GATE Mechanical Revision Notes

Engineering Materials

WHY MATERIALS ?

Every machine part is only as good as the metal it is made of. This subject links a material's inner structure to the strength, hardness and life we see outside. Pick the wrong material and even a perfect design fails.

The golden chain :

→ structure -> properties -> processing -> use

Classification :-

→ Metals : strong, ductile, conduct heat

→ Ceramics : hard, brittle, heat resistant

→ Polymers : light, cheap, low strength

→ Composites : mix, best of two worlds

STRUCTURE OF SOLIDS

Atoms in a solid can sit in a neat repeating pattern or lie jumbled. This one difference decides most properties.

→ Crystalline : ordered, e.g. metals

→ Amorphous : random, e.g. glass

CRYSTAL STRUCTURE

Definition :-

A crystal is a solid whose atoms repeat in a fixed 3D pattern called the lattice. The smallest block that repeats to build the whole crystal is the unit cell.

Concept :-

Study one unit cell and you know the whole crystal. Its size and atom count set density, packing and slip behaviour.

Terms you must know :

→ Lattice : imaginary grid of points

→ Basis : atom(s) placed on each point

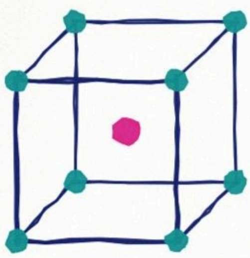
→ Lattice parameter (a) : edge length

→ 7 crystal systems, 14 Bravais lattices

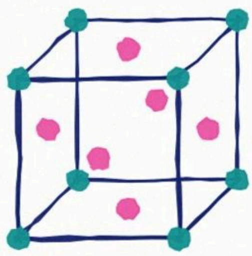
Metals mostly take three simple cubic-family cells, shown next. How tightly they pack decides how ductile they are.

BCC, FCC, HCP

These are the three common metal cells. Count the atoms per cell by sharing corner and face atoms with the neighbours.



BCC : 2 atoms



FCC : 4 atoms

Atoms per unit cell :

→ BCC : 8 corners $\times$ 1/8 + 1 centre = 2

→ FCC : 8 $\times$ 1/8 + 6 faces $\times$ 1/2 = 4

→ HCP : 6 atoms per cell

Examples :-

→ BCC : alpha-iron, chromium, tungsten

→ FCC : gamma-iron, copper, aluminium

→ HCP : zinc, magnesium, titanium

PACKING & DENSITY

Atomic packing factor :-

APF is the fraction of the cell volume actually filled by atoms, treating them as hard spheres. A higher APF means atoms sit closer and the metal is usually denser and more ductile.

APF = (n x vol. of atom) / vol. of cell

Standard values :

→ FCC & HCP : APF = 0.74 (closest packed)

→ BCC : APF = 0.68

→ Simple cubic : APF = 0.52

Coordination number :-

It is the number of nearest atoms touching one atom. More contacts means tighter packing.

→ FCC & HCP : 12, BCC : 8, SC : 6

Theoretical density :-

$\rho = nA / (V_c N_A)$

n=atoms, A=at.wt

MILLER INDICES

Idea :-

Miller indices are a short code for planes and directions in a crystal. Slip and cleavage always follow certain planes, so we must name them.

For a plane (hkl) :

→ 1. read intercepts on x, y, z axes

→ 2. take reciprocals of the intercepts

→ 3. clear fractions to smallest integers

A bar over a number means a negative intercept. Directions use square brackets [uvw] found from the vector components.

Why it matters :-

FCC metals slip on close-packed (111) planes, which is why copper and aluminium are so ductile. Naming the plane lets us predict how a metal will deform.

CRYSTAL IMPERFECTIONS

Concept :-

No real crystal is perfect. Defects sound bad but they actually control strength, diffusion and colour. Real engineering lives on these defects.

Point defects (0-D) :

→ Vacancy : a missing atom

→ Interstitial : atom in a gap (carbon in Fe)

→ Substitutional : foreign atom on a site

→ Frenkel & Schottky (in ionic solids)

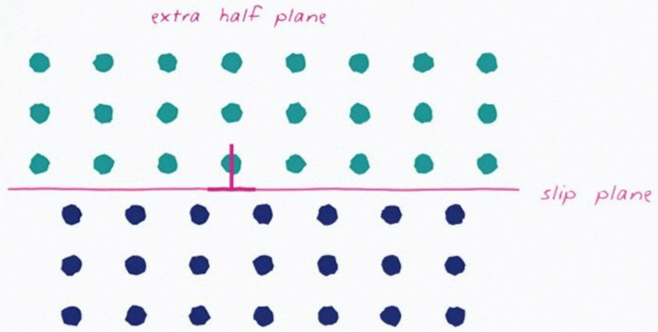
Effect :-

Vacancies let atoms diffuse, which is how heat treatment and carburising work. Solute atoms distort the lattice and make the metal harder, called solid-solution strengthening.

DISLOCATIONS

Definition :-

A dislocation is a line defect, an extra half plane of atoms squeezed into the crystal. It is the single most important defect in metals.



Why it matters :-

Metals bend at low stress because dislocations glide one row at a time, like moving a carpet by a ripple. Real strength is far below the ideal bond strength for this reason.

Burgers vector (b) :

It is the size and direction of the lattice slip carried by one dislocation. Edge, screw and mixed are the three types.

STRENGTHENING

Core idea :-

To make a metal stronger, block the dislocations from moving. Every strengthening trick is just a way to pin them.

Four main methods :

- → Grain refinement : more grain boundaries
- → Solid solution : solute atoms distort lattice
- → Strain / work hardening : tangled lines
- → Precipitation : fine particles block glide

Hall-Petch relation :-

Smaller grains give more boundary area to stop dislocations, so the yield stress rises as grain size falls.

$$\sigma_y = \sigma_0 + k / \text{root}(d)$$

d = grain size

Cold work raises strength but cuts ductility. Later heating (recovery, recrystallisation, grain growth) softens it again.

PHASES & PHASE DIAGRAM

Phase :-

A phase is a region with the same structure and composition throughout. Ice and water are two phases of one substance.

Phase diagram :-

It is a map that shows which phases exist at each temperature and composition. It is the roadmap for alloying and heat treatment.

Gibbs phase rule :-

It links the degrees of freedom to the phases present at equilibrium.

$$F = C - P + 2$$

$P = 1$ atm : $F = C - P + 1$

→ F = degrees of freedom

→ C = components, P = phases

At an invariant point (like eutectic) $F = 0$, so temperature and composition are both fixed.

LEVER RULE

Purpose :-

In a two-phase zone the lever rule tells you HOW MUCH of each phase is present. Draw a horizontal tie line at the temperature and read the ends.

$$\% \text{ liquid} = (C_o - C_s)/(C_l - C_s) \times 100$$

$$\% \text{ solid} = (C_l - C_o)/(C_l - C_s) \times 100$$

Trick :-

The phase amount is proportional to the length of the OPPOSITE arm of the tie line, just like a see-saw. That is why it is called the lever rule.

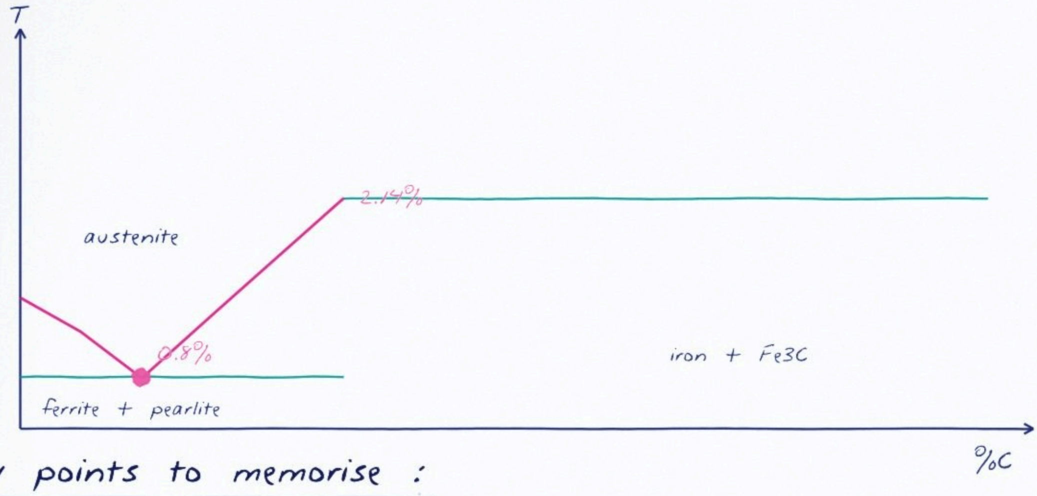
→ C_o = overall composition

→ C_s, C_l = solid and liquid ends

The two fractions must always add up to one. Use it in every phase-diagram numerical.

IRON - CARBON DIAGRAM

This is the master chart for all steels and cast irons. Learn the key points and you can read any steel's structure.



Key points to memorise :

→ Eutectoid : 0.8 %C at 723 C

→ Eutectic : 4.3 %C at 1147 C

→ Max C in austenite : 2.14 % at 1147

→ Steel < 2.14 %C ; cast iron above

MICRO-CONSTITUENTS

These are the structures you actually see under a microscope after cooling. Each has its own strength and hardness.

The main phases :-

→ Ferrite (a-Fe) : soft, ductile, BCC

→ Austenite (g-Fe) : FCC, holds carbon

→ Cementite (Fe3C) : hard, brittle carbide

Mixtures :-

→ Pearlite : layers of ferrite + cementite

→ Ledeburite : eutectic of cast iron

→ Martensite : hard, from fast cooling

Concept :-

More carbon and more cementite means harder but more brittle steel. Slow cooling gives soft pearlite; fast cooling traps carbon as hard martensite.

INVARIANT REACTIONS

Concept :-

At certain fixed points three phases sit in balance and one phase changes into two others on cooling. These are the invariant reactions.

The three to know :

Eutectic : L -> S1 + S2

liquid to 2 solids

Eutectoid : S -> S1 + S2

solid to 2 solids

Peritectic : L + S1 -> S2

In steel :-

The eutectoid reaction is the star : austenite turns into pearlite at 723 C. This single change is behind almost all steel heat treatment.

→ Hypo-eutectoid steel : below 0.8 %C

→ Hyper-eutectoid steel : above 0.8 %C

HEAT TREATMENT - 1

What & why :-

Heat treatment is controlled heating and cooling to change the structure, and so the properties, WITHOUT changing the shape. It is how one steel can be made soft or very hard.

Annealing :-

Heat above the critical line, hold, then cool very slowly in the furnace. It softens the steel, removes stresses and improves machinability.

Normalising :-

Same heating but cool in still air, which is faster. It gives finer pearlite, so the steel is a little stronger and tougher than after annealing.

→ anneal : furnace cool (softest)

→ normalise : air cool (finer grains)

HEAT TREATMENT - 2

Hardening (quenching) :-

Heat to austenite, then cool very fast in water or oil. Carbon has no time to leave, so it traps as hard, brittle martensite. This gives maximum hardness.

> O‾ hardness up, ductility down

Tempering :-

Quenched steel is too brittle to use. Reheat it to a moderate temperature to relax stresses and win back toughness, giving up a little hardness.

→ low temper : keeps hardness (tools)

→ high temper : more toughness (springs)

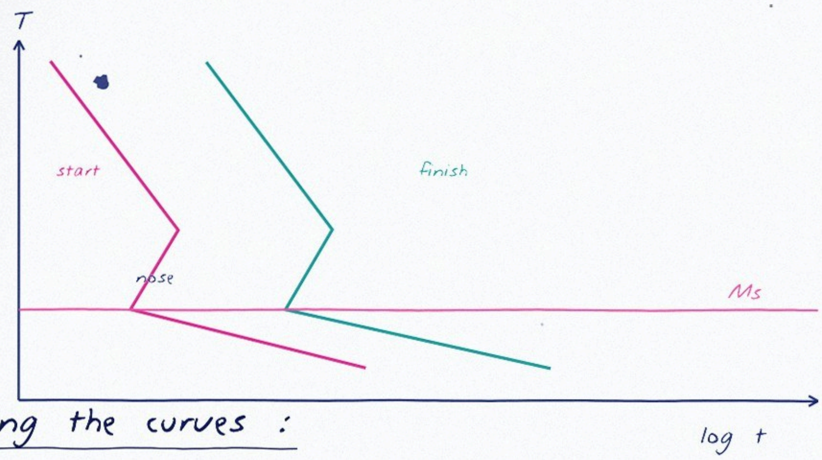
Trap :-

Martensite forms only on fast cooling and needs no time to hold, unlike pearlite. Quench then always temper.

TTT & CCT DIAGRAMS

Idea :-

A TTT diagram plots what austenite turns into at each temperature and holding time. The C-shaped curves show where each structure begins and ends.



Reading the curves :

→ slow cool right of nose : pearlite

→ fast cool past the nose : martensite

→ between : bainite

Hardenability :-

It is the depth to which a steel hardens, tested by the Jominy end quench. Alloying pushes the nose right, so martensite forms even on slow cooling.

SURFACE HARDENING

Why :-

Gears and shafts need a hard skin to resist wear but a tough core to take shock. Surface hardening gives both in one part.

Add carbon or nitrogen :

→ Carburising : add carbon to skin, quench

→ Nitriding : add nitrogen, no quench

→ Cyaniding : carbon + nitrogen together

Heat only the skin :

→ Flame hardening : torch then quench

→ Induction hardening : eddy currents

Concept :-

The first group changes the skin's chemistry; the second only heats and quenches the surface layer. Both leave the tough core untouched.

HARDNESS TESTING

Definition :-

Hardness is a material's resistance to local plastic dents or scratches. It is quick, cheap and roughly tracks tensile strength.

Common tests :

→ Brinell : hard steel ball, wide dent

→ Vickers : diamond pyramid, any hardness

→ Rockwell : depth of dent, direct dial

→ Knoop : microhardness of thin layers

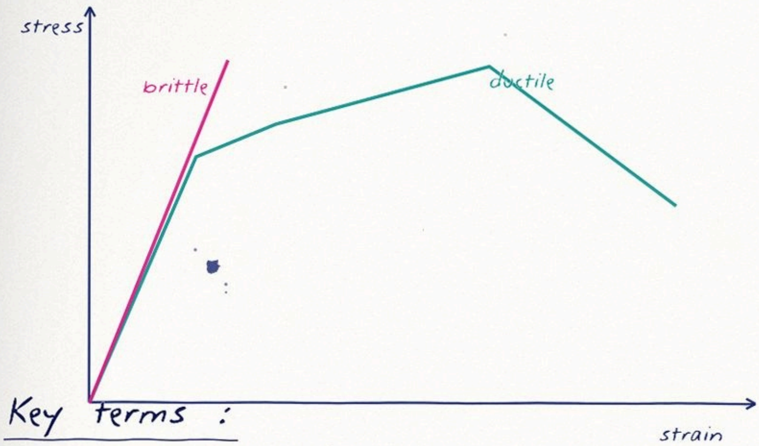
$$BHN = 2P / [\pi D(D - \sqrt{D^2 - d^2})]$$

Concept :-

Brinell and Vickers press an indenter and measure the dent area. Rockwell reads depth directly, so it is fastest on the shop floor.

MECHANICAL PROPERTIES

A tension test gives most design numbers at once. The stress-strain curve tells strength, stiffness and ductility.



Key terms :

→ Strength : stress it can take

→ Ductility : how much it stretches

→ Toughness : energy to fracture (area)

→ Stiffness : slope E, resists stretch

Ductile vs brittle :-

A ductile metal warns you with large strain and necking. A brittle one snaps suddenly with little warning, which is more dangerous.

IMPACT, CREEP, FATIGUE

Impact / toughness :-

Izod and Charpy tests break a notched bar with a swinging hammer. The energy absorbed is the impact toughness. It falls sharply below the ductile-brittle transition temperature.

Creep :-

Creep is slow, steady stretching under a constant load at high temperature, even below yield. It limits turbine blades and boiler tubes over long service.

→ stages : primary, secondary, tertiary

Fatigue :-

Fatigue is failure under repeated cyclic loads at a stress far below the static strength. Most machine parts die this way, starting from a tiny surface crack.

→ endurance limit : safe stress for steel

FERROUS MATERIALS

Steels :-

Steel is iron with up to 2.14 percent carbon. More carbon means more hardness and strength but less ductility and weldability.

→ Low C (<0.3%) : soft, ductile, sheets

→ Medium C : shafts, gears, rails

→ High C (>0.6%) : tools, springs

Alloy steels add chromium, nickel or molybdenum for hardenability, wear or corrosion resistance. Stainless steel needs about 12 percent chromium.

Cast irons :-

Cast iron has 2 to 4 percent carbon, so it is cheap, easy to cast and good in compression, but brittle.

→ Grey CI : graphite flakes, damps vibration

→ Ductile / SG : nodules, much tougher

NON-FERROUS & OTHERS

Non-ferrous metals :-

→ Aluminium : light, soft, corrosion free

→ Copper : best cheap conductor, ductile

→ Brass (Cu+Zn), Bronze (Cu+Sn)

→ Titanium : strong, light, costly

Polymers :-

Polymers are long carbon chains. Thermoplastics soften on heating and can be reshaped; thermosets set once and cannot be remelted.

Ceramics & composites :-

Ceramics are hard, brittle and take high heat, like tool tips and insulators. A composite joins a strong fibre with a light matrix, as in glass or carbon fibre, to beat either one alone.

QUICK FACTS SHEET

APF : FCC/HCP = 0.74, BCC = 0.68, SC = 0.52

Coord no : FCC/HCP=12, BCC=8, SC=6

Atoms/cell : BCC=2, FCC=4, HCP=6

$\rho = nA / (V_c N_A)$

F = C - P + 2 (Gibbs phase rule)

Eutectoid : 0.8 %C, 723 C (A -> pearlite)

Eutectic : 4.3 %C, 1147 C

Steel < 2.14 %C < cast iron

$\sigma_y = \sigma_0 + k/\text{root}(d)$ (Hall-Petch)

Quench -> martensite (hard, brittle)

Temper -> regain toughness

Slow cool -> pearlite (soft)

Fatigue = cyclic load ; creep = high temp

GATE TIPS & TRAPS

High-weightage topics :-

→ iron-carbon diagram + lever rule

→ heat treatment & TTT curves

→ crystal structure : APF, coord no

→ strengthening & dislocations

Common mistakes :-

→ eutectic (L->2S) vs eutectoid (S->2S)

→ martensite needs FAST cooling, no hold

→ lever rule uses the OPPOSITE arm

→ nitriding needs no quench

Quick checks :-

→ FCC ductile (12 slip), BCC less so

→ more carbon = harder but brittle

All the best !