UNIT IX · LESSON 03

Phase Diagrams, Fe–C System & Heat Treatment

crystal structure · solid solutions · phase rule · lever rule · invariant reactions · iron–carbon diagram · TTT & CCT · heat treatments · surface hardening · ferrous & non-ferrous alloys

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METALS CRYSTAL STRUCTURES

Structure	Atoms/cell	Coordination no.	APF	Examples
Simple cubic	1	6	0.52	Po
BCC	2	8	**0.68**	α-Fe, Cr, W, Mo, V
FCC	4	12	**0.74**	γ-Fe, Al, Cu, Ni, Au, Ag
HCP	6	12	0.74	Zn, Mg, Ti, Cd

- BCC: $a = 4r/\sqrt{3}$; FCC: $a = 2\sqrt{2}\, r$
- FCC metals are most **ductile** (12 slip systems on close-packed planes); HCP least
- **Imperfections**: point (vacancy, interstitial, substitutional), line (**dislocations** — edge, screw → plastic deformation), surface (grain boundaries), volume
- Miller indices (hkl); grain size by ASTM number; finer grain → stronger & tougher (**Hall–Petch** $\sigma_y = \sigma_0 + k\, d^{-1/2}$)
- Strengthening: grain refinement, solid-solution, **strain (work) hardening**, precipitation, dispersion

HUME-ROTHERY SOLID SOLUTIONS

- **Substitutional** (Cu–Ni, atoms of similar size) vs **interstitial** (C in Fe — small atoms: C, N, H, B)
- Hume-Rothery rules for full solubility: atomic size difference **< 15 %**, same crystal structure, similar electronegativity, same valency
- Intermetallic compounds (Fe_3C, $CuAl_2$): fixed composition, hard & brittle

EQUILIBRIUM PHASE RULE & LEVER RULE

- **Gibbs phase rule: P + F = C + 2**; at constant pressure (condensed systems) **P + F = C + 1**
- Binary eutectic point: C = 2, P = 3 → F = 0 (**invariant**)

EQUILIBRIUM PHASE RULE & LEVER RULE (CONTD.)

- **Lever rule** (in a two-phase region at overall composition C_0): fraction of α = $(C_L - C_0)/(C_L - C_\alpha)$ — "opposite arm / total"
- Isomorphous system: complete solubility (Cu–Ni); **cooling curves** of pure metals show a horizontal arrest
- Coring in non-equilibrium cooling → homogenising anneal

BINARY INVARIANT REACTIONS

Reaction	On cooling	Fe–C example
Eutectic	L → α + β	L(4.3 % C) → γ + Fe_3C at **1147 °C** (ledeburite)
Eutectoid	γ → α + β (solid)	γ(0.8 % C) → α + Fe_3C at **727 °C** (pearlite)
Peritectic	L + δ → γ	L + δ → γ at **1493 °C** (0.16–0.18 % C)
Peritectoid	α + β → γ (solid)	—
Monotectic	$L_1 \rightarrow L_2$ + α	Cu–Pb

FE–FE_3C IRON–CARBON DIAGRAM

Phase	Structure	Max C	Properties
Ferrite (α)	BCC	**0.022 %** (727 °C)	soft, ductile, magnetic below 768 °C
Austenite (γ)	FCC	**2.11 %** (1147 °C)	non-magnetic, ductile; stable above 727 °C
δ-ferrite	BCC	0.09 %	high temperature (> 1394 °C)
Cementite (Fe_3C)	orthorhombic	**6.67 %**	very hard, brittle
Pearlite	α + Fe_3C lamellae	0.8 % (eutectoid)	strong, moderately ductile
Ledeburite	γ + Fe_3C	4.3 % (eutectic)	hard, brittle (in cast iron)

- **Steel**: up to 2.11 % C (hypo-eutectoid < 0.8 % → ferrite + pearlite; hyper-eutectoid > 0.8 % → pearlite + cementite)
- **Cast iron**: 2.11–6.67 % C
- Critical temperatures: **A_1 = 727 °C**, A_3 (γ ↔ α boundary, 912 °C for pure Fe), A_{cm} (γ ↔ Fe_3C), A_2 = 768 °C (Curie)
- Allotropy of iron: δ (BCC, 1394–1538 °C) ↔ γ (FCC, 912–1394 °C) ↔ α (BCC, < 912 °C)
- Lever rule, 0.4 % C steel just below 727 °C: pearlite = (0.4 − 0.022)/(0.8 − 0.022) ≈ **48.6 %**, ferrite ≈ 51.4 %

TRANSFORMATION KINETICS TTT & CCT

- **TTT (isothermal transformation) diagram**: C-shaped curves (start/finish) for eutectoid steel
- Above the nose (≈ 550 °C): **coarse → fine pearlite**; below nose: **bainite** (upper, lower)
- Below $\mathbf{M_s}$ (≈ 220 °C for eutectoid): **martensite** (diffusionless, BCT, supersaturated C, very hard & brittle)
- **Critical cooling rate**: minimum rate that just misses the nose → full martensite
- **CCT** diagram: continuous cooling, curves shifted down and right; used for real heat treatment
- Alloying elements (except Co) shift curves **right** → higher hardenability
- **Hardenability**: depth to which steel can be hardened — **Jominy end-quench test**

PROCESSES HEAT TREATMENTS

Process	Heat to	Cool	Result
Full annealing	30–50 °C above A_3 (hypo) / A_1 (hyper)	**furnace** (very slow)	soft, ductile, coarse pearlite; relieves stresses
Process annealing	below A_1 (550–650 °C)	air	removes cold-work effects
Spheroidising	just below/around A_1, long time	slow	spheroidite — best machinability of high-C steel
Stress relieving	below A_1	slow	removes residual stresses
Normalising	40–50 °C above A_3 / A_{cm}	**still air**	fine pearlite, uniform grain, stronger than annealed
Hardening	above A_3 (hypo) / A_1 (hyper)	**quench** (water, oil, brine)	martensite — hard, brittle
Tempering	reheat below A_1 (150–650 °C)	air	toughness ↑, hardness ↓, relieves quench stresses

PROCESSES HEAT TREATMENTS (CONTD.)

Process	Heat to	Cool	Result
Austempering	quench to above M_s, hold	isothermal	**bainite**, less distortion
Martempering (marquenching)	quench to just above M_s, equalise	then air	martensite with less cracking

- Tempering types: low (150–250 °C, tools), medium (350–450 °C, springs), high (500–650 °C, **sorbite**, shafts) — quench + high temper = "hardening and tempering"
- Quench media severity: brine > water > oil > air
- Quench defects: cracks, distortion, soft spots, retained austenite (→ sub-zero treatment)

CASE HARDENING SURFACE HARDENING

Process	Medium / temperature	Case
Carburising (pack / gas / liquid)	C diffused at 900–950 °C, then quench	hard high-C case on low-C steel
Nitriding	NH_3 at 500–550 °C, **no quench**	very hard nitrides, least distortion (Al, Cr steels)
Cyaniding	NaCN bath 800–870 °C	thin C + N case
Carbonitriding	gas (C + N) 700–900 °C	thin case
Flame hardening	oxy-acetylene flame + quench	medium-C steels, large parts
Induction hardening	high-frequency induced current + quench	depth ∝ 1/√f; gears, crankshafts

CASE HARDENING SURFACE HARDENING (CONTD.)

Process	Medium / temperature	Case
Laser / electron-beam hardening	localised	thin, precise

- Purpose: hard wear-resistant surface with a **tough core**

FERROUS STEELS & CAST IRONS

- **Plain carbon steel**: low (< 0.3 % C: structural, sheets), medium (0.3–0.6 %: shafts, gears, rails), high (0.6–1.5 %: tools, springs)
- **Alloy steel** elements: **Ni** (toughness), **Cr** (hardness, corrosion), **Mo** (temper brittleness ↓, creep), **V** (fine grain), **W** (red hardness), **Mn** (hardenability, desulphurising), **Si** (electrical steel, deoxidiser), **Co** (high-speed steel)
- **Stainless steel** ≥ **10.5–12 % Cr** (Cr_2O_3 passive film): austenitic (18-8, 304, non-magnetic), ferritic, martensitic (cutlery), duplex, PH

FERROUS STEELS & CAST IRONS (CONTD.)

- **High-speed steel** 18-4-1 (W-Cr-V); tool steels; maraging steel; Hadfield manganese steel (12–14 % Mn, work-hardening)
- **Cast irons**: grey (graphite **flakes**, damping, machine beds), white (cementite, hard & brittle), **malleable** (heat-treated white CI, graphite rosettes), **ductile / SG / nodular** (Mg or Ce → graphite **spheroids**), alloy CI
- Designation: IS / AISI 1040 = 0.40 % C plain carbon steel; EN series

Q → A RAPID RECALL

APF of FCC	0.74
Coordination number of BCC	8
Max C in austenite	2.11 %
Max C in ferrite	0.022 %
C in cementite	6.67 %
Eutectoid composition & temperature	0.8 % C, 727 °C
Eutectic product in Fe–C	ledeburite
Phase rule (constant pressure)	P + F = C + 1
Cooling in normalising	still air
Structure after quenching	martensite
Process giving bainite	austempering

COMMON NON-FERROUS ALLOYS

Alloy	Composition	Use
Brass	Cu + Zn (70/30 cartridge, 60/40 Muntz)	fittings, ammunition
Bronze	Cu + Sn (phosphor bronze + P)	bearings, springs, statues
Gun metal	Cu–Sn–Zn (88/10/2)	valves, bearings
Aluminium bronze	Cu + Al	corrosion resistant, marine
Duralumin	Al + 4 % Cu + Mg + Mn	aircraft (**age-hardenable**)
Y-alloy	Al–Cu–Ni–Mg	pistons (high temperature)
Monel	Ni 67 % + Cu	chemical plant, marine
Inconel / Nimonic	Ni–Cr (–Fe/–Co)	gas turbines, high temperature
Babbitt (white metal)	Sn–Sb–Cu (or Pb base)	bearing linings
Solder	Sn–Pb (lead-free Sn–Ag–Cu)	joining electronics
Invar	Fe + 36 % Ni	very low thermal expansion

- **Precipitation (age) hardening**: solution treat → quench → age (natural/artificial) → fine precipitates (Al–Cu, duralumin)

Q → A RAPID RECALL (CONTD.)

Case hardening without quench	nitriding
Minimum Cr in stainless steel	≈ 10.5–12 %
Cast iron with spheroidal graphite	ductile (SG) iron
Brass is	Cu + Zn

TRAP EXAM TRAPS

- Normalised steel is stronger and harder than annealed steel (finer pearlite)
- Martensite forms without diffusion — cooling rate, not holding time, matters
- Pearlite is a two-phase **mixture** (microconstituent), not a phase
- Bronze = Cu + Sn; brass = Cu + Zn — do not swap
- Austenitic stainless steel is non-magnetic and cannot be hardened by quenching