Metallurgy of Low Carbon Steel And Potential for A Passivated Magnetite Layer

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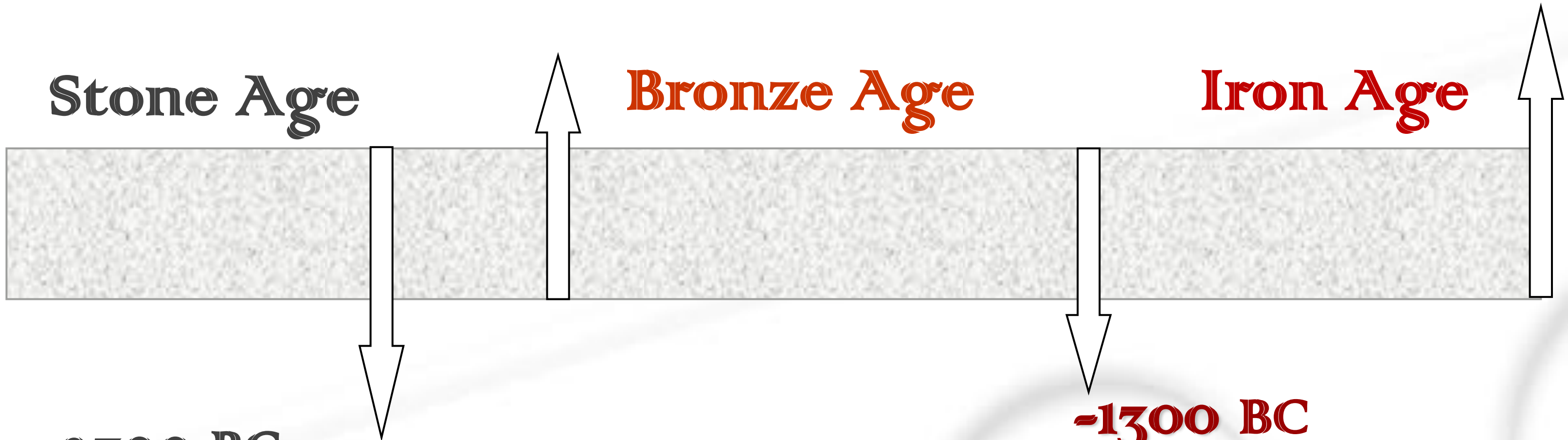
Agenda

- History of Steel
- Crystallography of Ferrous Alloys
- Microstructures of Carbon and Stainless Steel
- Comparison of Steel Grades
- Welding Carbon Steel to Stainless Steel
- Properties of Magnetite
- Potential for a Magnetite Passive Layer

Historic Metallurgy



9300 BC

Advent of metalworking ended roughly 3.4 million year Stone Age where stone widely used to make implements with a sharp edge or point.

3300 BC

Innovation of the technique of smelting ore

-1300 BC

Start of iron metallurgy and utilization of iron objects. Developing implements and weapons that are hammered into shape

700 AD

Widespread use of iron or steel coinciding with other changes in society, including differing agricultural practices, religious beliefs and artistic styles

What is Steel?

Steel is an alloy of iron and carbon.

Additional elements may also present naturally: manganese, phosphorus, sulfur, silicon, and traces of oxygen, nitrogen and aluminum.

Additional alloying elements sometimes added: nickel, chromium, molybdenum, boron, titanium, vanadium and niobium.

Steelmaking Process (Controlling carbon and oxygen)

- Iron extracted from iron ore
  - Blast furnace coke (carbon) used as reducing agent to reduce Fe_2O_3 to pig iron
  - $Fe_2O_3 + 3CO$ --- $2Fe + 3CO_2$
  - Pig iron contains about 4% carbon along with impurities
- Converting pig iron to steel (1855)
  - Pig iron and <30% steel scrap are charged into barrel-shaped refractory-lined converter
  - Pure oxygen is lanced into liquid metal to form iron oxide $Fe + O_2$ --- FeO
  - Carbon in the steel reacts with iron oxide to form iron and carbon monoxide

$FeO + C$ --- $Fe + CO$

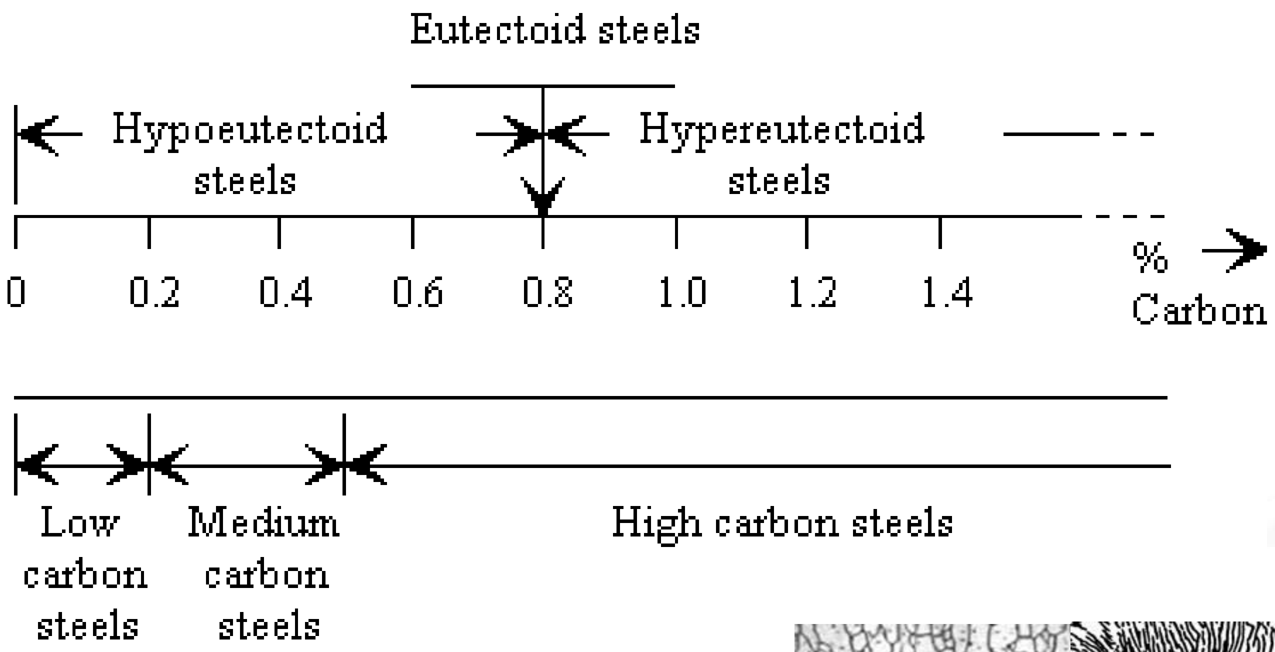
Slag-forming fluxes (lime) are added

Carbon drastically reduced along with impurities (S, P)

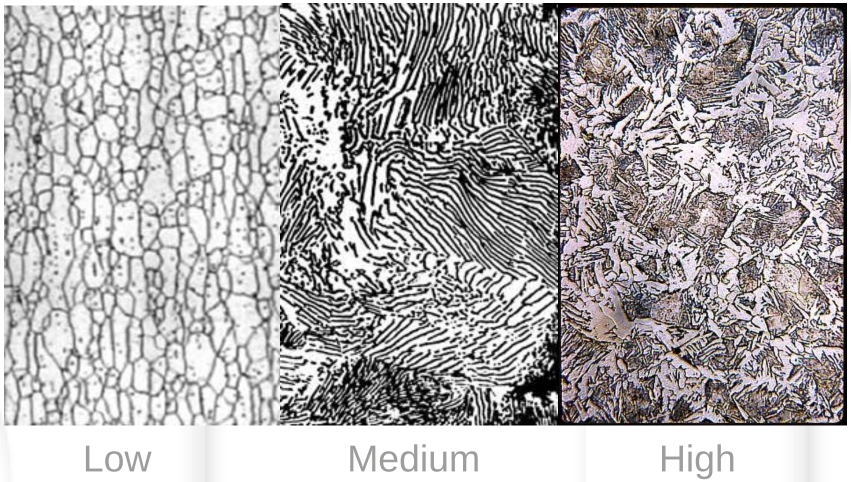
Molten steel cast into slabs, billets or blooms

Ref. Smith, Principles of Mat. Sci. & Eng.

Percent Carbon in Steel

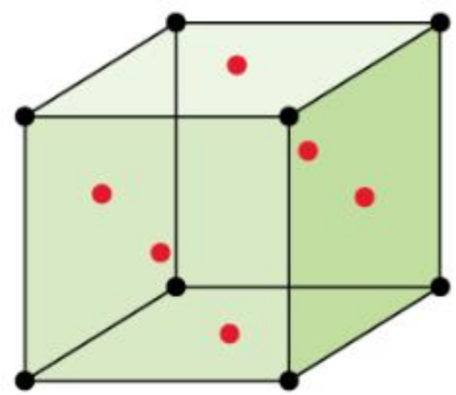


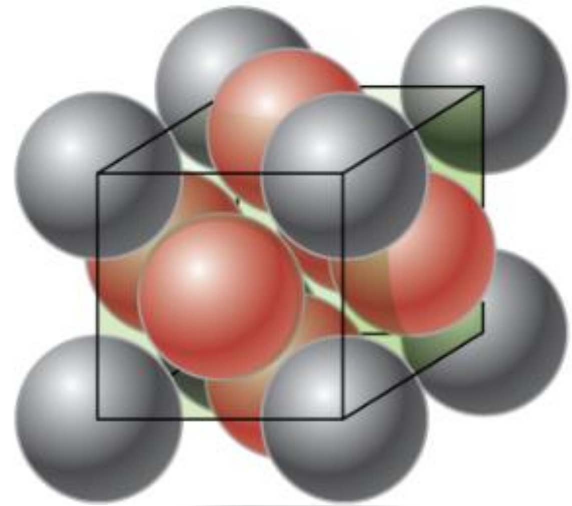
Ref. Henkel and Pense



γ Austenitic Iron
Face-Centered Cubic (FCC)

- Close-packed structure
- Carbon diffusivity 2x10^{-5} m^2/s
- 2.08% at 1148^{o}C; decreases to 0.83% at 723^{o}C





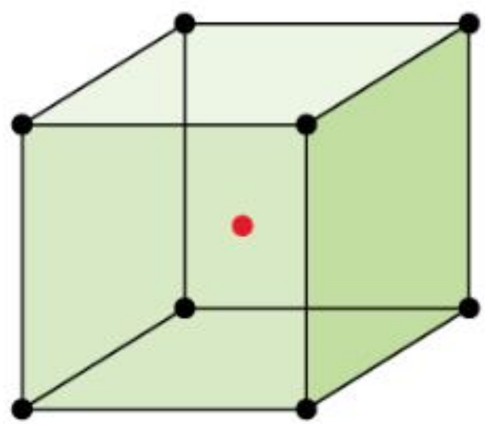
Packing fraction is 74%. So, the void space in the unit cell will be (100-74) = 26%.

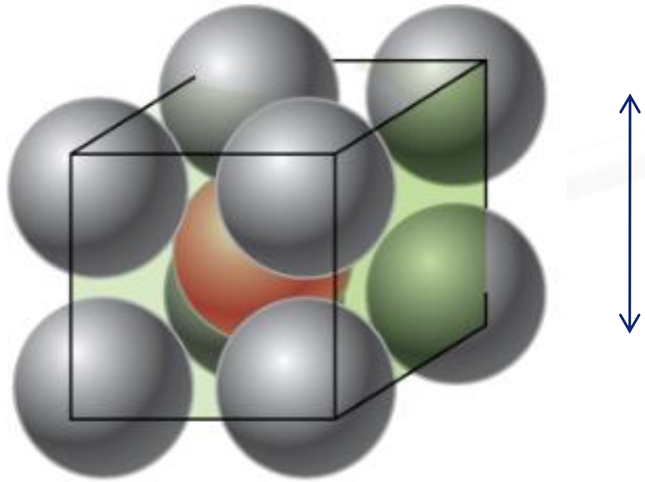
Ref. Henkel and Pense

α Ferritic Iron

Body-Centered Cubic (BCC)

- Not a close-packed structure
- Carbon diffusivity 22×10^{-5} m^2/s
- Carbon solubility 0.02% at 723°C; decreases to 0.005% at 0°C

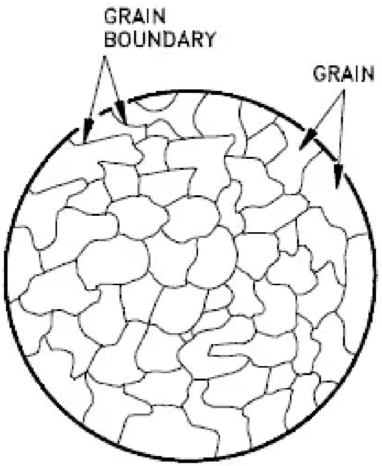


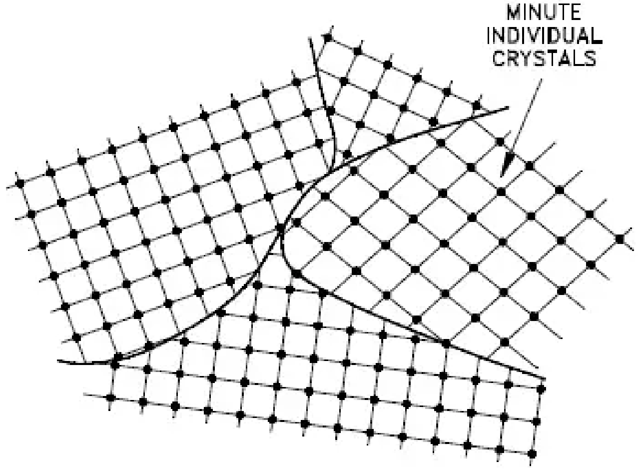


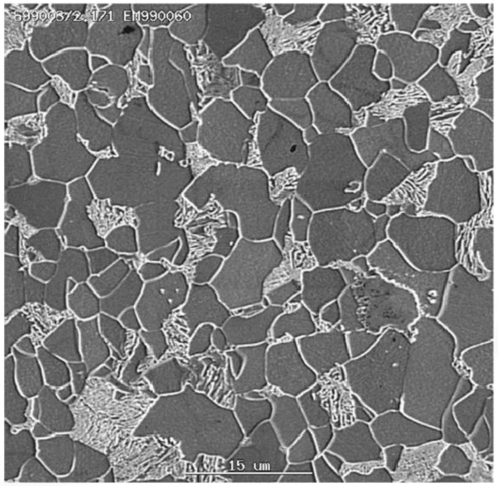
Packing fraction is 68%. So, the void space in the unit cell will be (100-68) = 32%.

Ref. Henkel and Pense

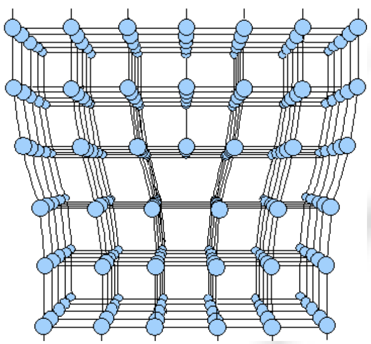
Microstructure discovered in late 1800's

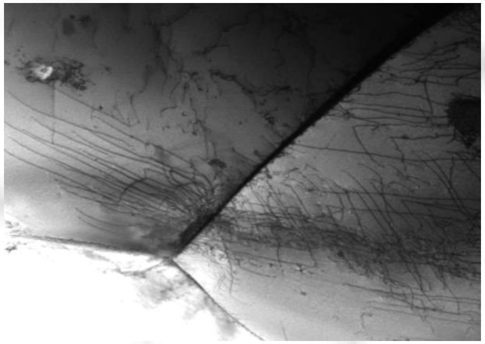






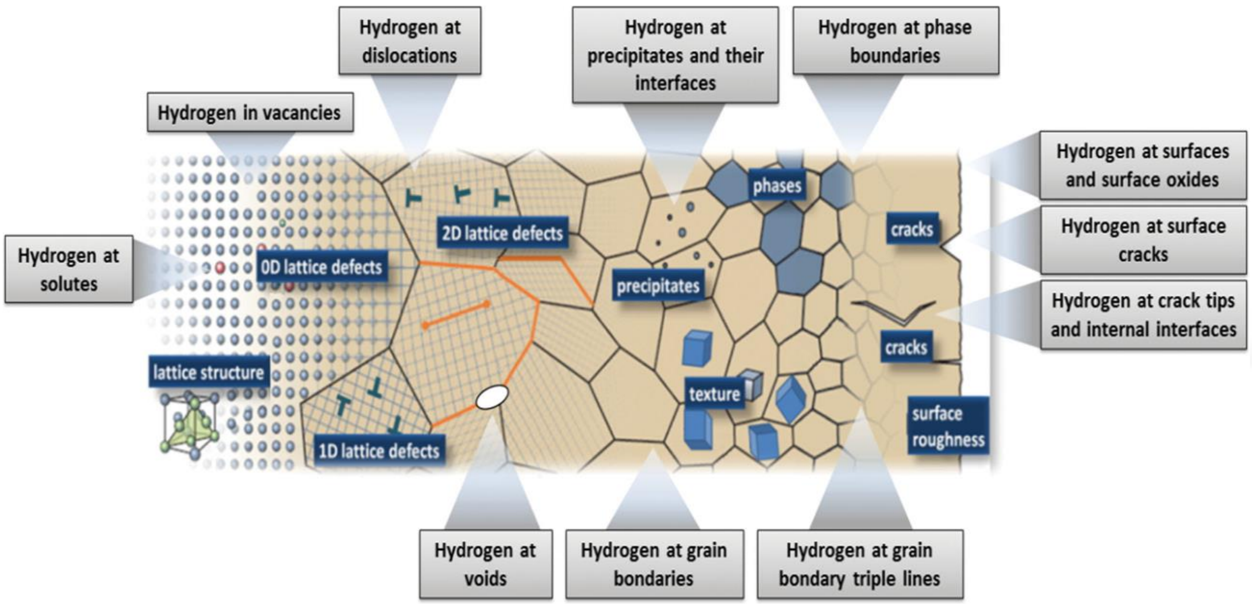
Dislocations discovered in early 1960's





Ref. RWK Honeycombe

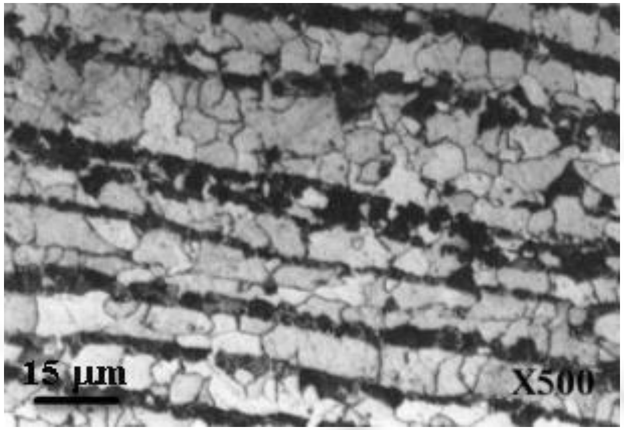
Defects that Trap Hydrogen



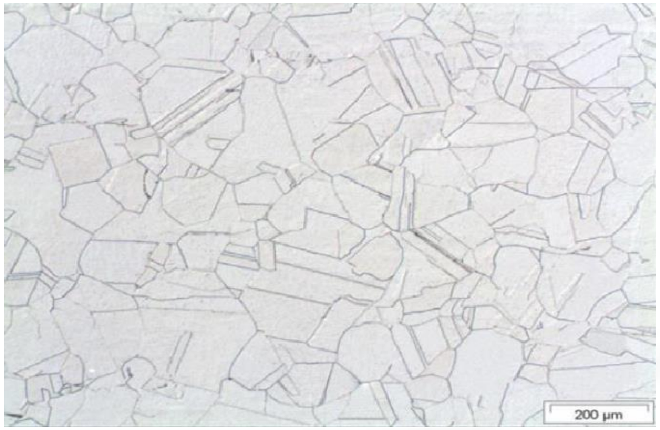
Ref. M. Koyama, M. Rohwerder, et al

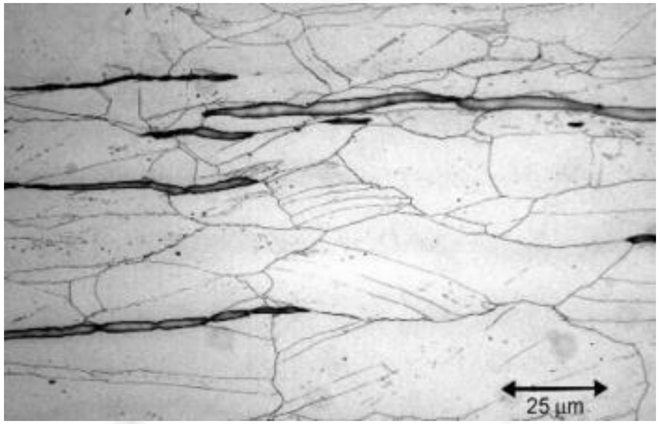
Microstructures

X52 Pipe Steel



304L Stainless Steel





Ref. Henkel and Pense

Steel Standards

AISI 1020 0.2C, 0.5Mn
(ferritic steel)

API X60 0.16C, 1.65Mn, 0.45Si, 0.02P, 0.01S, 0.08V, 0.05Nb and 0.04Ti
(ferritic, bainitic, or pearlitic steel)

S355J2+AR 0.22C, 1.60Mn, 0.55Si, 0.03P, 0.03S, 0.30Ni
(ferritic, bainitic, or pearlitic steel)

S is short for structural steel
355 refers to minimum yield strength (355 MPa)
JR means impact strength is 27 minimum at room temp
+AR means as rolled; +N means normalized

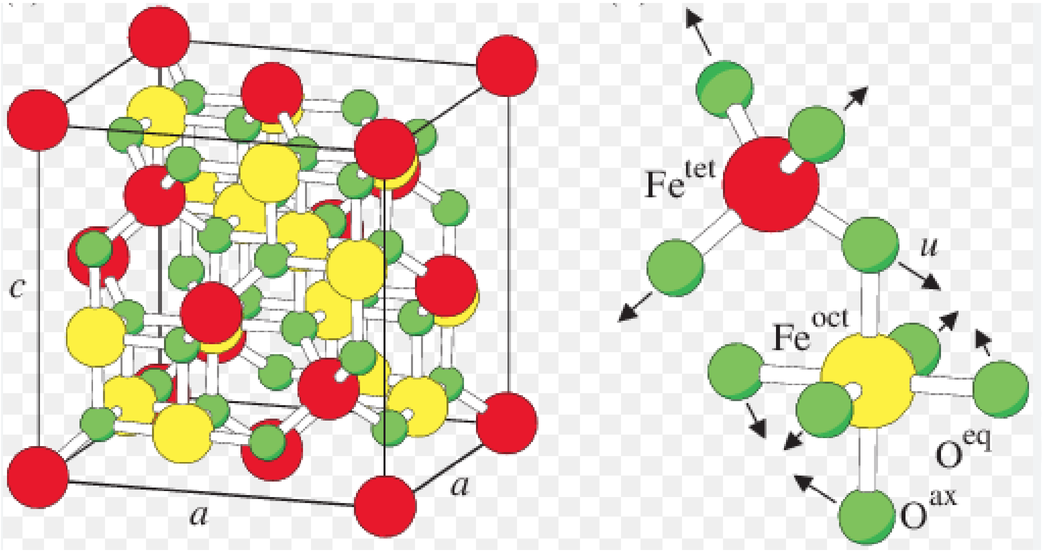
Magnetite

$6Fe_2O_3 – 4Fe_3O_4 + O_2$

Hematite – red rust, porous, easily spalled or removed, leaving clean surface

Magnetite –matte black, nonreflective, non-porous, tightly adhering, may reduce binding energy and requirement for bakeout

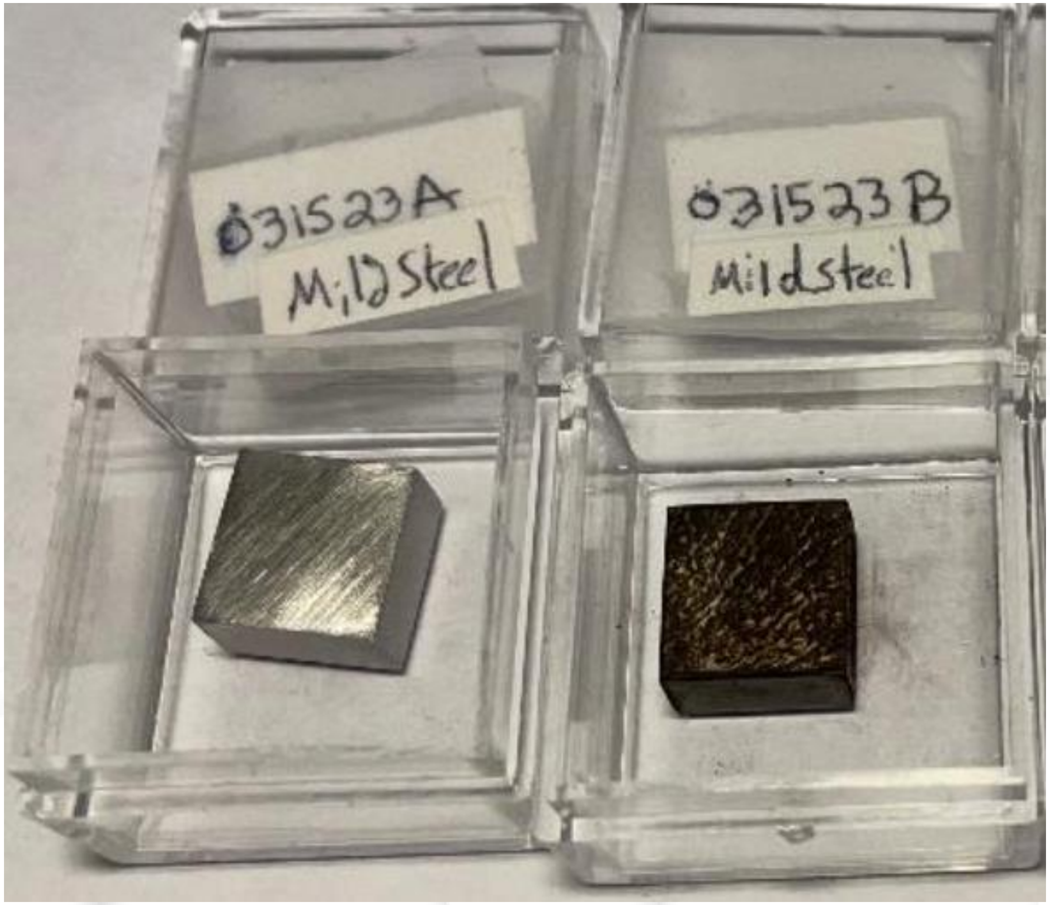
Properties of Magnetite



- Inverse-spinel
- Close-packed structure, similar to fcc
- Unit cell has thirty-two oxygen atoms
- Iron cations at octahedral and tetrahedral sites
- Unit cell edge length is 0.839 nm.

Ref. Fleet, 1986

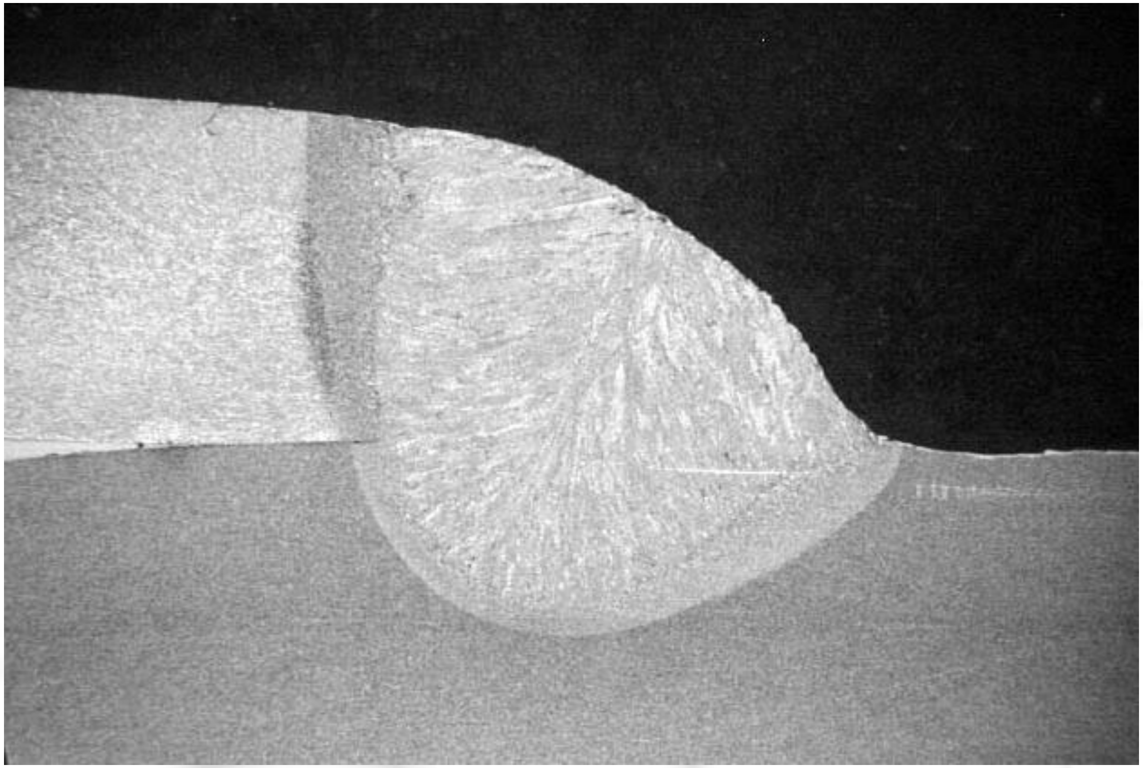
Experimental Passivation



Courtesy: D. Manos

Welding Carbon Steel to Stainless Steel

(MIG weld with 309L filler)

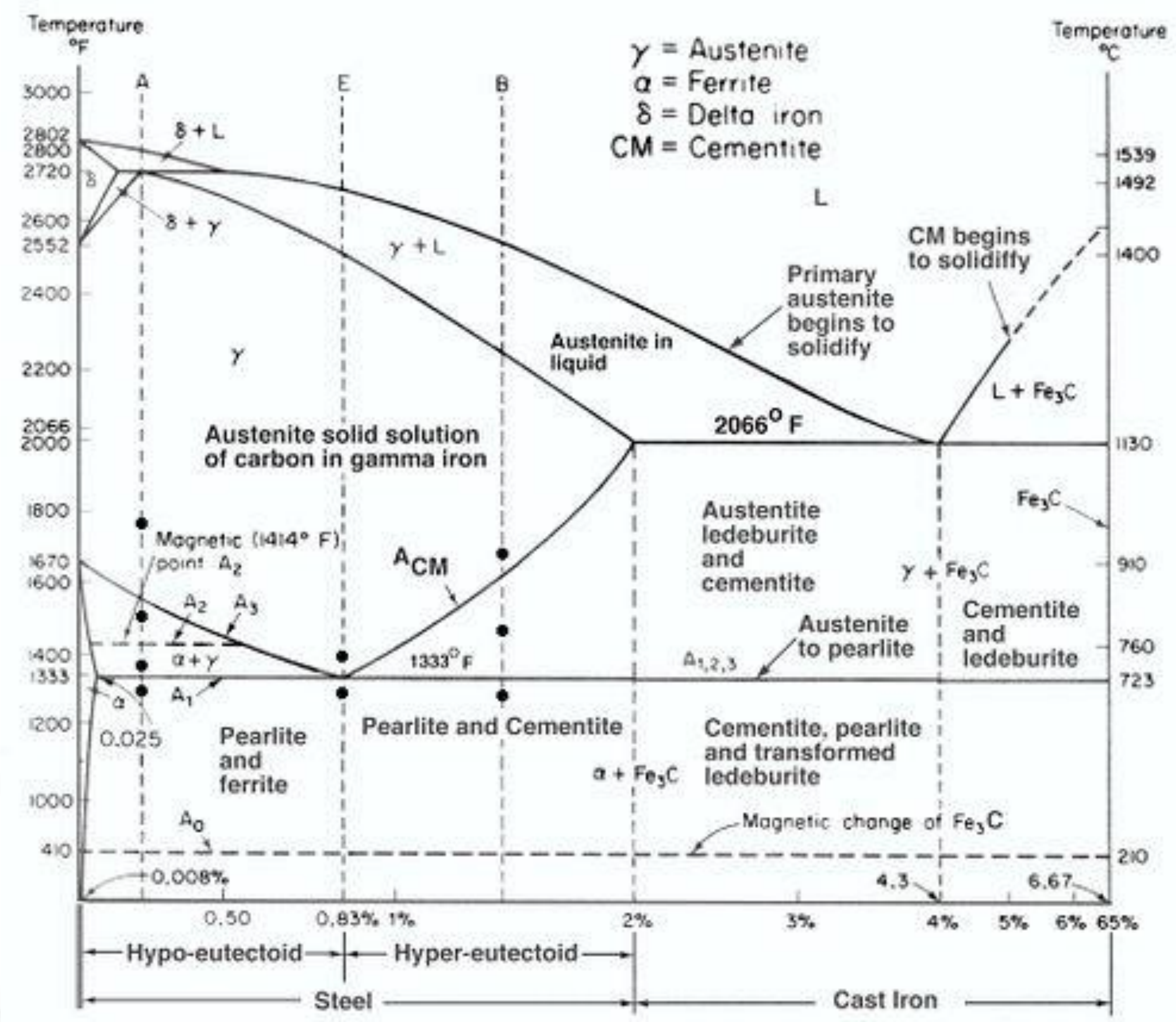


Ref. K. Easterling

Thank you

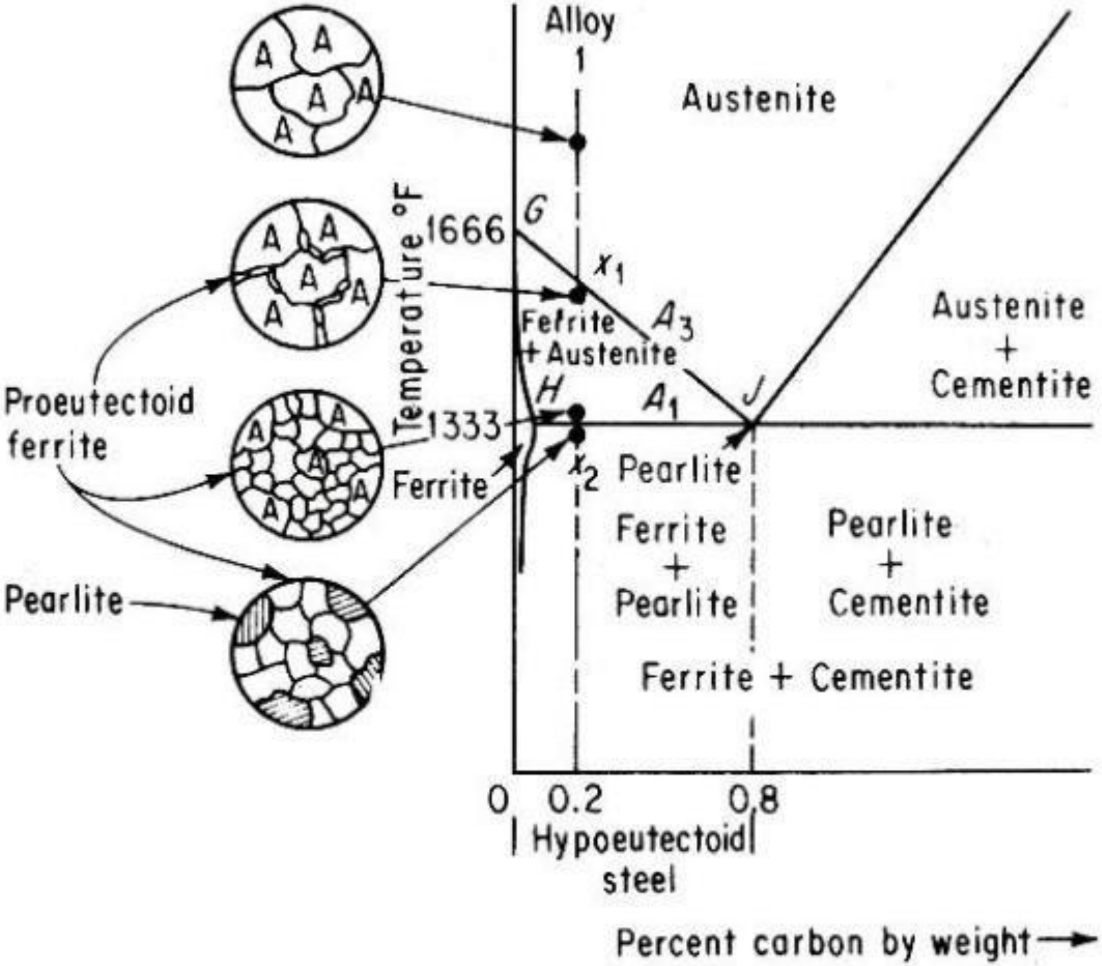
Appendix

Iron Carbon Phase Diagram



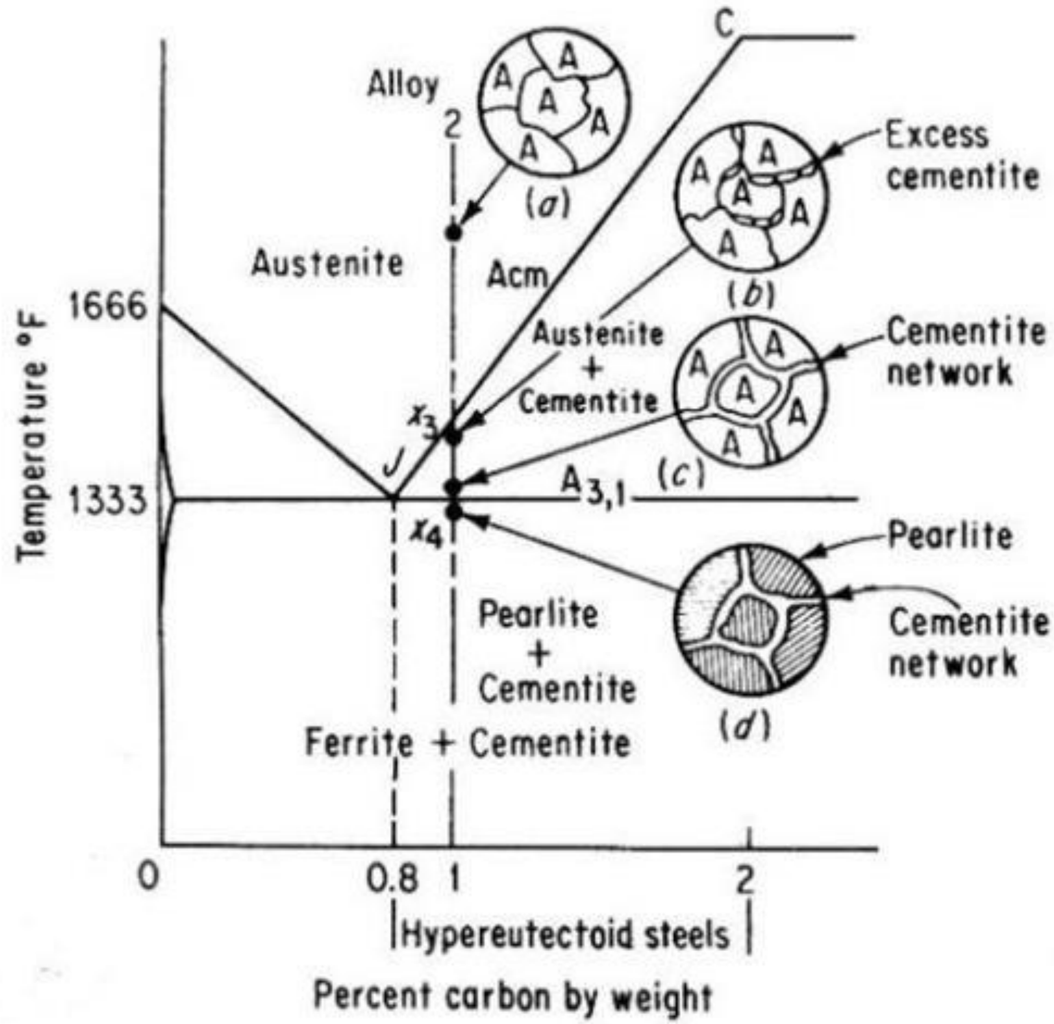
Low Carbon Steel

Hypoeutectoid

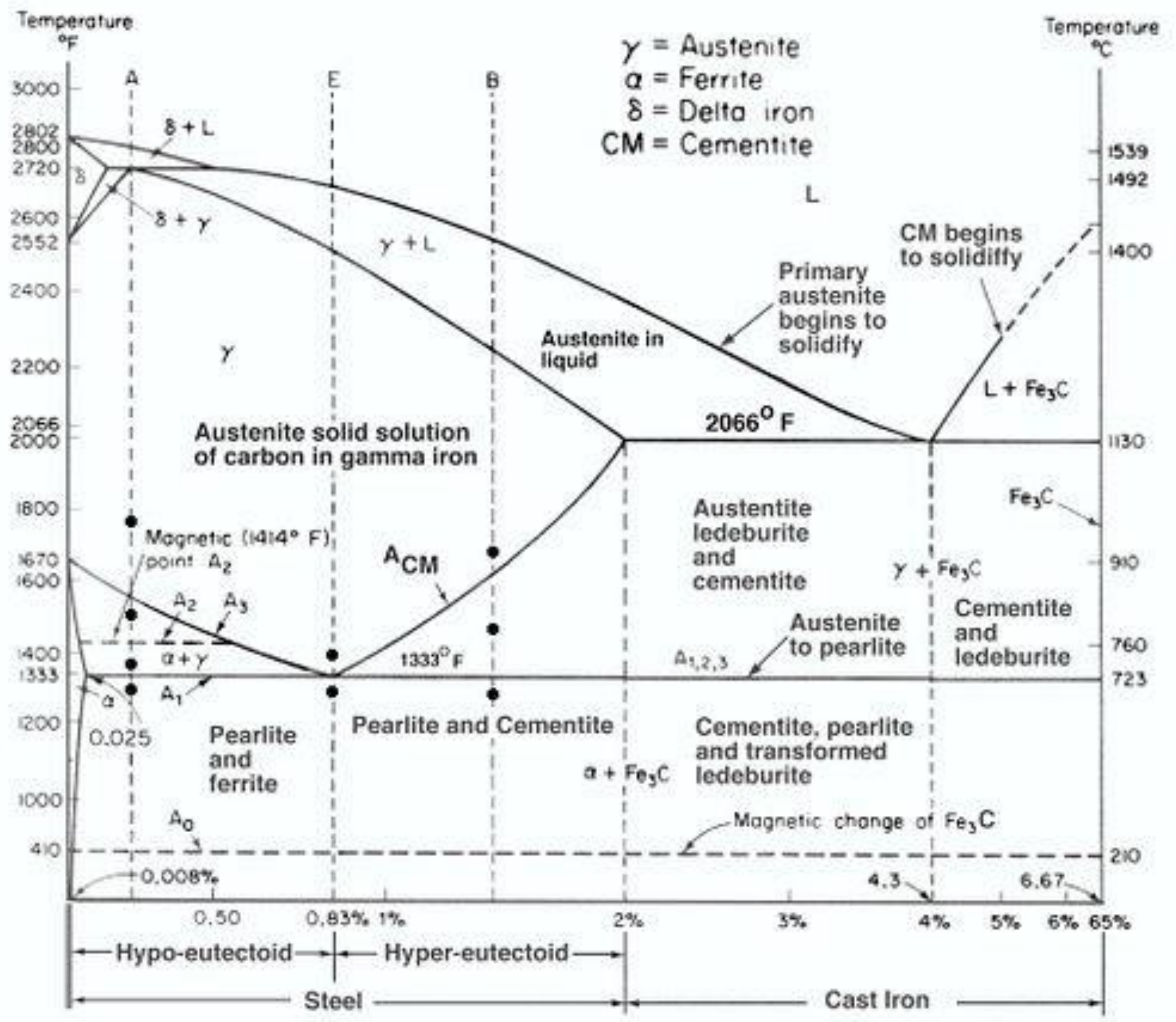


High Carbon Steel

Hypereutectoid

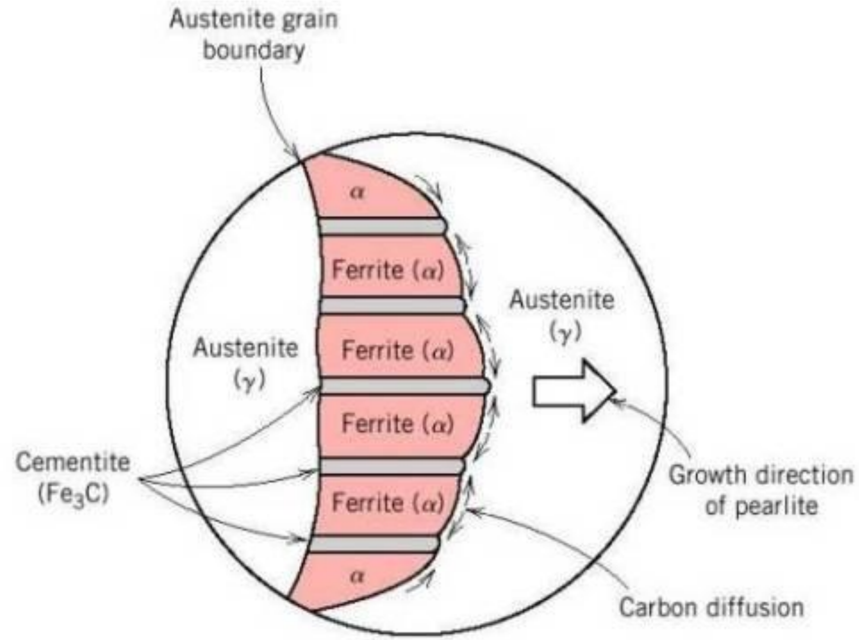


Fe-C Equilibrium Phase Diagram

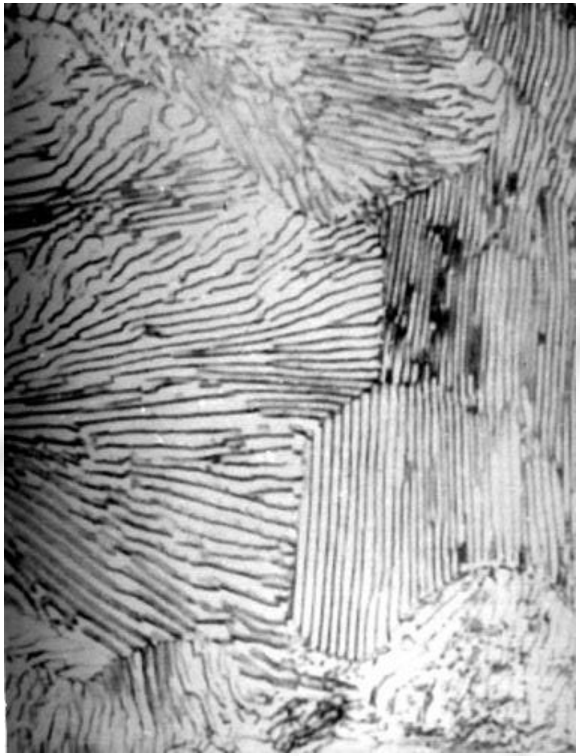


Pearlite

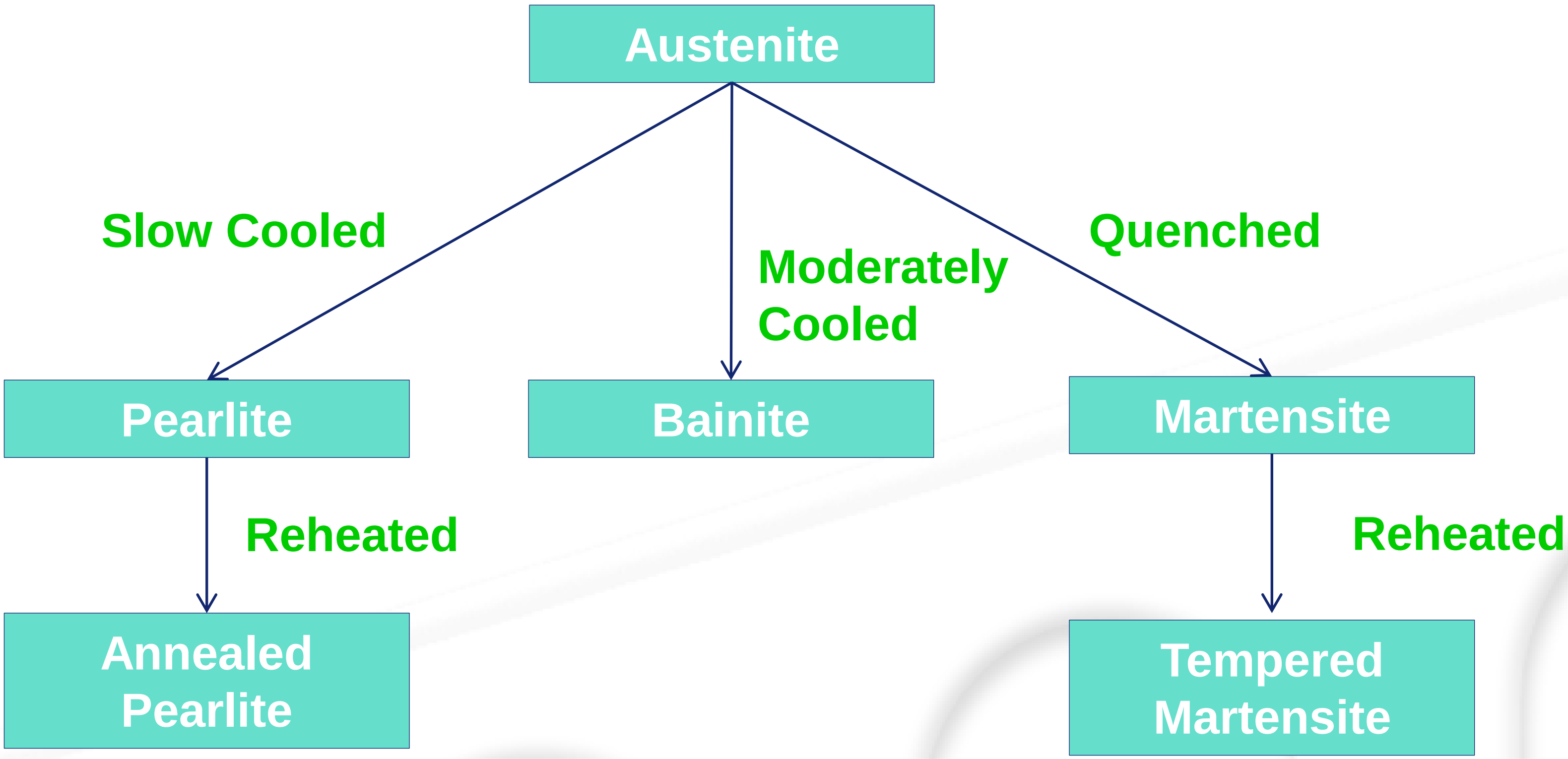
- 2-Phase eutectoid structure of $\gamma + \alpha$
- Lamellar structure of alternating plates
- Resembles mother-of-pearl
- Composition unchanged from 0°C to 723°C
- Intermediate hardness & ductility



Formation and Growth of Pearlite



Non-Equilibrium Kinetics



Major Classifications of Steels

SAE designation	Type
1xxx	Carbon steels
2xxx	Nickel steels
3xxx	Nickel-chromium steels
4xxx	Molybdenum steels
5xxx	Chromium steels
6xxx	Chromium-vanadium steels
7xxx	Tungsten steels
8xxx	Nickel-chromium-molybdenum steels
9xxx	Silicon-manganese steels

Carbon and alloy steel grades

Carbon steels		
	10xx	Plain carbon (Mn 1.00% max)
	11xx	Resulfurized
	12xx	Resulfurized and rephosphorized
	15xx	Plain carbon (Mn 1.00% to 1.65%)
Manganese steels		
	13xx	Mn 1.75%
Nickel steels		
	23xx	Ni 3.50%
	25xx	Ni 5.00%
Nickel-chromium steels		
	31xx	Ni 1.25%, Cr 0.65% or 0.80%
	32xx	Ni 1.25%, Cr 1.07%
	33xx	Ni 3.50%, Cr 1.50% or 1.57%
	34xx	Ni 3.00%, Cr 0.77%

Carbon and alloy steel grades

Molybdenum steels

40xx	Mo 0.20% or 0.25% or 0.25% Mo & 0.042 S
44xx	Mo 0.40% or 0.52%

Chromium-molybdenum (Chromoly) steels

41xx	Cr 0.50% or 0.80% or 0.95%, Mo 0.12% or 0.20% or 0.25% or 0.30%

Nickel-chromium-molybdenum steels

43xx	Ni 1.82%, Cr 0.50% to 0.80%, Mo 0.25%
43BVxx	Ni 1.82%, Cr 0.50%, Mo 0.12% or 0.35%, V 0.03% min
47xx	Ni 1.05%, Cr 0.45%, Mo 0.20% or 0.35%
81xx	Ni 0.30%, Cr 0.40%, Mo 0.12%

Carbon and alloy steel grades

Molybdenum steels

40xx	Mo 0.20% or 0.25% or 0.25% Mo & 0.042 S
44xx	Mo 0.40% or 0.52%

Chromium-molybdenum (Chromoly) steels

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Nickel-chromium-molybdenum steels

43xx	Ni 1.82%, Cr 0.50% to 0.80%, Mo 0.25%
43BVxx	Ni 1.82%, Cr 0.50%, Mo 0.12% or 0.35%, V 0.03% min
47xx	Ni 1.05%, Cr 0.45%, Mo 0.20% or 0.35%
81xx	Ni 0.30%, Cr 0.40%, Mo 0.12%

Carbon and alloy steel grades

Nickel-molybdenum steels	
46xx	Ni 0.85% or 1.82%, Mo 0.20% or 0.25%
48xx	Ni 3.50%, Mo 0.25%
Chromium steels	
50xx	Cr 0.27% or 0.40% or 0.50% or 0.65%
50xxx	Cr 0.50%, C 1.00% min
50Bxx	Cr 0.28% or 0.50%, and added boron
51xx	Cr 0.80% or 0.87% or 0.92% or 1.00% or 1.05%
51xxx	Cr 1.02%, C 1.00% min
Chromium-vanadium steels	
61xx	Cr 0.60% or 0.80% or 0.95%, V 0.10% or 0.15% min

Carbon and alloy steel grades

Tungsten-chromium steels	
72xx	W 1.75%, Cr 0.75%
Silicon-manganese steels	
92xx	Si 1.40% or 2.00%, Mn 0.65% or 0.82% or 0.85%, Cr 0.00% or 0.65%
High-strength low-alloy steels	
9xx	Various SAE grades
xxBxx	Boron steels
xxLxx	Leaded steels

Structural Steels

ASTM - Composition, strength, hardness, etc.

A36	Bridges and buildings
A515	Pressure vessels, boilers
A542	Chemical and refinery vessels
A553	Cryogenic tanks
A662	Pressure vessels, low temperature

Mechanical Properties

	TS	YS	Elong.
1010	325	180	28
1080	800	480	24
A36	400	220	23
A516 Grade 70	485	260	21
4340	1960	1570	10