- Mg Alloys

-very low ρ: 1.7 g/cm^3
-ignites easily
-aircraft, missiles

- Ti Alloys

-relatively low ρ: 4.5 g/cm^3 vs 7.9 for steel
-reactive at high *T's*
-space applic.

- Noble metals

-Ag, Au, Pt
-oxid./corr. resistant

- Refractory metals

-high melting *T's*
-Nb, Mo, W, Ta

(taken from Callister, Rethwisch, 10e Support slides)

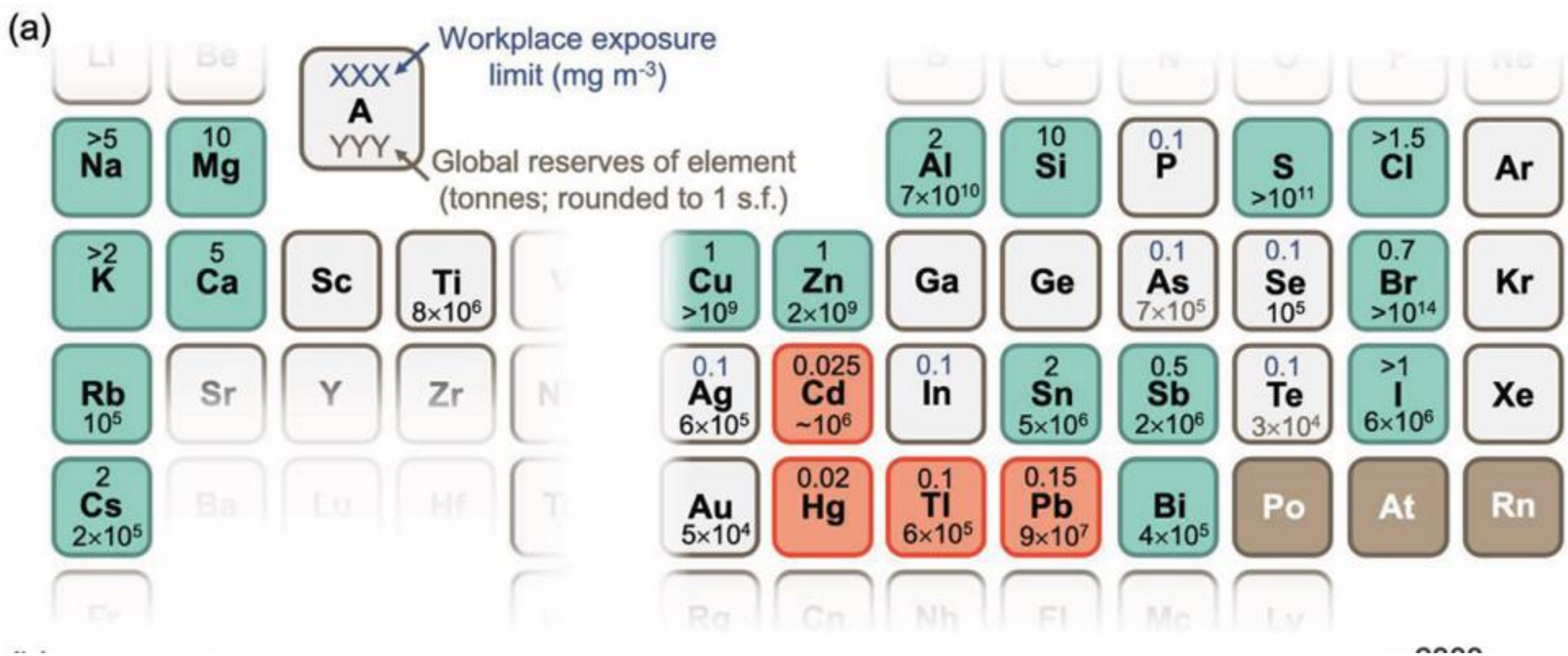
TABLES of Materials Properties

- mechanical
- electrical
- thermal
- …

APPENDIX B Callister Retwisch

THE POISONERS CORRIDOR

Cd, Hg, Tl, Pb: extremely toxic
Po, At, Rn: Radioactive

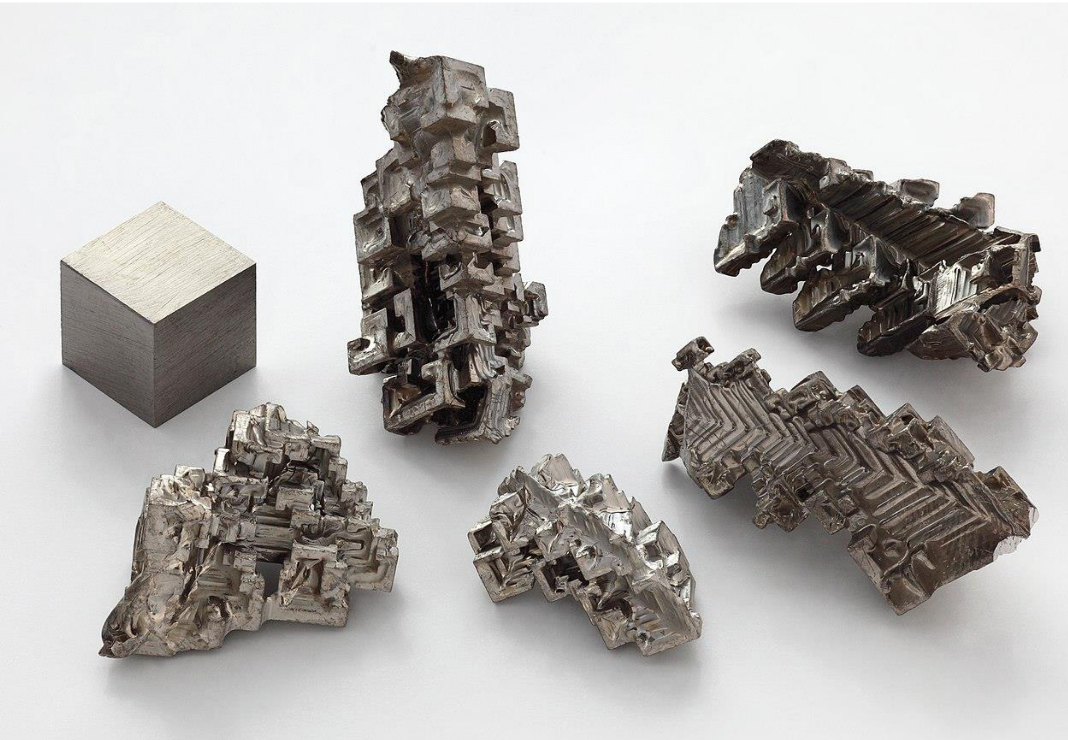


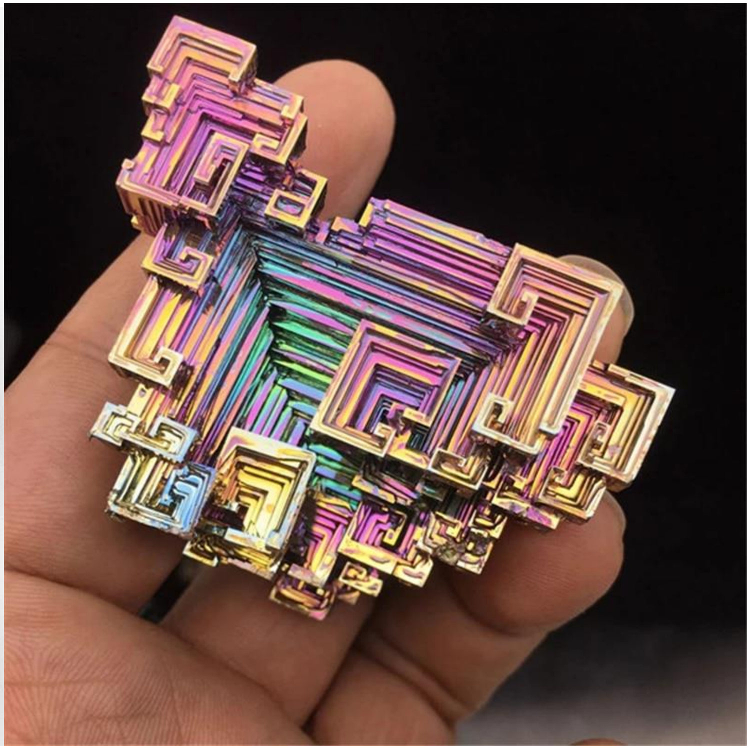
from: Pecunia et al. Adv Energy Mater. **2021** 11, 2100698

DOI: 10.1002/aenm.202100698

THE ANOMALY: BISMUTH

Bismuth   Bi





[Bismuth: A Gentleman Among Scoundrels]

«Green Bismuth»

[Green bismuth | Nature Chemistry]

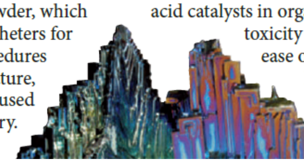
in your element

Green bismuth

Ram Mohan looks at how bismuth — a remarkably harmless element among the toxic heavy metals in the periodic table — has sparked interest in areas varying from medicinal to industrial chemistry.

Bismuth, the 83rd element in the periodic table, has been known since ancient times, but was often confused with lead and tin. In 1753, Claude François Geoffroy from France demonstrated that bismuth is distinct from these elements. The word bismuth itself is derived from the German word 'wismuth' (white mass). Studies showed that it was used as early as the sixteenth century by the Incas, who mixed it with tin to prepare bismuth bronze for knives[1]. Bismuth was also the instrument of alchemy fraud in the London Stock Exchange — in the 1860s, a Hungarian refugee named Nicholas Papaffy convinced a large number of investors to support many bismuth compounds are even less toxic than table salt (sodium chloride)[4]! This makes bismuth unique among the heavy metals, and has earned it the status of a 'green element'. For this reason, the world of cosmetic and medicinal chemistry has paid it particular attention. Bismuth oxychloride, for example, is used to impart a silvery sheen to cosmetics and personal care products. It is also marketed as BIRON powder, which has found applications in catheters for diagnostic and surgical procedures owing to its radio-opaque nature, and bismuth nitrate oxide is used as an antiseptic during surgery.

Perhaps the most well-



is also, along with graphite, one of the most diamagnetic materials known — it is repelled by a magnetic field — and has found applications in magnetic levitation (Maglev) trains, which can achieve speeds of over 250 mph.

More recently, bismuth and its compounds in the +3 oxidation state have found significant applications as green Lewis acid catalysts in organic synthesis. The low toxicity of bismuth salts, their ease of handling and relatively low cost make bismuth compounds more attractive than other corrosive Lewis

HOME READING ASSIGNMENT

BISMUTH

YOUTUBE VIDEO – Verge Science channel (6:27)

https://youtu.be/xG7n0dl5I60

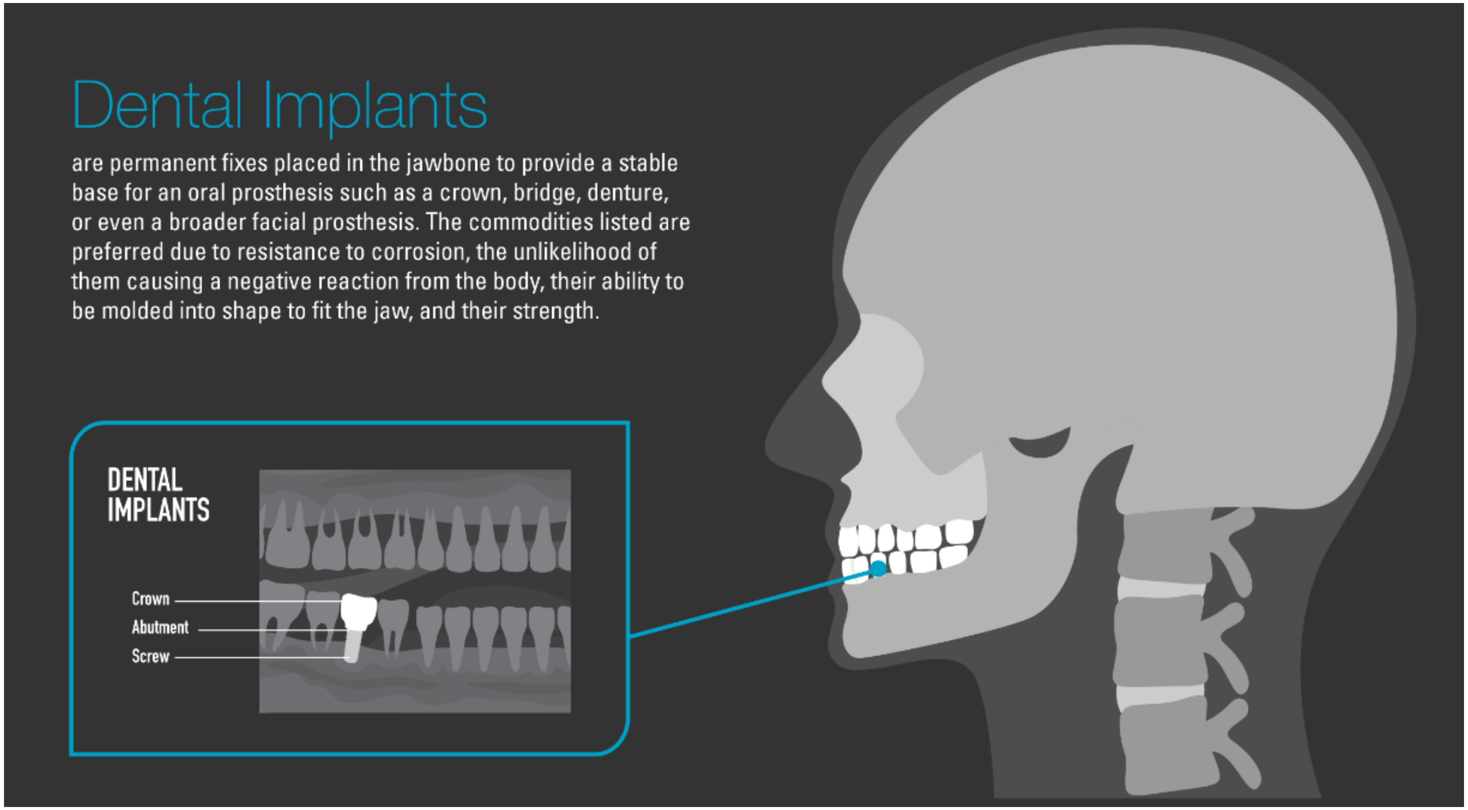
L5.5

METALS: MEDICAL IMPLANTS, TRANSIENT ELECTRONICS

METALS IN MEDICAL IMPLANTS

HOME READING ASSIGNMENT

METALS IN MEDICAL IMPLANTS: DENTAL



Co (alloys w Cr, Mo): denture frameworks

Au (alloys w Cu, Pt, Zn, Ag): dental prostheses, crowns, bridges

Fe (stainless steel): dental crowns, surgical tools

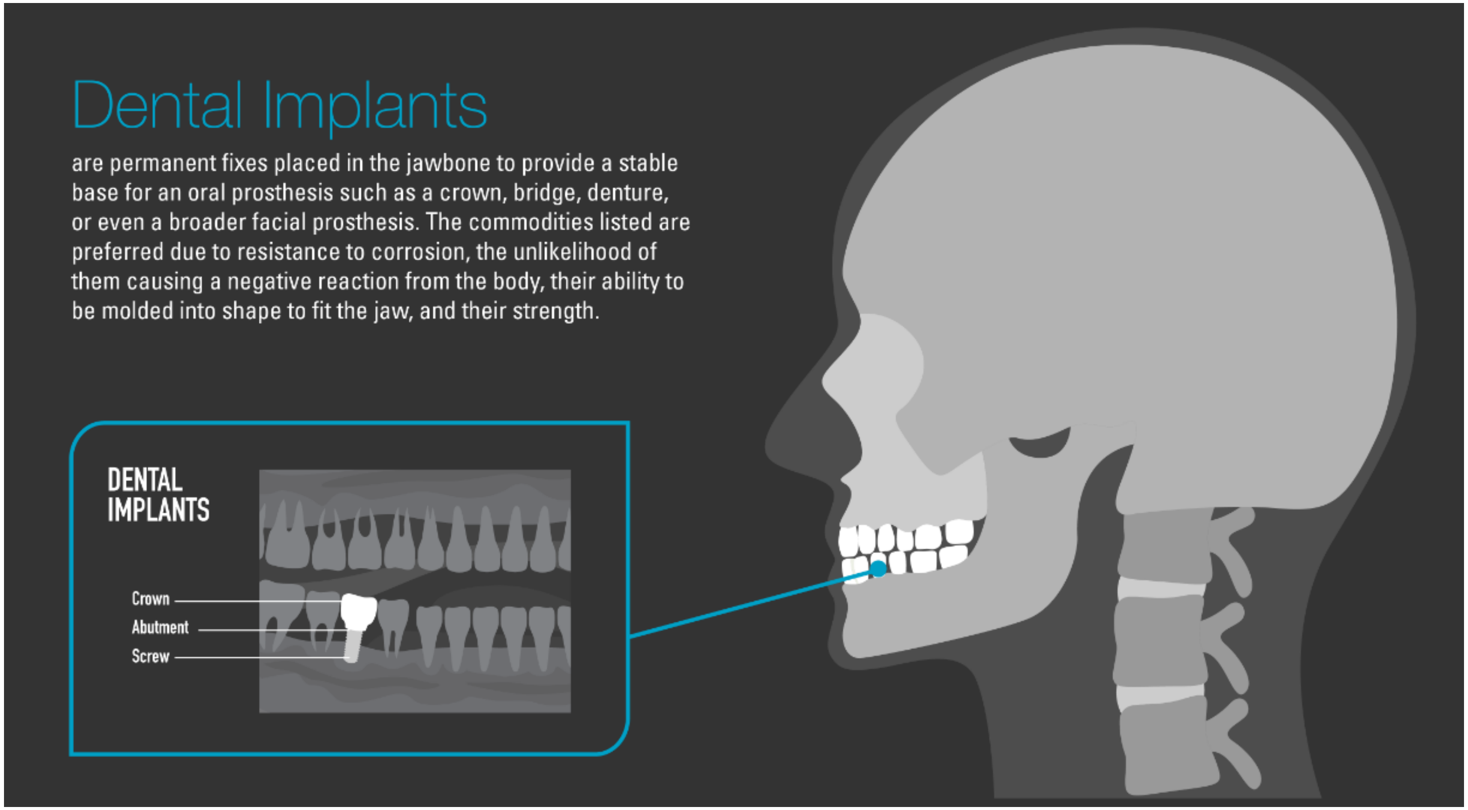
Ni (alloys w Ti): dental braces, drills

Ta: coat of carbon foam scaffold in biocompatible bone implants

Ag (alloys w Cu, Sn, Zn): dental fillings

https://www.usgs.gov/

Metals in Medical Implants: dental



Ti:
mech properties similar to bone, promotes osseointegration

Zr:
major constituent in ceramics for dental applications, wear resistant, inert, mech prop suited for dental crowns

https://www.usgs.gov/

METALS IN MEDICAL IMPLANTS: SENSORY & NEURO

Sensory and Neurological Implants

are implantable devices that communicate with the nervous system to either record electrical nerve activity or to electrically stimulate nerve cells that would improve senses that are not functioning properly. Examples include:

Cochlear Implants

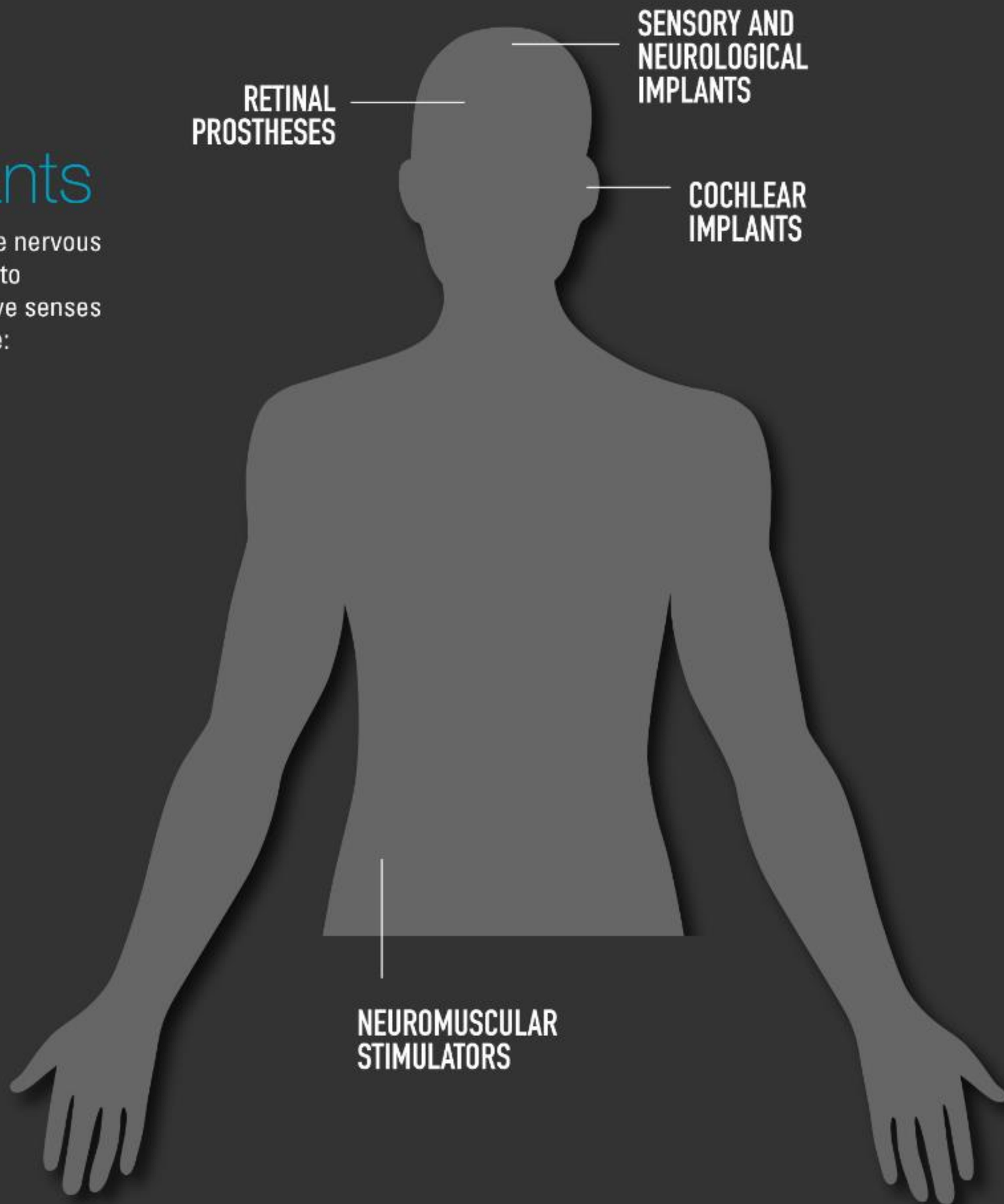
are designed to transmit sounds of speech into the brain, allowing the person to hear.

Retinal Prostheses

are fitted with sensors that trigger an electronic pulse. This pulse then stimulates nerves in the retina, which pass signals down the optic nerve to the brain to create an image.

Electrical Stimulators or Functional Neuromuscular Stimulation

are devices that deliver electrical impulses to nerves in the brain, treating disorders as deafness, incontinence, chronic pain, depression, and Parkinson's disease, among others.



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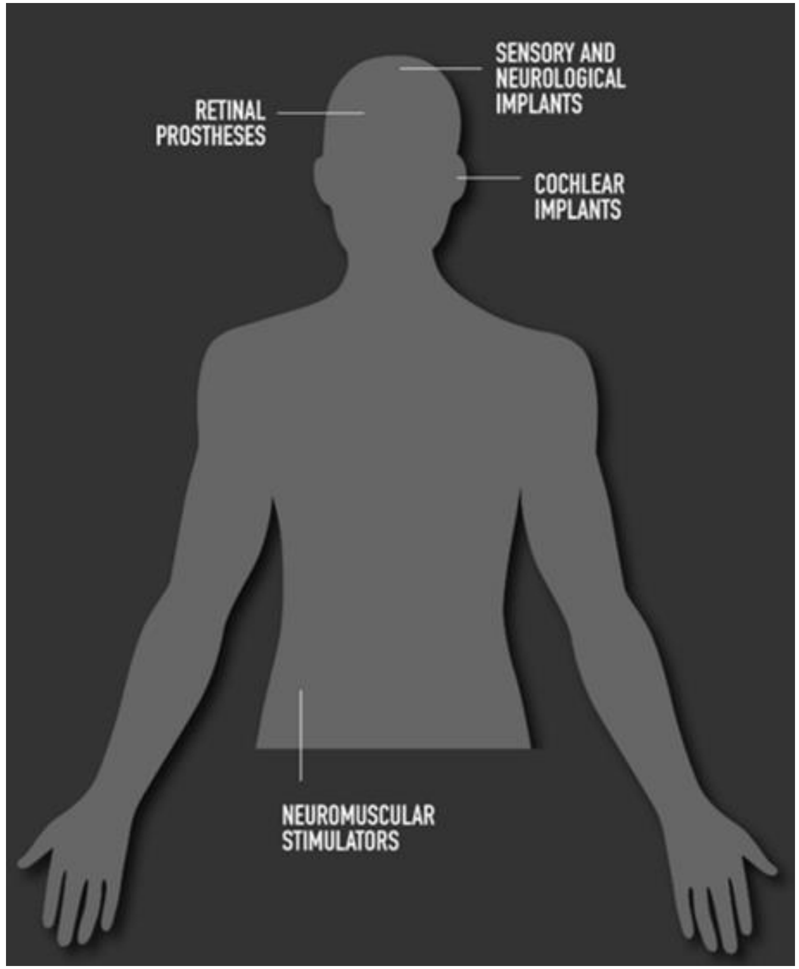
Metals in Medical Implants: Sensory & Neuro

Au electrodes: **bioelectronics**, brain-machine interfaces, cochlear implants, glucose biosensors

Ir (oxide): coating for Au, Cu, Ti wires for functional stimulation electrodes

Pt:
one of best electrode materials, neuromodulation devices, guidewires, stents, coils, catheters



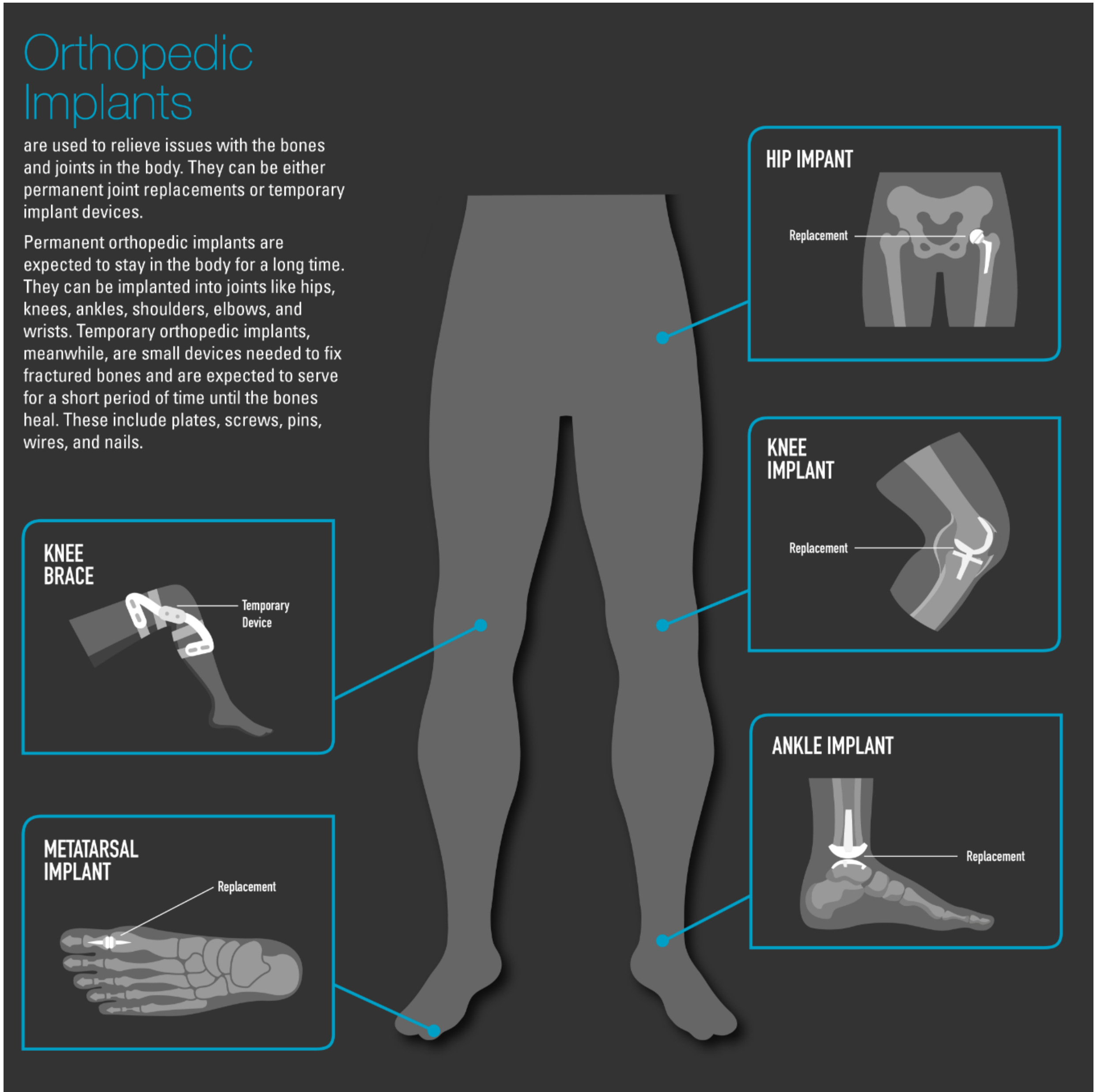
Ti: electrodes, non-toxic exterior of medical implants

Ag:
coating agent, anti-inflammatory, infection suppressant properties

Li (Li-I):
lithium iodide batteries suitable for implantable devices (long lifespan, stable voltage, reliable performance), also small and lightweight batteries

https://www.usgs.gov/

Metals in Medical Implants: Orthopedic



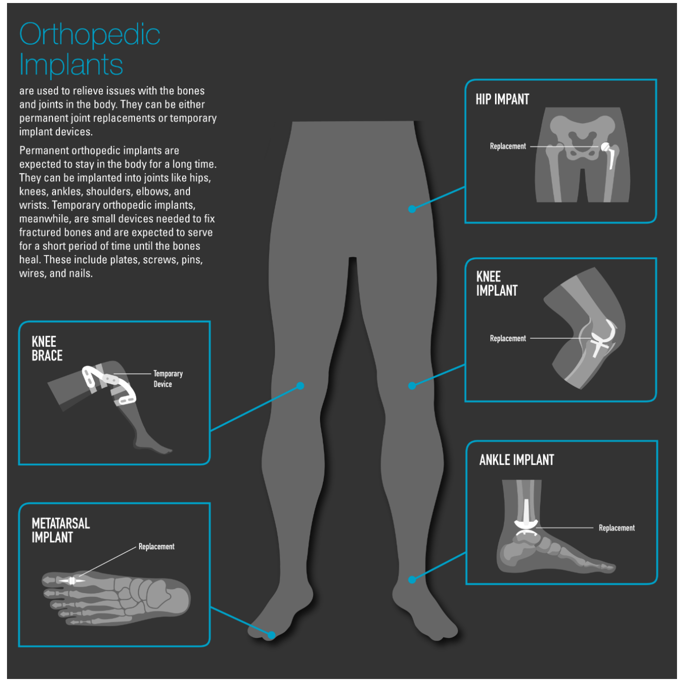
METALS IN MEDICAL IMPLANTS: ORTHOPEDIC

Al (alloys): major element for alloying w Ti for ortopedic appl; ceramics (Al oxides)

Fe (stainless steel): major component stainless steel, fracture fixing plates, bone screws

Cr (Co-Cr-**Mo** alloys): corrosion resistant alloys; Mo impart hardness

Co: orthopedic prostheses for knee, shoulder, hip, fracture-fixing devices



Mg (and alloys): degradable metal implants: bone screws, plates; alloyed w Zn, Al to control degradation rate

Zr (and oxides): hard, resistant to wear, biocompatible; ceramics in joint replacement

Ni (in Ni-Ti alloys): spinal fixation, compression screws, plates, limb-lengthening devices

Ni (in stainless steels): improve pitting corrosion resistance in orthopedic implants

Ti (alloys): improve mech prop, e.g. w Al, V; ability to physically bond w bone

METALS IN MEDICAL IMPLANTS: CARDIOVASCULAR

Cardiovascular Implants

are used in cases where the heart, its valves, and the rest of the circulatory systems are in disorder. These include artificial hearts, artificial heart valves, cardiac pacemakers, implantable cardioverter-defibrillators, and coronary stents.

Cr (and alloys):
used in heart valves [29]

Co (and alloys):
defibrillators; Co-Cr stainless steels used in catheters and stents [30,31]

Ni (Ni-Ti alloys): cardiac implantable devices [36,37,38]

Ti (and alloys):
pacemaker encapsulation [45,46]

Au: good electrical cond, used on electronic circuits, interfaces, implantable pacemakers, defibrillators [32]

Fe (steels):
guidewires, catheters, endovascular grafts [33]

Ta: radio-opacity, used as radiomarker on stents and endovascular grafts [42, 43, 44]

Mg:
degradable metallic stents, alloyed with Al etc to control rate of degradation [35]

Pt:
corrosion resistance, used as lead tips for pacemakers. radiomarkers on stents, catheters, guidewires: improve visibility during cardiovascular procedures (balloon angioplasty or stenting).[39,40,41]

Li (Li-I):
lithium-iodide batteries suitable for implantable peacemakers [34]

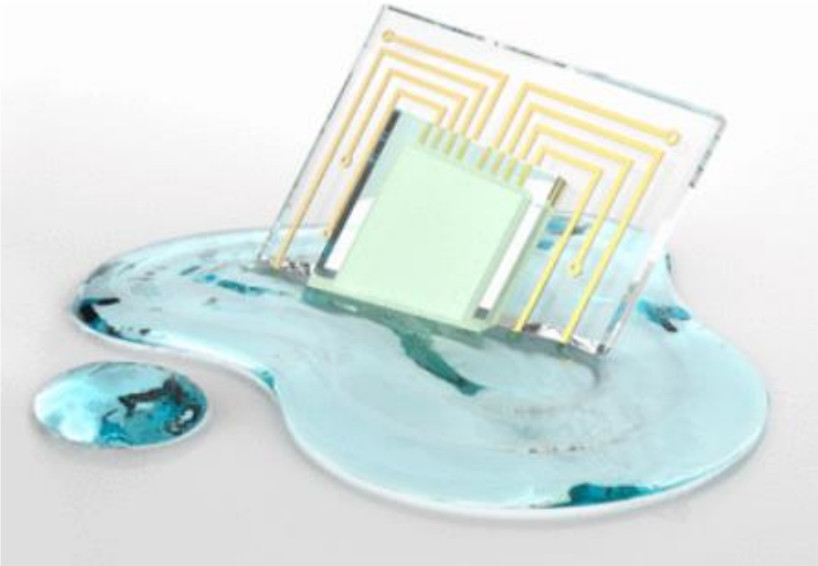
Table 1.1 Biomedical metals and alloys and their primary use in the medical field.[4]

Type	Primary use	FDA Class
Routinely applied materials		
Stainless steels	Temporary fracture plates, screws, hip nails, *etc.*	II
	Total hip replacements	II
Co-based alloys	Total joint replacement	II
	Dentistry castings	II
Ti-based alloys	Stem and cup of total hip replacements with CoCrMo or ceramic femoral heads	II
	Other permanent devices (nails, pacemakers)	III
Emerging FDA approved materials		
NiTi	Orthodontic dental archwires	I
	Vascular stents	III
	Vena cava filter	II
	Intracranial aneurysm clips	II
	Catheter guide wires	II
	Orthopaedic staples	I
Ta	Wire sutures for plastic surgery and neurosurgery	III
	Radiographic markers for diagnostic applications	II
Materials in clinical trials and research		
NiTi	Contractile artificial muscles for an artificial heart	III
Mg	Biodegradable orthopaedic implants	III

O. Bazaka, K. Bazaka, P. Kingshott, R. J. Crawford and E. P. Ivanova, Chapter 1:Metallic Implants for Biomedical Applications , in *The Chemistry of Inorganic Biomaterials*, 2021, pp. 1-98 DOI: 10.1039/9781788019828-00001

TRANSIENT ELECTRONICS

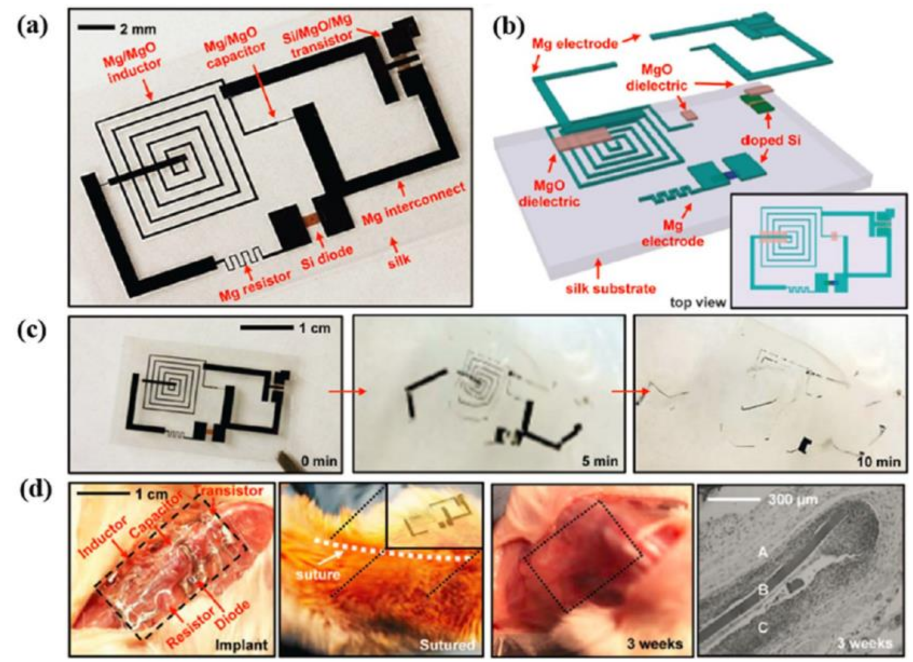
- electronics with the capability of disintegrating or vanishing after stable operation
- materials, devices, and systems to be capable of disappearing with minimal or non-traceable remains over a period of stable operation
- **applications:** intelligence, bioelectronics and environmental monitoring systems, energy harvesters and storage



REVIEW : *Chem. Mater.* 2016, 28, 11, 3527−3539 DOI

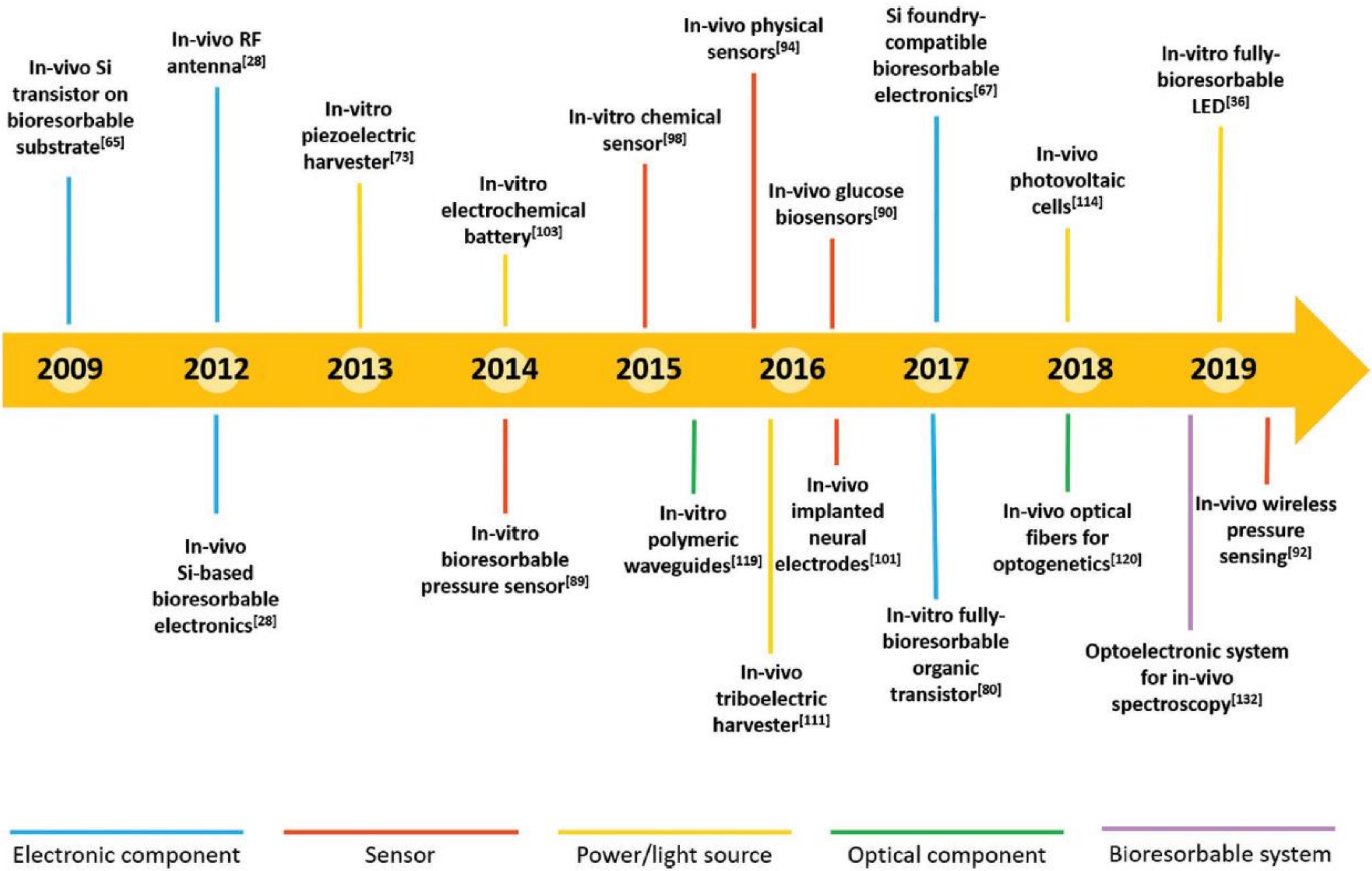
BIORESORBABLE ELECTRONICS

- electrical, optical, and sensing components able to operate in physiological conditions for a prescribed time and then **disappear**
- made of materials that fully dissolve in vivo with biologically benign byproducts upon external stimulation
- GOAL: transient implantable systems interacting with organs, tissues, and biofluids in real-time, retrieve clinical parameters, and provide therapeutic actions tailored to the disease and patient clinical evolution
- biodegrade without the need for device-retrieving surgery that may cause tissue lesion or infection



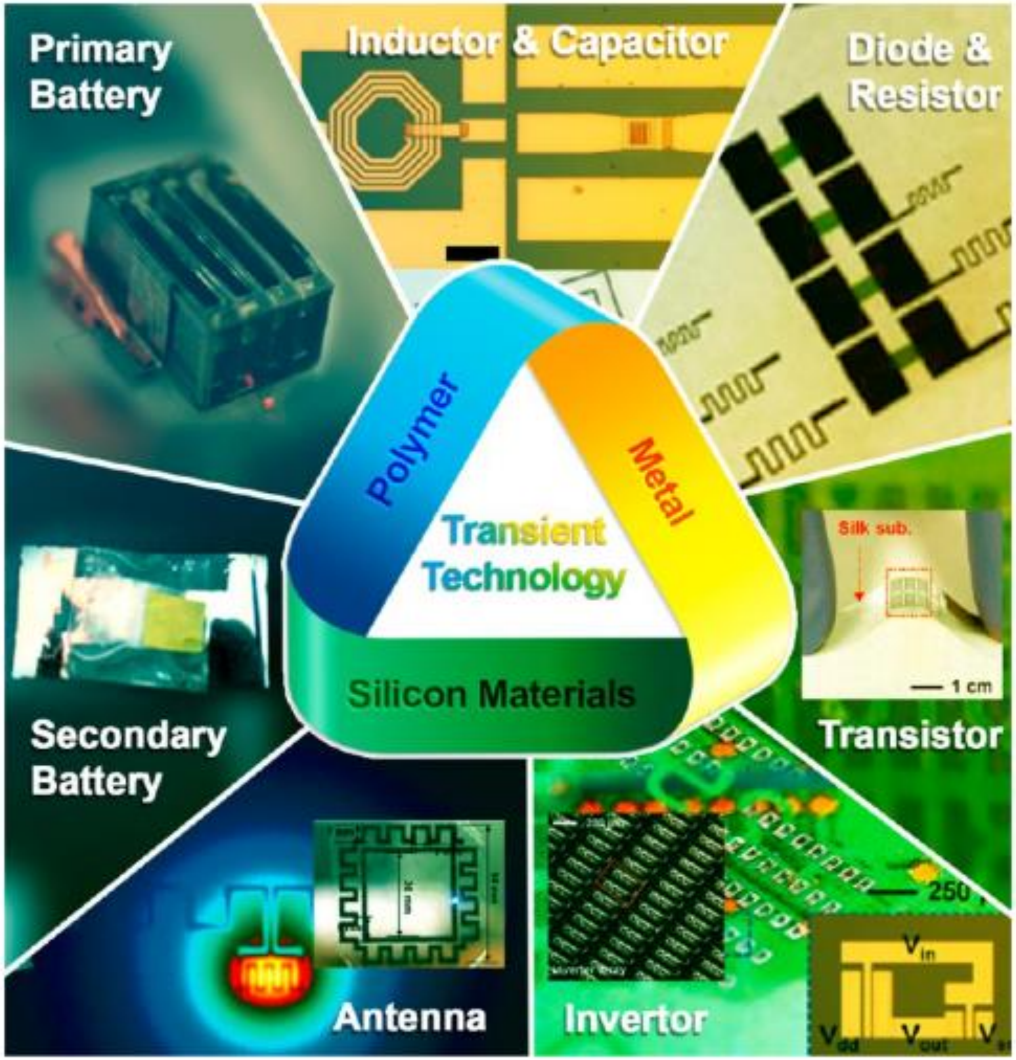
REVIEW *Adv. Sci.* **2020**, *7*, 1902872 DOI: 10.1002/advs.201902872

BIORESORBABLE ELECTRONICS



REVIEW *Adv. Sci.* **2020**, *7*, 1902872 DOI: 10.1002/advs.201902872

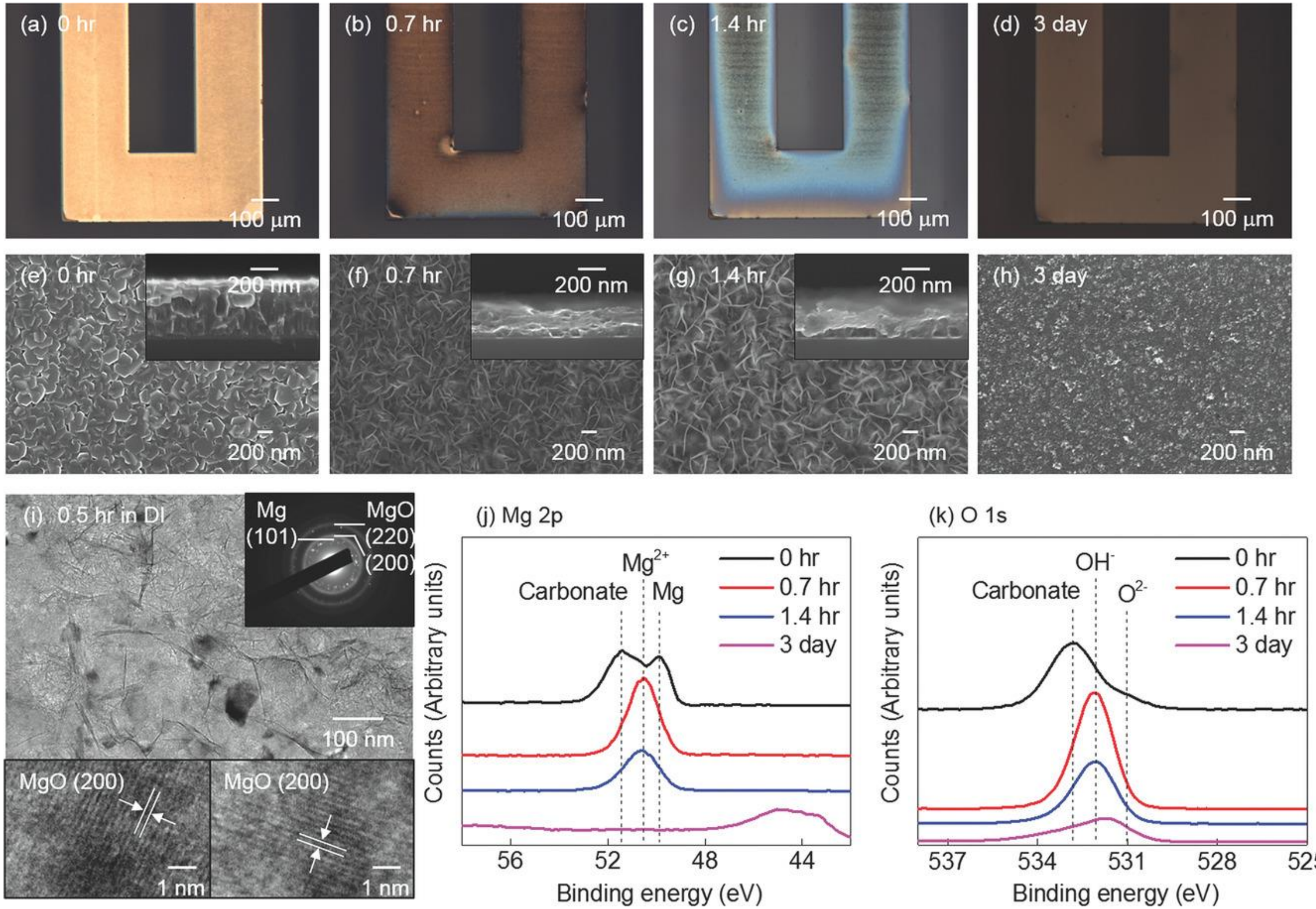
MATERIALS FOR TRANSIENT AND BIORESORBABLE ELECTRONICS



MORE in next Lectures

Chem. Mater. 2016, 28, 11, 3527−3539 [DOI]

Metals in Transient and Bioresorbable Electronics

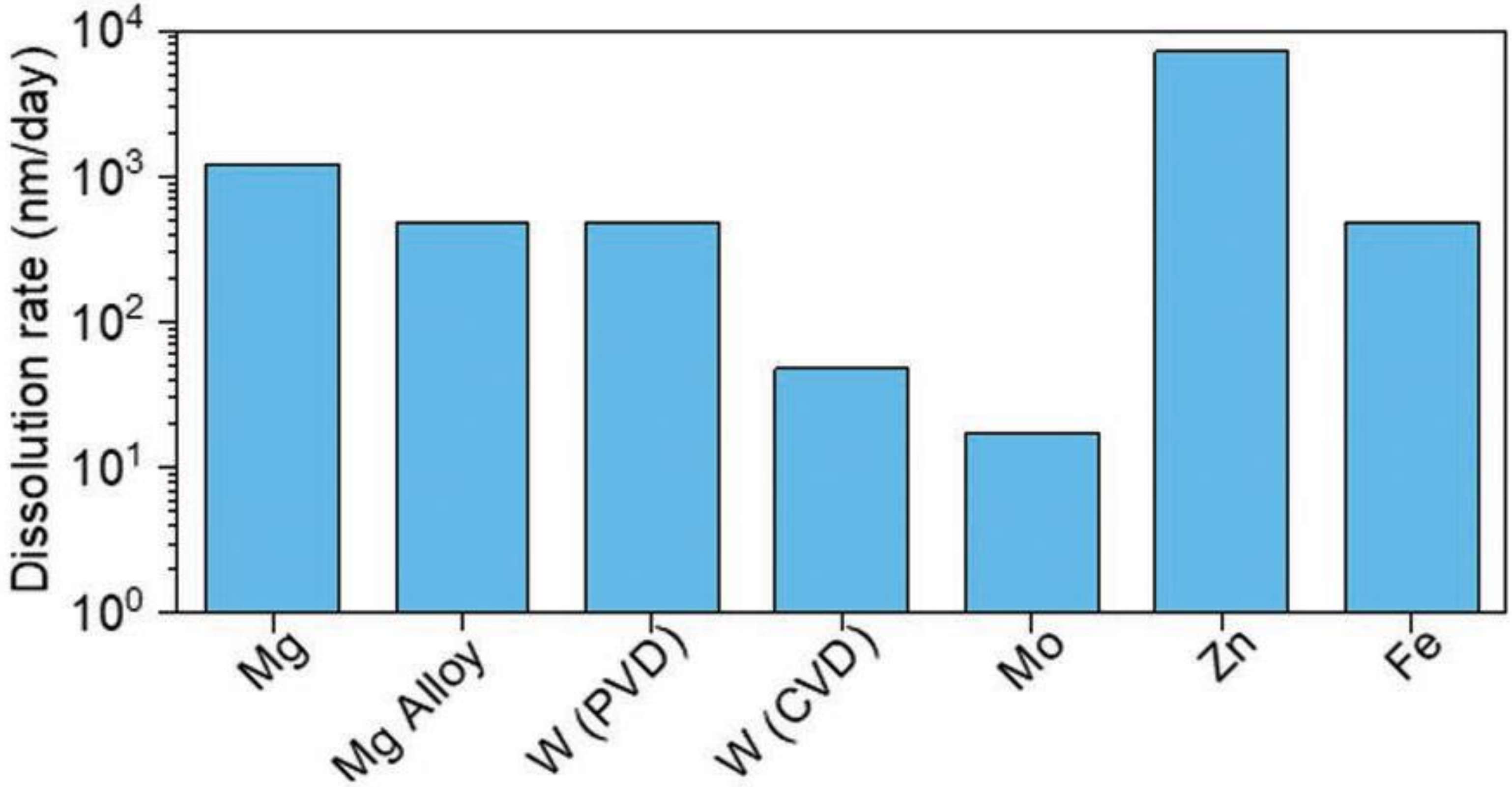


Evolution of microstructure and surface chemistry associated with dissolution of Mg in DI water. a–d) optical images; e–h) SEM images with cross-sectional views in the insets; i) TEM bright field image with diffraction patterns and lattice fringes; j,k) XPS data.

Adv. Funct. Mater., 24: 645-658 (2013). https://doi.org/10.1002/adfm.201301847

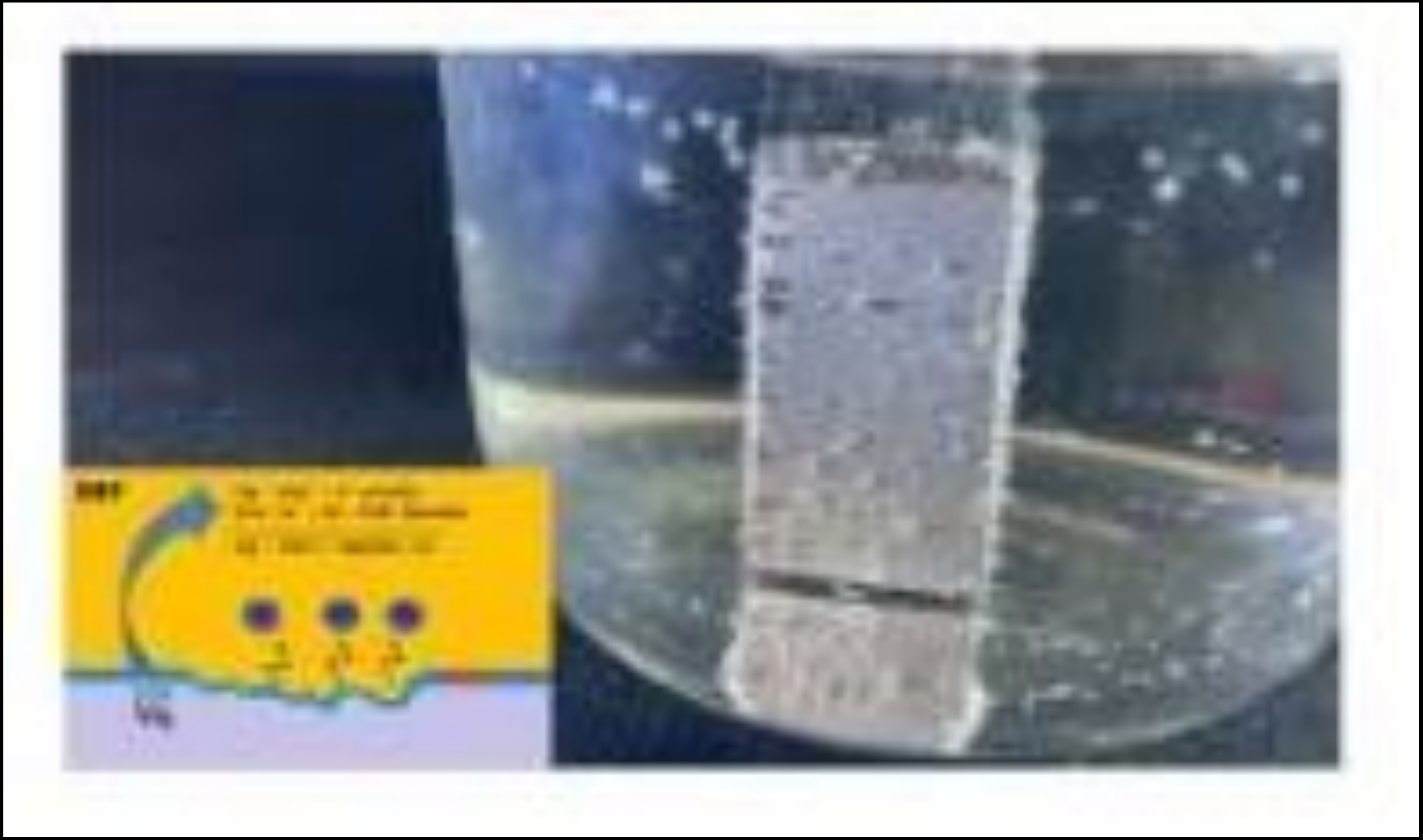
METALS IN TRANSIENT AND BIORESORBABLE ELECTRONICS

Dissolution rates of the principal bioresorbable metals in physiological conditions: pH 7.4, 37°C



REVIEW *Adv. Sci.* **2020**, *7*, 1902872 **DOI: 10.1002/advs.201902872**

Mg Alloys for Bioresorbable devices



YOUTUBE VIDEO (channel «Real Engineering»)

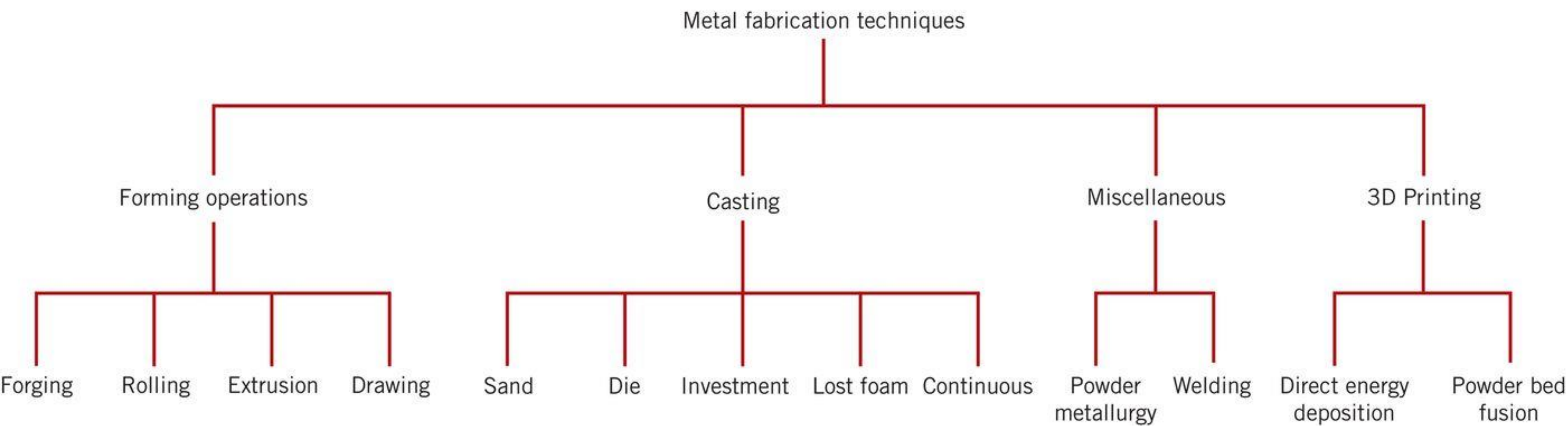
[Magnesium Alloys for Bioresorbable Metallic Devices - YouTube]

(02:01)

L5.6

SHORT NOTES ON METALS FABRICATION

METAL FABRICATION TECHNIQUES



Forming operations

shape of a metal piece is changed by plastic deformation

hot working $T > T_{recryst}$

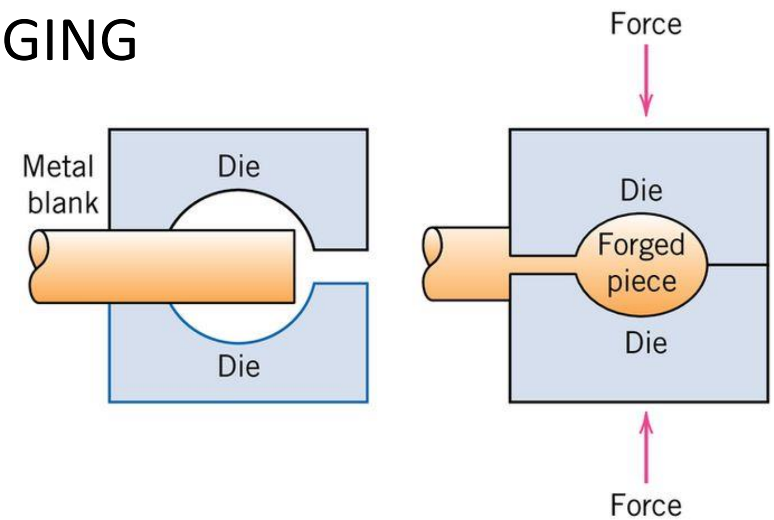
✓ more ductile, larger deformation
X oxidation, worst surface finish

cold working $T < T_{recryst}$

✓ better final resistance, dimension control
X less deformation (less ductility)

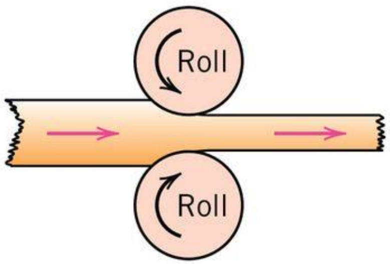
FORMING EXAMPLES

FORGING



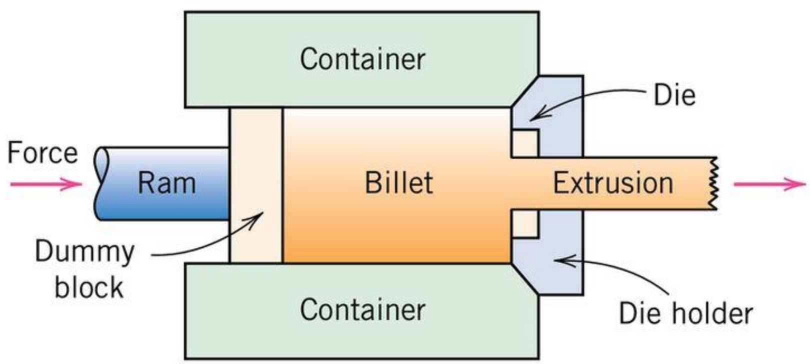
(a)

LAMINATION



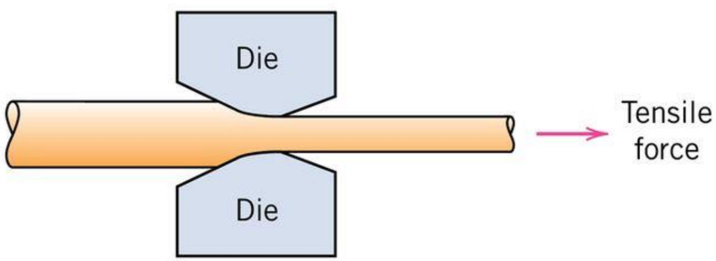
(b)

EXTRUSION



(c)

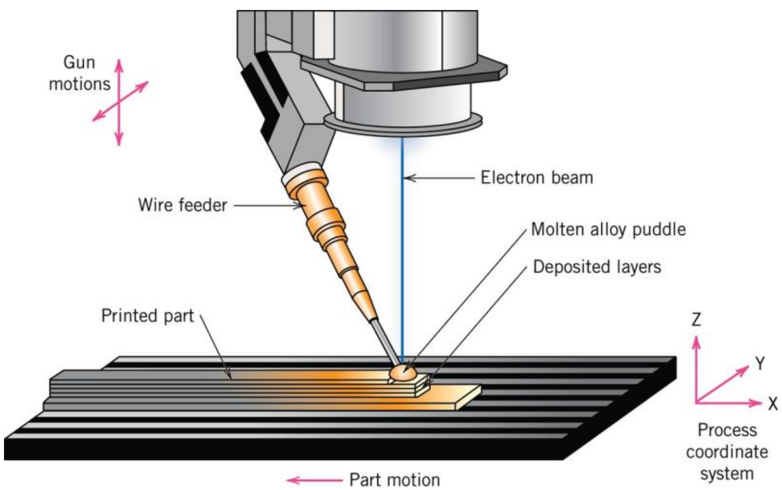
DRAWING

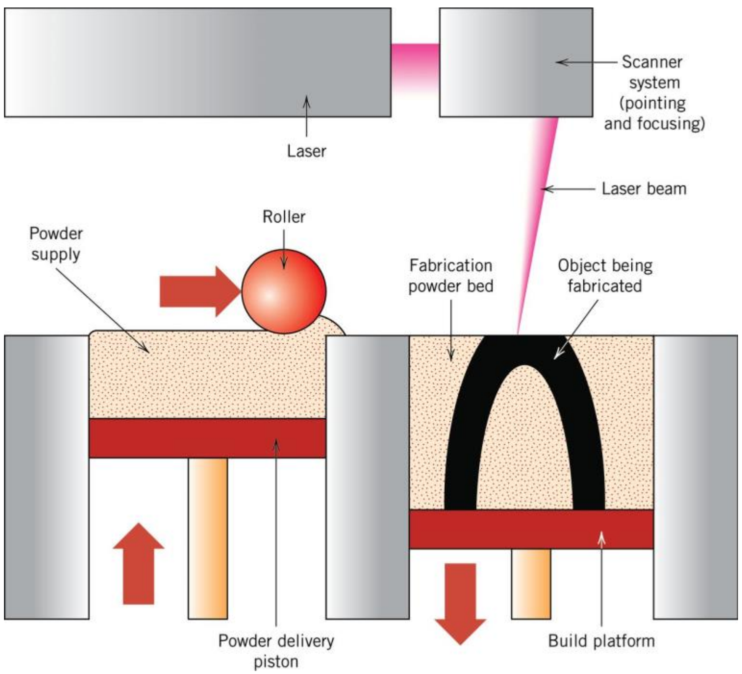


(d)

3D Printing of Metals

more about this (and other 3d printing/additive manufacturing tech) in LESSON 16)



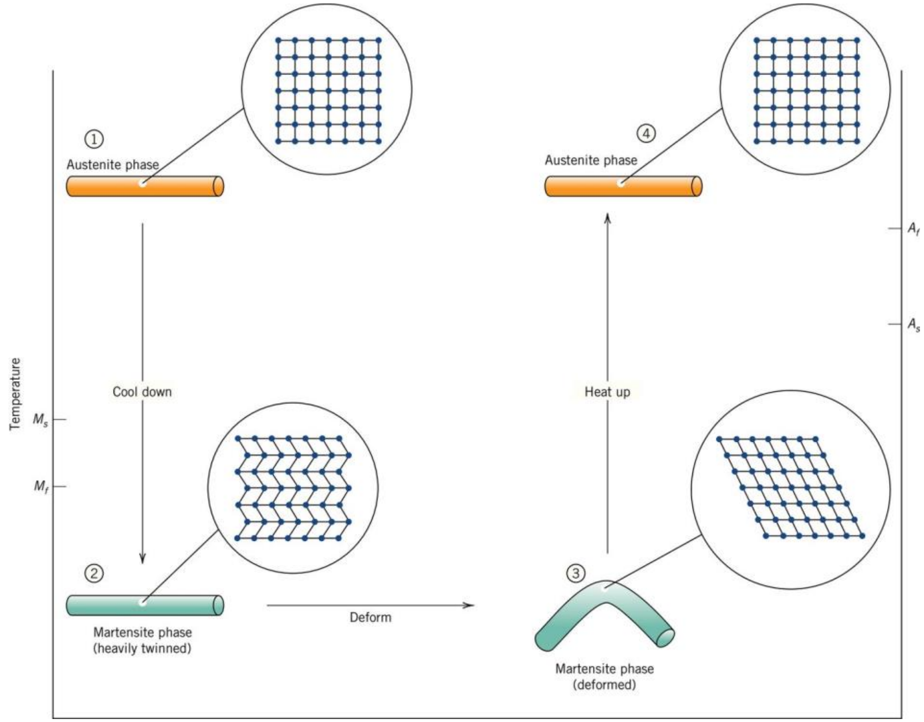


SEMINAR TOPIC	**3D printing of metals and its applications in Bionics**

L5.7

SHAPE MEMORY ALLOYS

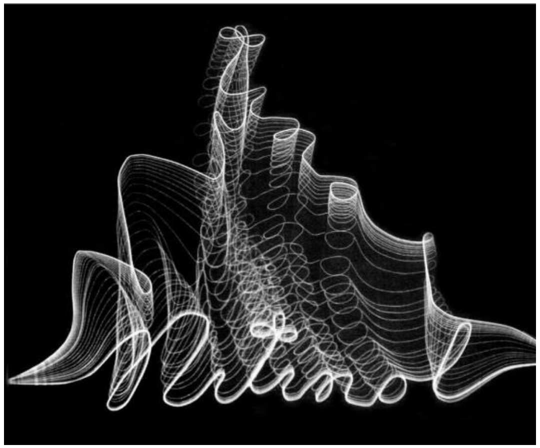
SHAPE MEMORY ALLOYS

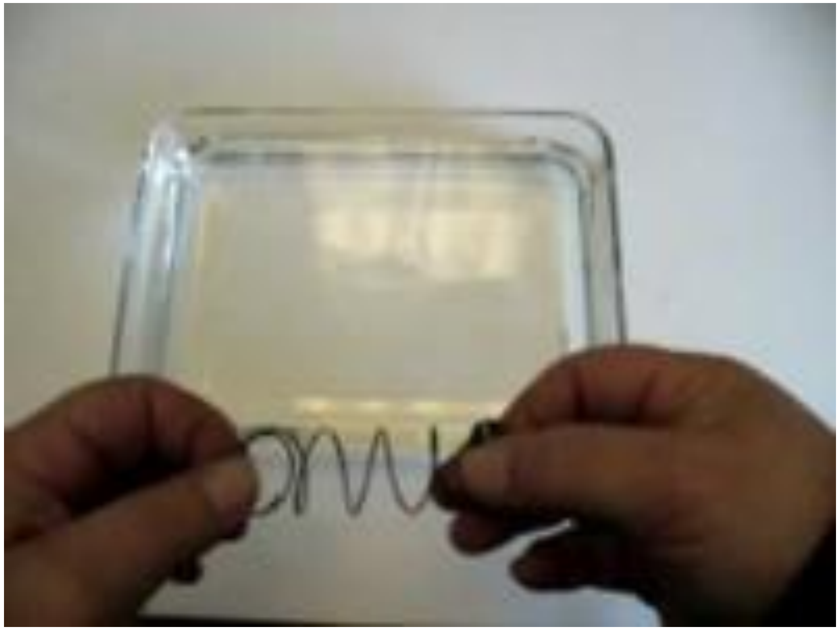


- Ni-Ti alloys

Most Famous: NITINOL

- Cu-Zn-Al alloys
- Cu-Al-Ni alloys

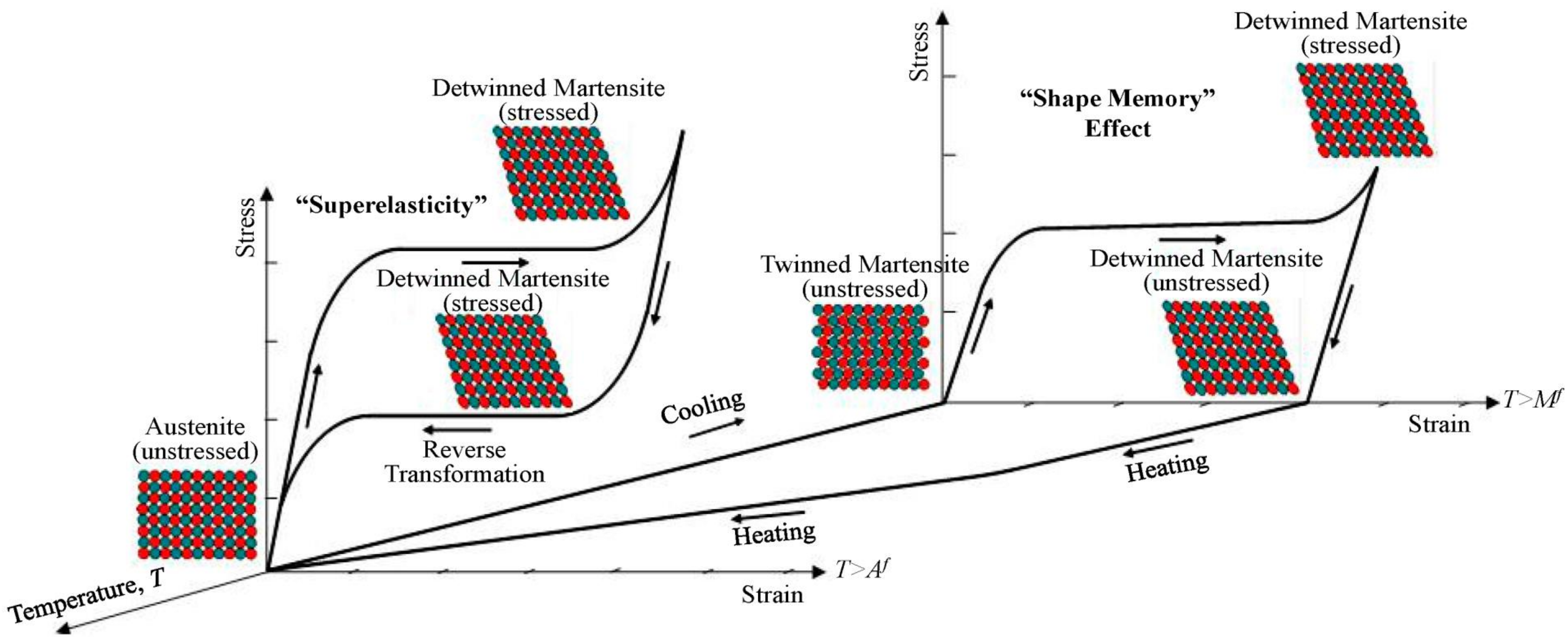




[Nitinol Memory Wire - YouTube]

SHAPE MEMORY ALLOYS

- superelasticity
- shape memory effect



Shape Memory Alloys

YOUTUBE VIDEO (channel «Engineerguy», Prof. B. Hammack Univ Illinois)

Nitinol: The Shape Memory Effect and Superelasticity - YouTube

(09:40)

Shape Memory Alloys

YOUTUBE VIDEO (channel «Real Engineering»)

[How NASA Reinvented The Wheel - Shape Memory Alloys - YouTube]

(09:22)

Shape Memory Alloys

Matteo Cianchetti's course

THE BIOROBOTICS INSTITUTE

Scuola Superiore Sant'Anna

Master of Science in Bionics Engineering

Academic Year 2020-2021

Pisa, November 5, 2020

Materials and instrumentation for bionics engineering

Soft and smart materials

Shape Memory Alloys

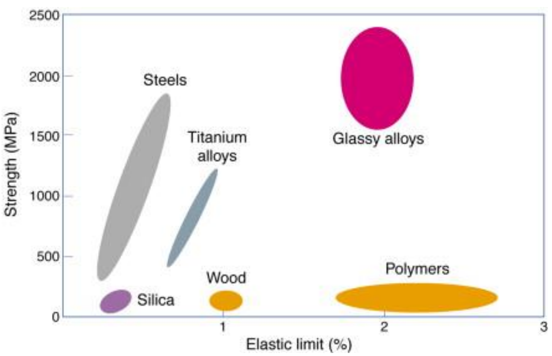
Matteo Cianchetti - matteo.cianchetti@santannapisa.it

L5.8

«STRANGE» ALLOYS?

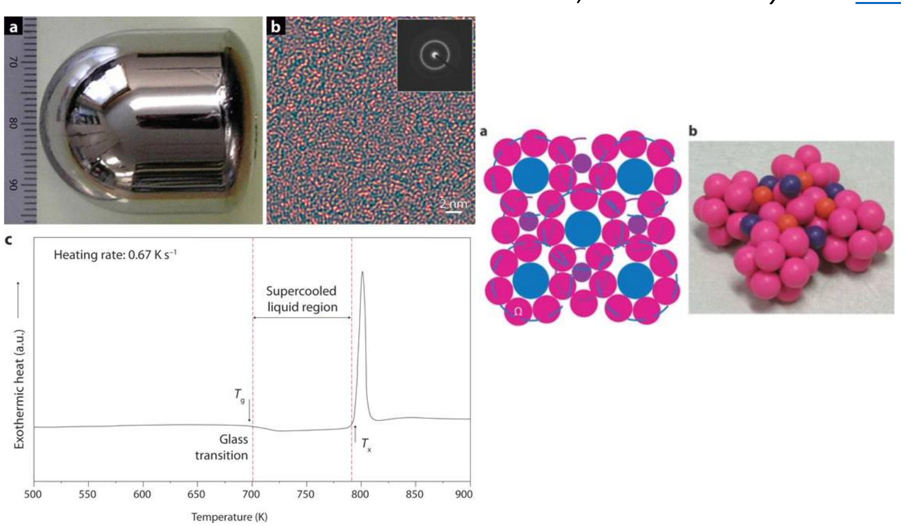
METALLIC GLASSES

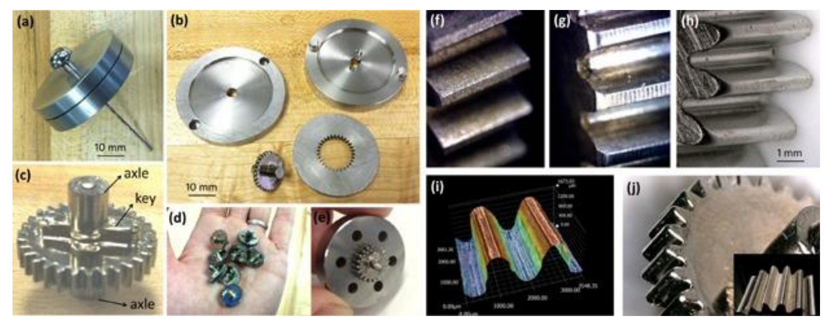
- more on glasses in Section 2 of the course



M. Telford, *Materials Today* **2004** DOI

SEMINAR TOPIC 30	Metallic glasses: current and potential uses

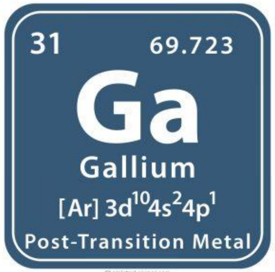


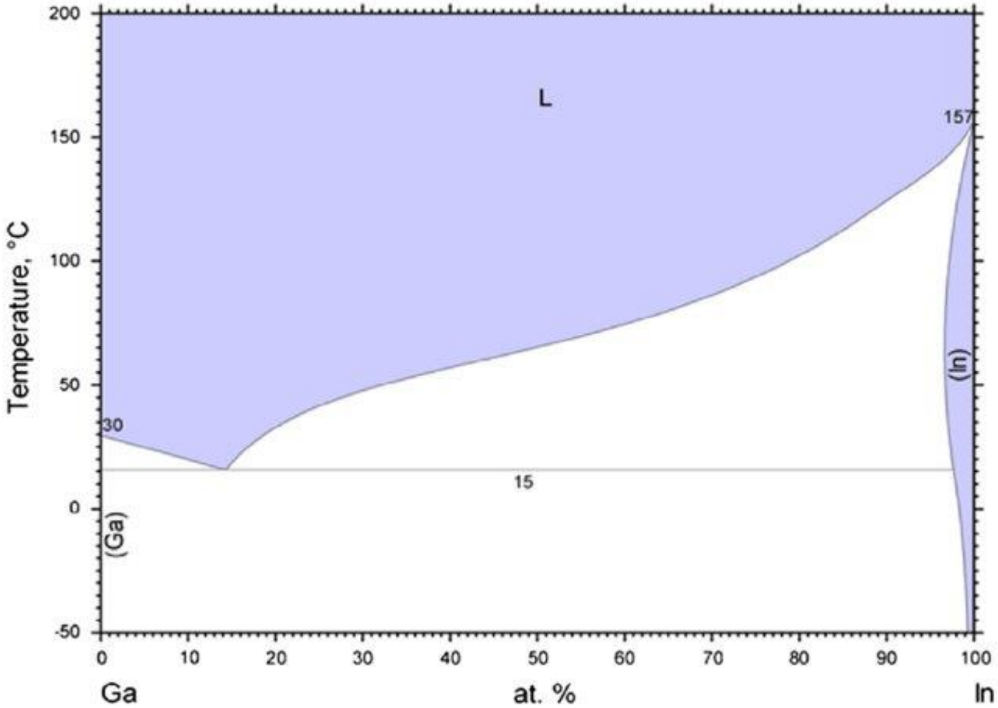


Adv Eng Mater, Volume: 19, Issue: 1, First published: 04 October 2016, DOI: (10.1002/adem.201600541)

Chen, M. A brief overview of bulk metallic glasses. *NPG Asia Mater* **3,** 82–90 (2011). DOI

GA-IN PHASE DIAGRAM





Phase Diagram from [Bo et al. Adv Phys X 2018]

Images: Wikipedia, Chemistry Learner

STRANGE ALLOYS?

YOUTUBE VIDEO -
«Ga-In eutectic alloy”

https://youtu.be/4-ZDDkamfAc

LIQUID METALS

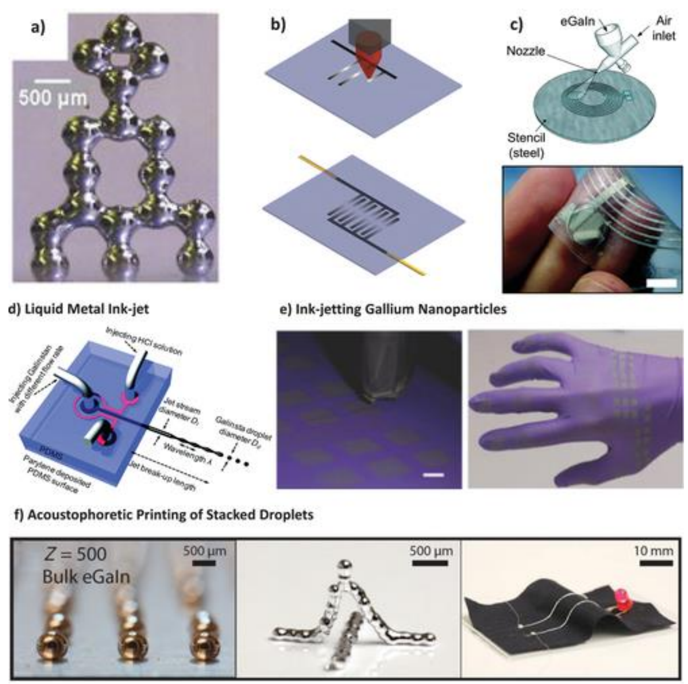
FOR STRETCHABLE ELECTRONICS AND BIONICS

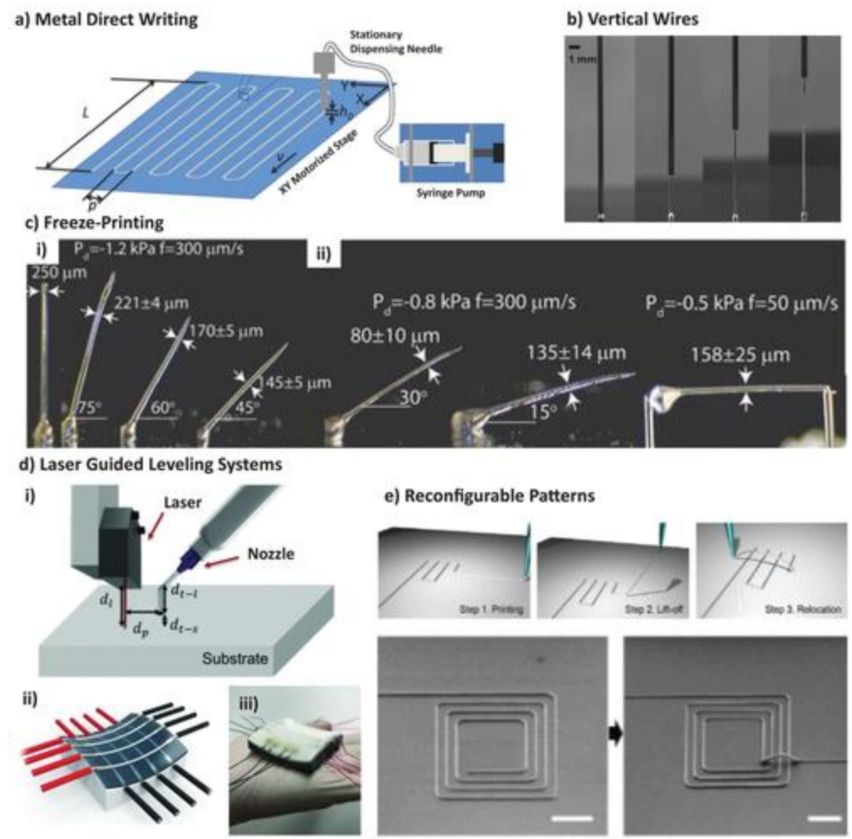
EGaIn: eutectic Ga-In $T_m = 15.7°C$

(75.5 wt. % Ga, 24.5wt. % In)

Galinstan $T_m = -19.0°C$

(68.5 wt. % Ga, 21.5 wt. % In, 10.0 wt. % Sn)



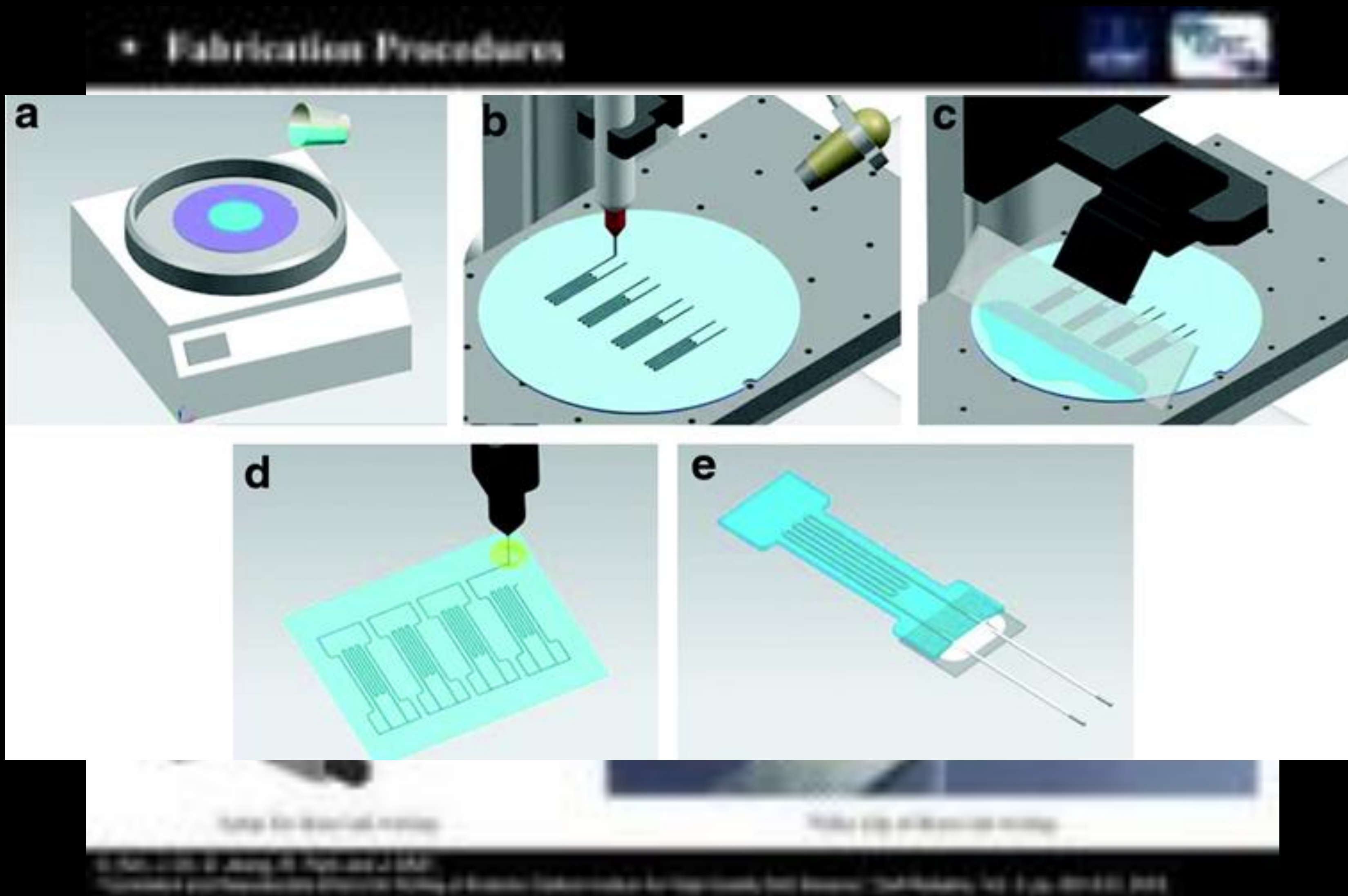


REVIEW PAPER: **Liquid Metal Direct Write and 3D Printing: A Review**

T. V. Neumann, M.J. Dickey Adv Mater Technol. 2020 5, 2000070

https://doi.org/10.1002/admt.202000070

LIQUID METAL BASED SOFT SENSORS



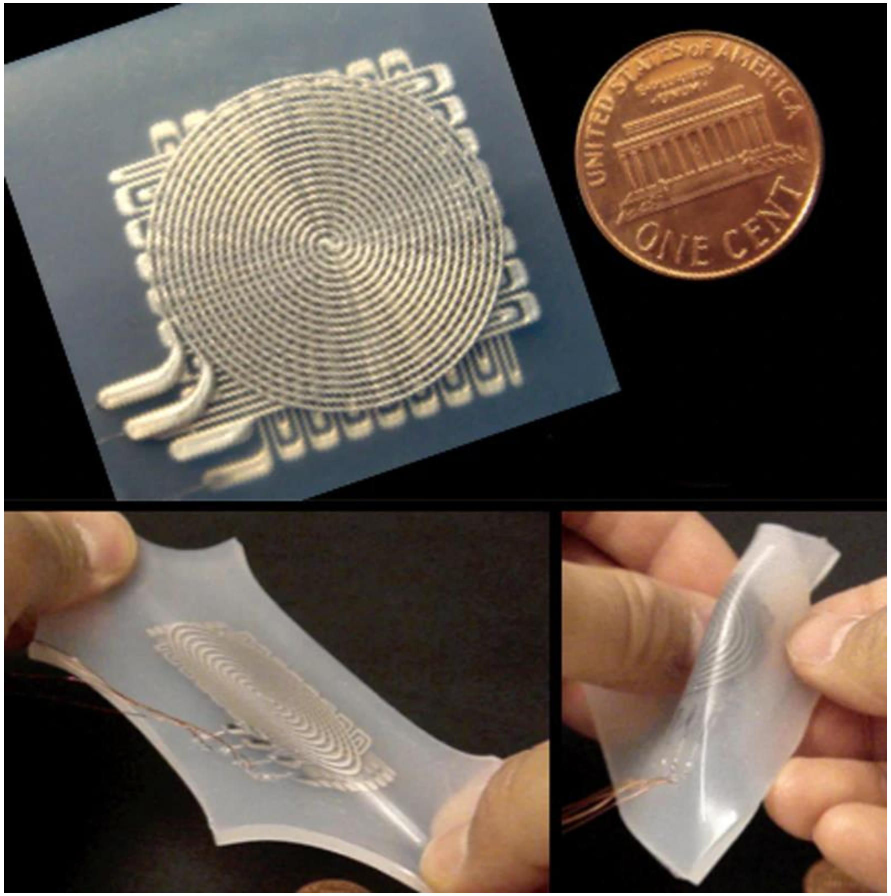
YOUTUBE VIDEO [Direct Ink Writing (DIW) of Eutectic Gallium–Indium (eGaIn) for Soft Sensors - YouTube]

from paper: S. Kim et al. Soft Robotics 2018https://doi.org/10.1089/soro.2017.0103

LIQUID METALS

FOR STRETCHABLE ELECTRONICS AND BIONICS

- embedded in soft elastomers



source: R. Wood, Wyss Institute/Harvard (USA)

[Flexible Embedded Liquid Sensors (harvard.edu)]

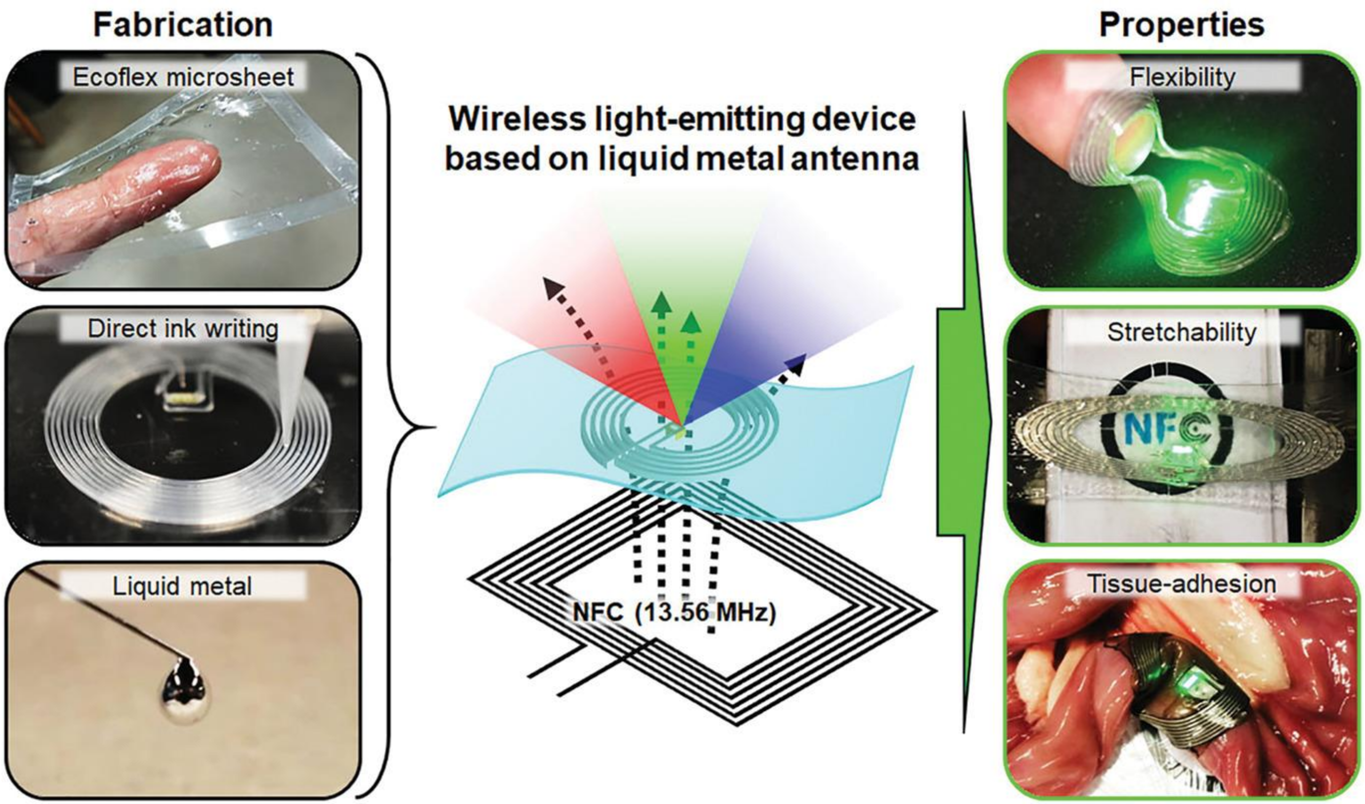
Liquid Metal – Soft Sensor Suit- Harvard

Soft Sensor Suit (1:37)

YOUTUBE VIDEO (Channel Wyss Institute) https://youtu.be/0m5koRcZ4j0

LIQUID METALS
FOR STRETCHABLE ELECTRONICS AND BIONICS

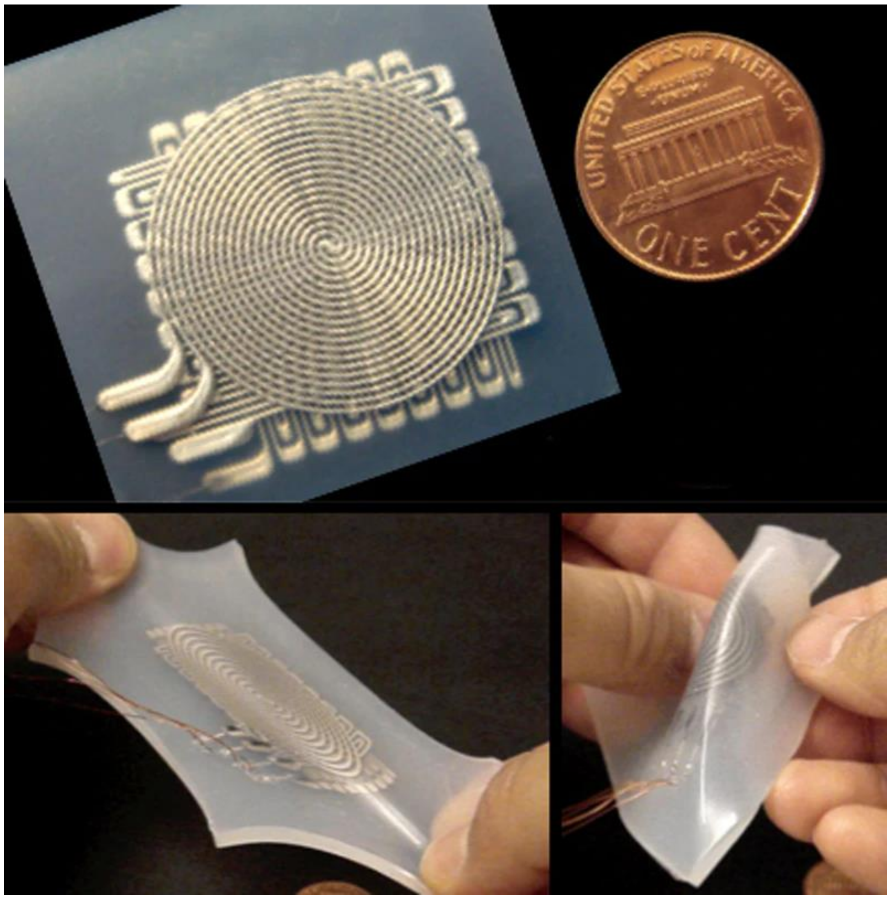
- Ultra-Deformable and Tissue-Adhesive Liquid Metal Antennas with High Wireless Powering Efficiency

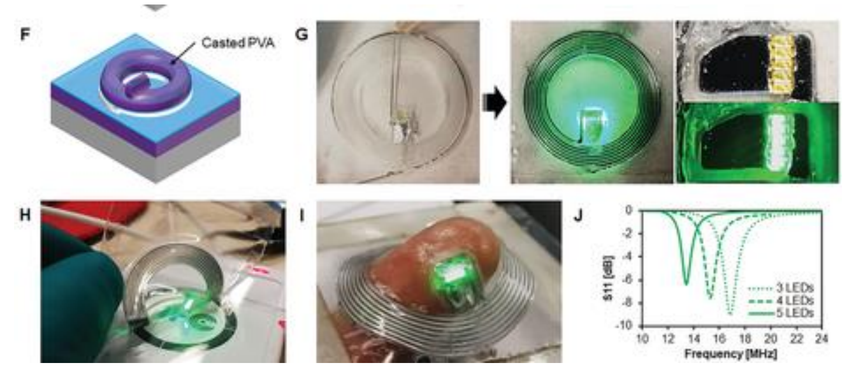


Yamagishi, K. et al. *Adv Mater* **2021** DOI: 10.1002/adma.202008062

LIQUID METALS

FOR STRETCHABLE ELECTRONICS AND BIONICS





SEMINAR TOPIC	LIQUID METALS for Stretchable Electronics and Bionics

Metals-related topics

Seminar?

SEMINAR TOPIC 3	Metal-based NEURAL INTERFACES
SEMINAR TOPIC 30	Metallic glasses: current and potential uses
SEMINAR TOPIC 7	SMA or shape memory polymers in Bionics
SEMINAR TOPIC 31	Metals for Bionic Implants
SEMINAR TOPIC 11	LIQUID METALS for Stretchable Electronics and Bionics
SEMINAR TOPIC 32	Metals for Transient and Bioresorbable Electronics

Summary Questions

- how can metals be classified?
- which crystalline structures are preferred in metals?
- what are the most engineering relevant metals?
- how Fe/Fe_3C phase diagrams look like?
- what's the composition/microstructure of ferrous alloys?
- why stainless steel is not rusting?
- which properties make Al important in applications? and Ti?
- what are noble meatls? why are they called «noble»?
- what are SMA? what is shape memory effect? what is superelasticity?
- why some alloys can be liquid metals at RT? why interesting for bionics?

SUMMARY L5

ADDITIONAL RESOURCES, READINGS

YOUTUBE VIDEOS:

- The Efficient Engineer Channel – «Understanding Metals»
- B. Hammack - Nitinol: The Shape Memory Effect and Superelasticity
- Real Engineering channel – How NASA reinvented the wheel - SMA

READINGS:

- Callister, Rethwisch – selected parts of Chapters 7,9,10, 11

NOBLE METALS

YOUTUBE VIDEO – Periodic Videos channel (7:43)

[Super Expensive Metals - Periodic Table of Videos - YouTube]

NITINOL

YOUTUBE VIDEO - (6:12)

[How a metal with a memory will shape our future on Mars - YouTube]

Ti in Medical Implants

YOUTUBE VIDEO -
”Titanium Implants- Nickel MCV”

[Titanium Implants- Nickel MCV - YouTube]

Literature about Metal Implants

Citations:
1.Al Jabbari, Y. S., 2014, Physico-mechanical properties and prosthodontic applications of Co-Cr dental alloys: a review of the literature: The Journal of Advanced Prosthodontics, v. 6, no. 2, p. 138–145, accessed October 16, 2020, at https://doi.org/10.4047/jap.2014.6.2.138.
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3.B. Kempf, and J. Haußelt, 1992, Gold, its Alloys and their Uses in Dentistry: Interdisciplinary Science Reviews, v. 17, no. 3, p. 251-260, accessed October 16, 2020, at https://doi.org/10.1179/030801892791925457.
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9.Sahwil, H., 2017, Best Materials for Dental Implants, DDS Lab, accessed October 16, 2020, at https://blog.ddslab.com/best-materials-for-dental-implants.
10.Saini, M., Singh, Y., Arora, P., Arora, V., and Jain, K., 2015, Implant biomaterials: A comprehensive review: World Journal of Clinical Cases, v. 3, no. 1, p. 52–57, accessed October 16, 2020, at https://doi.org/10.12998/wjcc.v3.i1.52.
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12.Mehrali, M., Bagherifard, S., Akbari, M., Thakur, A., Mirani, B., Mehrali, M., Hasany, M., Orive, G., Das, P., Emneus, J., Andresen, T. L., and Dolatshahi-Pirouz, A., 2018, Blending Electronics with the Human Body: A Pathway toward a Cybernetic Future: Advanced Science, v. 5, no. 10, p. 1-39, accessed October 16, 2020, at https://doi.org/10.1002/advs.201700931.
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14.Bock, D. C., Marschilok, A. C., Takeuchi, K. J., and Takeuchi, E. S., 2012, Batteries used to Power Implantable Biomedical Devices: Electrochimica Acta, v. 84, p. 155-164, accessed October 16, 2020, at https://doi.org/10.1016/j.electacta.2012.03.057.
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ADDITIONAL SLIDES

Cast Irons

italian: «ghise»

Ferrous alloys with > 2.1 wt% C

- more commonly 3 - 4.5 wt% C

Low melting– relatively easy to cast   Tm = 1150-1300°C

Generally brittle

Cementite decomposes to ferrite + graphite

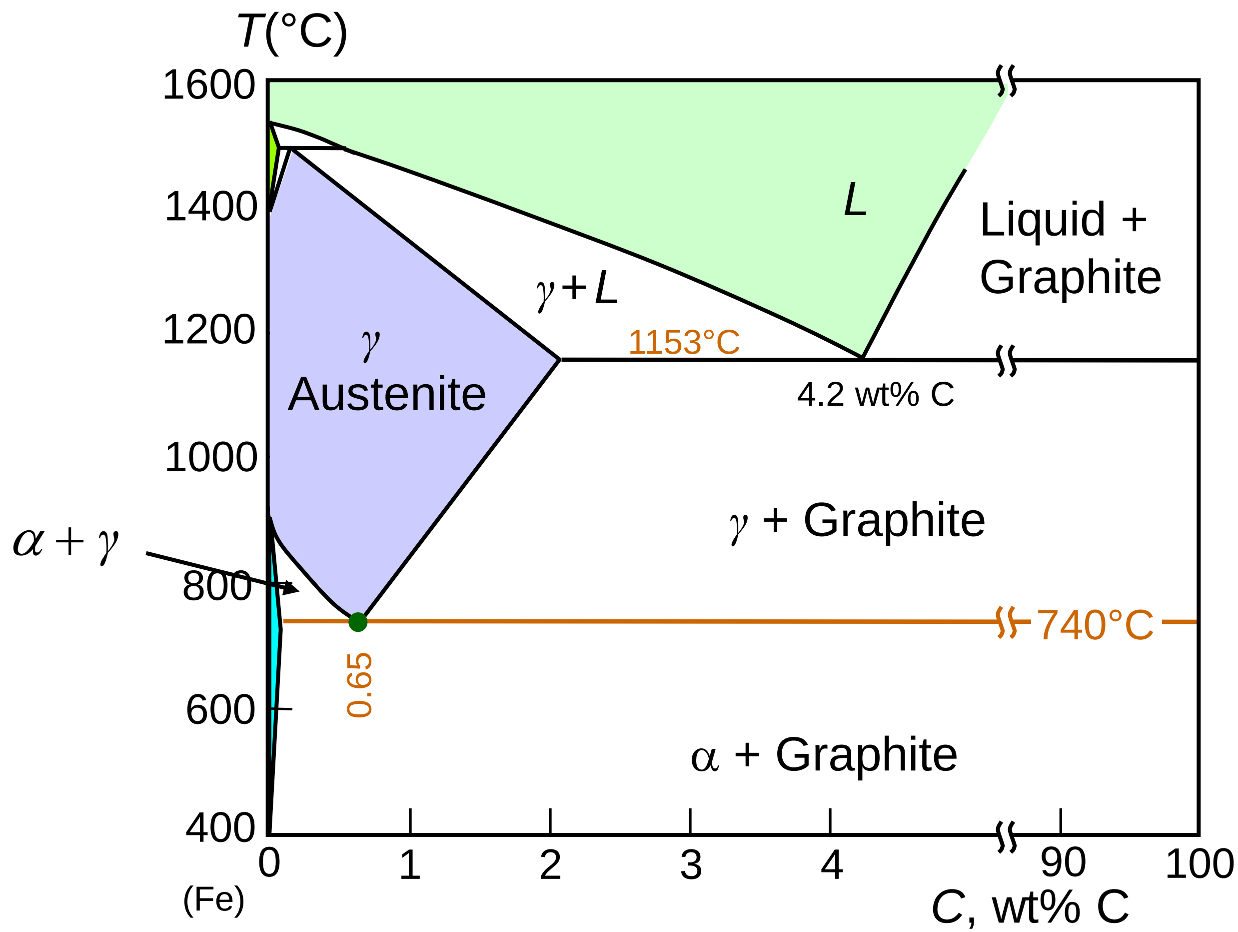
$Fe_3C \rightarrow 3\ Fe\ (\alpha) + C\ (graphite)$

- generally a slow process

Fe-C TRUE EQUILIBRIUM DIAGRAM

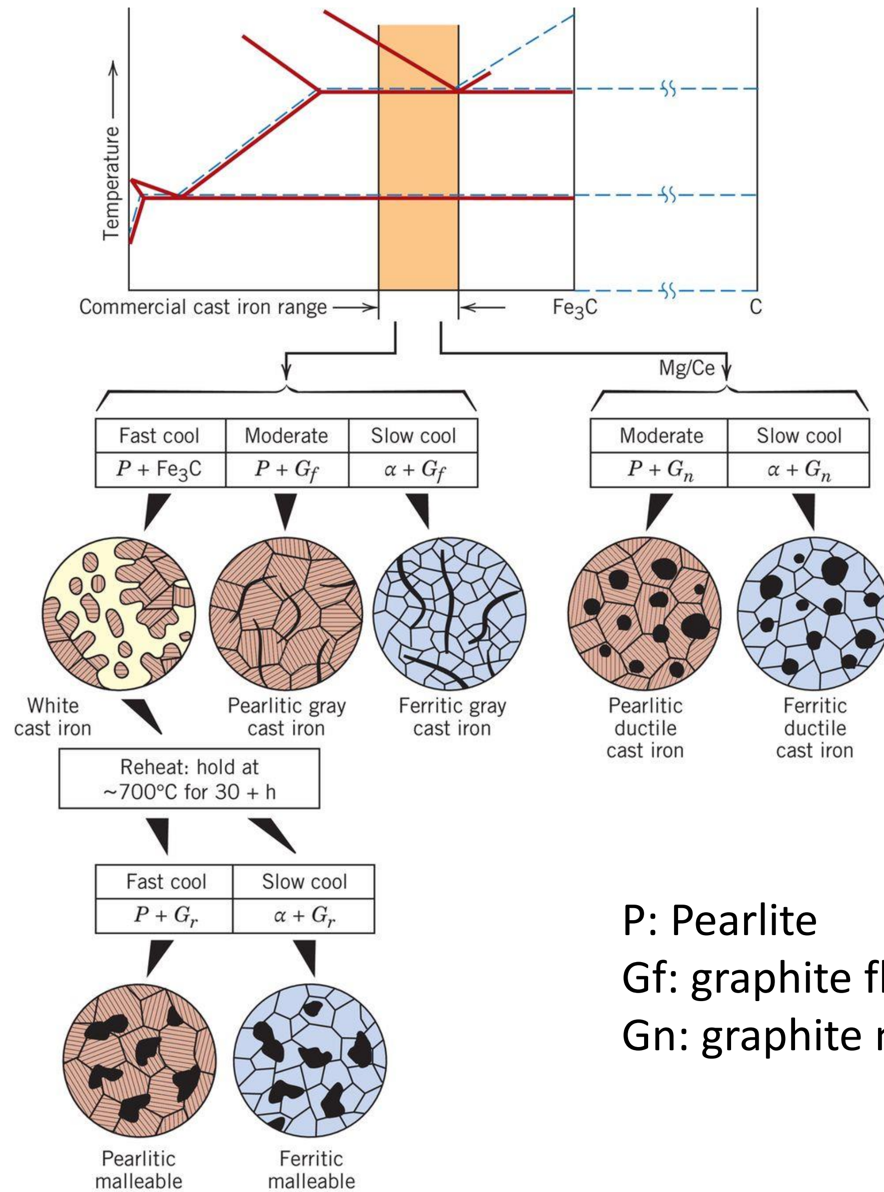
Graphite formation promoted by

- Si > 1 wt%
- slow cooling



TYPES OF CAST IRONS

- Gray Iron
- Nodular Iron
- White Iron
- Malleable Iron
- Compacted Graphite Iron



Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, John Wiley & Sons, 1964. Reproduced with permission of Janet M. Moffatt.

P: Pearlite
Gf: graphite flake
Gn: graphite nodules

TYPES OF CAST IRON

Gray iron

C: 2.5 – 4.0 wt.%

Si: 1.0 -3.0 wt.%

- **graphite flakes** surrounded by

an α-ferrite or pearlite matrix

- weak & brittle in tension, stronger in compression
- excellent vibrational dampening
- wear resistant
- high fluidity @casting temperature: casting w intrinticate shapes
- least expensive metallic materials

Figs. 11.3(a*Callister & Rethwisch 10e.*

USE: Base structures for machines, equipment exposed to vibrations.

Types of Cast Iron

Figs. 11.3(b*Callister & Rethwisch 10e.*

Ductile (or Nodular) Iron

add Mg, Ce

- **graphite nodules** surrounded by

an α-ferrite or pearlite matrix

- more strong and ductile than gray
- TS 350-480MPa
- Ductility: 10-20% elongation
- mechanical characteristics approaching those of steel

(b)

USE: valves, pump bodies, crankshafts, gears, and other automotive and machine components.

Types of Cast Iron

Figs. 11.3(b*Callister & Rethwisch 10e.*

(c)

White Iron

< 1 wt% Si, rapid cooling

- **C as Fe3C cementite (and not graphite)** in a pearlite matrix
- extremely hard
- very brittle
- unmachinable
- intermediate for malleable irons (see next)

USE: hard, wear-resistant surface components like rollers in rolling mills.

Types of Cast Iron

Figs. 11.3(d*Callister & Rethwisch 10e.*

Malleable Iron

heating white iron at 800 - 900° C

in inert atmosphere (prevent oxidation)

Fe_3C converted into graphite

- **graphite rosettes/clusters** in a pearlite or ferrite matrix
- high strength
- ductile

USE: rods, transmission gears, etc. for automotive industry, flanges, pipe fittings, valve parts for railroad, marine, heavy-duty services.

Types of Cast Iron

Figs. 11.3(e*Callister & Rethwisch 10e.*

Compacted Graphite Iron (CGI)

Si: 1.7 – 3.0 wt%, promotes graphite formation

- **C as graphite** in a pearlite matrix
- relatively high thermal conductivity
- good resistance to thermal shock
- lower oxidation at elevated temperatures

USE: hard, wear-resistant surface components like rollers in rolling mills.