

GOVERNMENT POLYTECHNIC NAYAGARH

LECTURE NOTE

MATERIAL SCIENCE AND ENGINEERING

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CHAPTER 1 - CRYSTAL STRUCTURES AND BONDS

Unit Specifics (Topics Covered):

- Introduction to Material Science & Engineering
- Classification of Engineering Materials
- Crystal Systems: 7 basic systems
- Crystal Structures for Metals: BCC, FCC, HCP
- Coordination Number & Atomic Radius for SC, BCC, FCC
- Atomic Packing Factor for SC, BCC, FCC, HCP
- Miller Indices for Directions and Planes
- Classification of Crystallographic Defects
- Bonds in Solids: Primary (Ionic, Covalent, Metallic) & Secondary (Van der Waals, Hydrogen)

1.1 INTRODUCTION TO MATERIAL SCIENCE & ENGINEERING

- **Material Science:** Involves understanding the **structure** and **properties** of materials.
- **Material Engineering:** Involves using the fundamental knowledge of materials to **develop useful products** (processing and performance).
- **Scope:** Forms a link between basic science and engineering disciplines, relevant to almost every industry.

Fig. 1.1: Scope of Material Science & Engineering

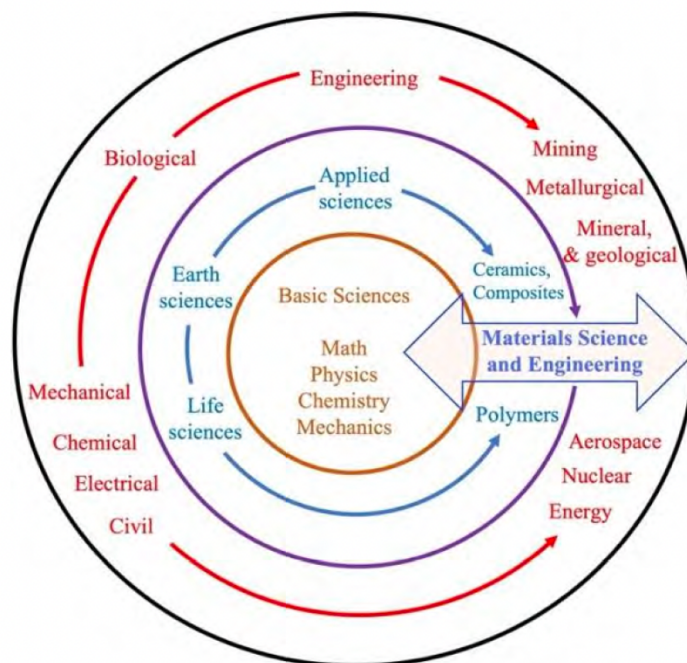


Fig. 1.1: Schematic illustrating scope of material science and engineering

1.2 GENERAL CHARACTERISTICS OF SOLID MATERIALS

- **States of Matter:** Solid, Liquid, Gas, Plasma (e.g., lightning, plasma TVs).
- **Stability Factors:** Stability of a state depends on the balance between:
 1. **Intermolecular forces** (pull atoms together)
 2. **Thermal energy** (pushes atoms apart)
- **Solid State:** Occurs at sufficiently low temperatures when intermolecular forces dominate.
- **Properties of Solids:**
 - Strong intermolecular forces
 - Definite shape and volume
 - Short intermolecular distances
 - Particles oscillate about fixed positions (rigid and incompressible)

1.2.1 CLASSIFICATION OF SOLIDS

A. Crystalline Solids

- **Definition:** Atoms/ions/molecules arranged in a specific pattern that repeats in 3D (**Long-Range Order, LRO**).
- **Examples:** Metals, alloys, minerals (NaCl, pyrite, amethyst).
- Can be a **single crystal** or **polycrystalline** (aggregate of many small crystals/grains).

B. Non-Crystalline (Amorphous) Solids

- **Definition:** Lacking a periodic arrangement; only **Short-Range Order (SRO)** exists.
- **Examples:** Glass, plastics, rubber, metallic glass.
- **Nature:** Often called "supercooled liquids" or pseudo-solids.

Table 1.3: Key Differences Between Crystalline & Amorphous Solids

Property	Crystalline Solids	Amorphous Solids
Shape	Definite, regular geometrical shape	Irregular shape
Order	Long-range order	Short-range order
Melting Point	Sharp, fixed temperature	Softens over a range of temperatures
Heat of Fusion	Definite	Indefinite

Property	Crystalline Solids	Amorphous Solids
Anisotropy	Properties differ with direction (anisotropic)	Properties are the same in all directions (isotropic)
Cleavage	Splits along smooth, flat surfaces	Cuts into irregular surfaces
X-ray Diffraction	Produces a distinctive pattern	Produces a poor, diffuse pattern

1.3 CLASSIFICATION OF ENGINEERING MATERIALS

Fig. 1.2: Five Major Groups of Engineering Materials

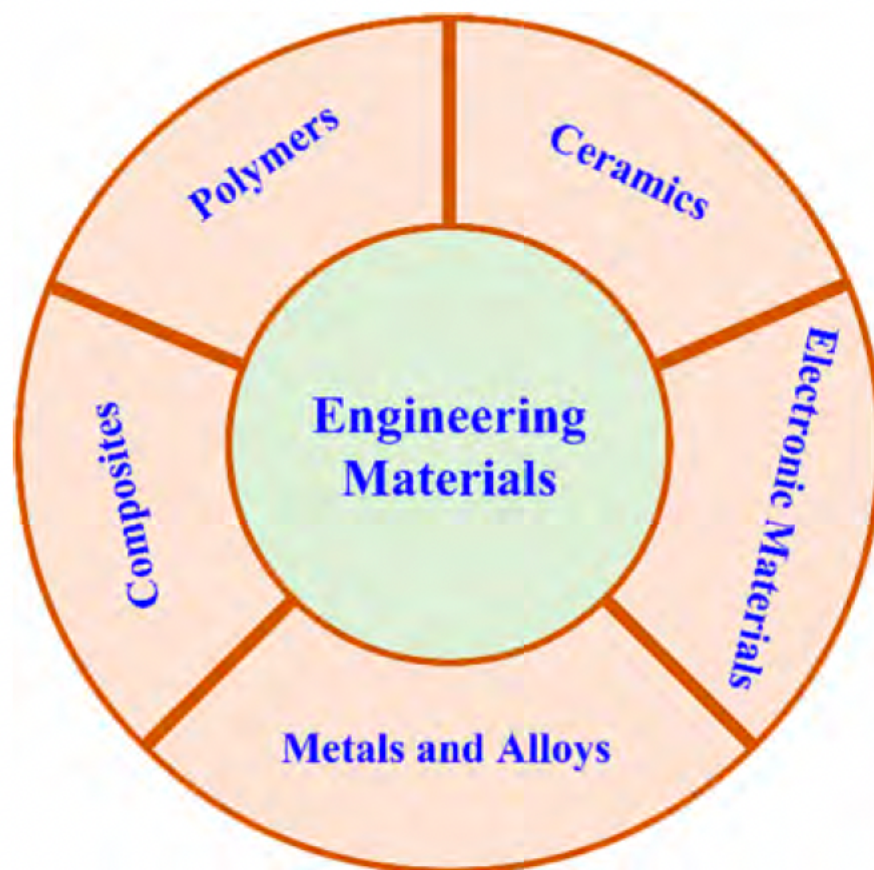


Fig. 1.2: Five major groups of engineering materials

1. Metals & Alloys

- **Nature:** Crystalline, dense, good electrical/thermal conductors due to free electrons.
- **Ferrous (Iron-based):** Steels, cast iron (high production & use).
- **Non-ferrous:** Al, Cu, Zn, Ti, Ni, etc.

2. Polymers (Plastics)

- **Nature:** Long molecular chains (organic, carbon-based). Mostly non-crystalline.
- **Properties:** Lightweight, low softening temperatures, generally poor conductors.
- **Examples:** Epoxy, polyaniline.

3. Ceramics

- **Nature:** Compounds of metallic & non-metallic elements (oxides, carbides, nitrides). Inorganic.
- **Properties:** High hardness, high-temperature strength, good wear/heat resistance, but brittle, good thermal insulators.
- **Traditional:** Refractories, glass, cement.
- **Advanced/Engineering:** SiC, Si₃N₄, Al₂O₃ (for engines, bearings).

4. Composite Materials

- **Definition:** Combination of two or more constituent materials (metal, polymer, or ceramic). $\text{Crystal} = \text{Lattice} + \text{Motif}$.
- **Components:** Matrix (base material) + Reinforcement (filler).
- **Examples:** Wood (natural), Al matrix with SiC reinforcement (MMC for automotive).

5. Electronic Materials

- **Examples:** Silicon, Graphene, GaN.
- **Applications:** Semiconductors, computers, mobile phones, ICs, microelectronics.

1.4 SPACE LATTICE, CRYSTAL & UNIT CELLS

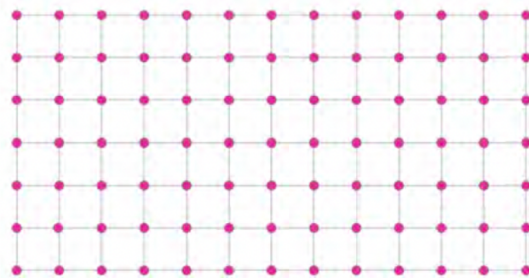


Fig. 1.3: A two-dimensional array of points on the plane of paper

- **Space Lattice:** A 3D infinite array of points where every point has an identical surrounding (Lattice Points/Sites).

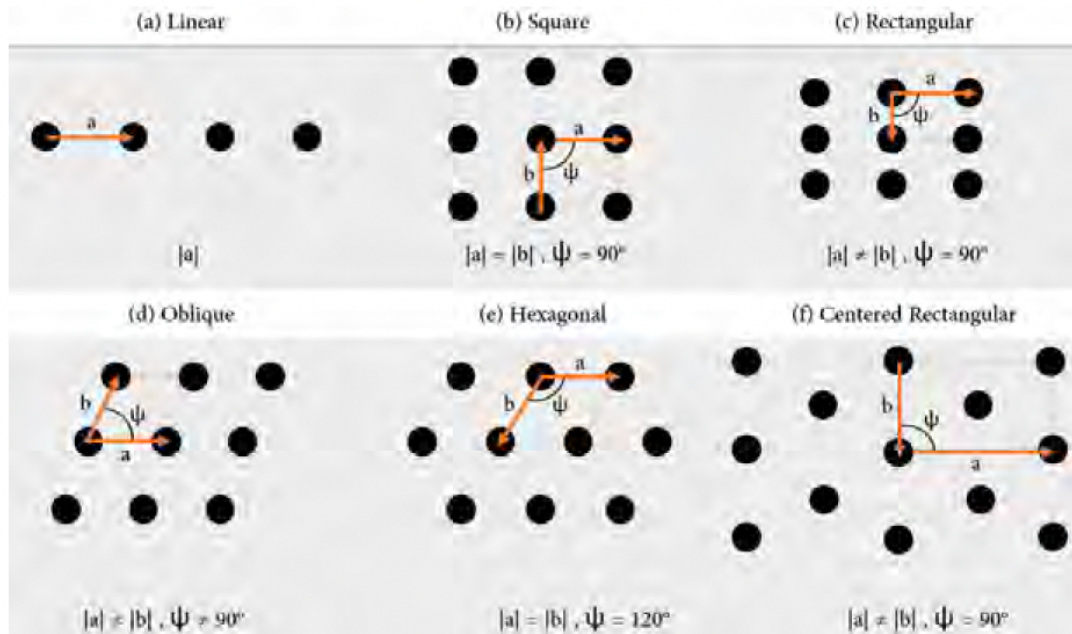


Fig. 1.4: Typical illustration of 1D and five 2D lattices

- **Motif (Basis):** An atom, ion, or molecule (or group of them) placed at each lattice point.
- **Crystal:** Crystal = Space Lattice + Motif (or Lattice + Basis).
- **Unit Cell:** The smallest repeating unit of a space lattice. Repeating it generates the entire crystal.
- **Lattice Constants (Parameters):** Axial lengths (a, b, c) and interaxial angles (α, β, γ) that define a unit cell.

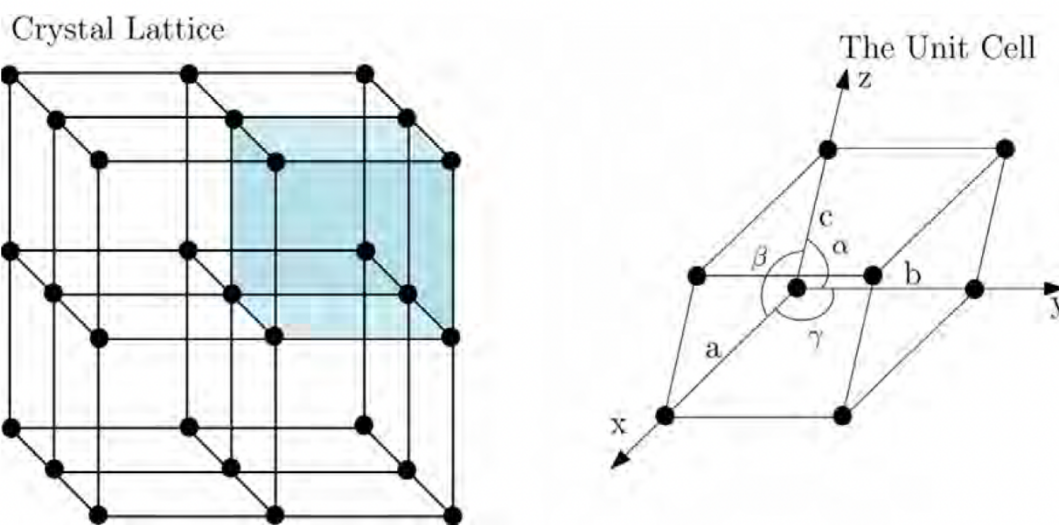


Fig. 1.5: A portion of a three-dimensional cubic lattice and illustration of the parameters of a unit cell.

- **Bravais Lattices:** There are **14** possible unique ways to arrange points in 3D space.

Table 1.4: 7 Crystal Systems & 14 Bravais Lattices (with Examples)

Crystal System	Bravais Lattices	Example Elements/Compounds
1. Cubic	Primitive, BCC, FCC	Po, Cr/Fe/W, Al/Cu/Au/Ni
2. Tetragonal	Primitive, BCC	Sn, In
3. Orthorhombic	Primitive, BCC, FCC, End-centered	Fe ₃ C, GaAs, α -S, α -U
4. Rhombohedral	Primitive	Hg, Bi
5. Hexagonal	Primitive	Mg, Cd, Zn, graphite
6. Monoclinic	Primitive, End-centered	Monoclinic sulphur, H ₃ BO ₃
7. Triclinic	Primitive	K ₂ Cr ₂ O ₇ , CuSO ₄ .5H ₂ O

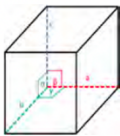
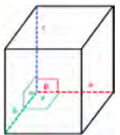
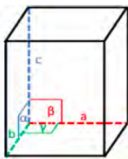
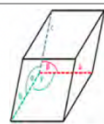
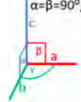
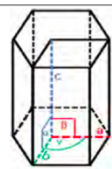
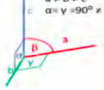
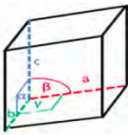
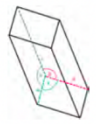
Key Concept: Symmetry

- Cubic system has **highest symmetry** (four 3-fold rotation axes).
- Triclinic system has **no symmetry**.

Table 1.5: Seven crystal systems and their associated characteristic symmetry

Crystal system	Characteristic symmetry
1. Cubic	Four 3-fold rotation axes (two will generate other two)
2. Hexagonal	Only one 6-fold rotation axis
3. Tetragonal	Only one 4-fold rotation axis
4. Trigonal	Only one 3-fold rotation axis
5. Orthorhombic	Only three 2-fold rotation axis
6. Monoclinic	Only one 2-fold rotation axis
7. Triclinic	None

Table 1.4: 7 Crystal systems and their possible variations along with unit cell with examples

Crystal system	Space lattice	Unit Cell	Typical Examples
1. Cubic  $a=b=c$ $\alpha=\beta=\gamma=90^\circ$	1. Primitive		Polonium (α -Po)
	2. Body Centered		Cr, W, Mo, Nb, α -Fe, β -Ti, V
	3. Face Centered		Al, Cu, Ag, Au, Pt, Ni, Pb, Pd, Rh, Ca
2. Tetragonal  $a=b \neq c$ $\alpha=\beta=\gamma=90^\circ$	4. Primitive		None in pure form
	5. Body Centered		Tin, Indium, Protactinium
3. Orthorhombic  $a \neq b \neq c$ $\alpha=\beta=\gamma=90^\circ$	6. Primitive		None in pure form (Fe ₃ C, CdTe)
	7. Body Centered		None in pure form (SiS ₂ , GaAs)
	8. Face Centered		None in pure form (α -S)
	9. End Centered		None in pure form (α -U)
4. Rhombohedral  $a=b=c$ $\alpha=\beta=\gamma \neq 90^\circ$	10. Primitive		Hg, Bi, Po, Pa
5. Hexagonal  $a=b \neq c$ $\alpha=\beta=90^\circ, \gamma=120^\circ$	11. Primitive		Mg, Cd, Zn, graphite, CdS, ZnO
6. Monoclinic  $a \neq b \neq c$ $\alpha=\gamma=90^\circ \neq \beta$	12. Primitive		Hydrated sodium sulphate (Na ₂ SO ₄ ·10H ₂ O)
	13. End Centered		Monoclinic sulphur
7. Triclinic  $a \neq b \neq c$ $\alpha \neq \beta \neq \gamma \neq 90^\circ$	14. Primitive		Hydrated copper sulphate (CuSO ₄ ·5H ₂ O), K ₂ Cr ₂ O ₇ , H ₃ BO ₃

1.6 CUBIC & NON-CUBIC STRUCTURES

1.6.1 PRIMITIVE (SIMPLE) CUBIC (SC)

- **Atoms per unit cell:** 1 (8 corners $\times$ 1/8).
- **Coordination Number (CN):** 6 (number of nearest neighbors).
- **Atomic Radius (r) & Lattice Parameter (a) relation:** $a = 2r$.
- **Atomic Packing Factor (APF):** (volume of atoms in cell) / (volume of cell) = 52.4%.
 - **Formula:** $APF = (1 \times 4/3\pi r^3) / (2r)^3 = \pi/6 = 0.524$
- **Example:** Polonium (α -Po). (**Very rare**)

Fig. 1.6: Primitive Cubic Structure

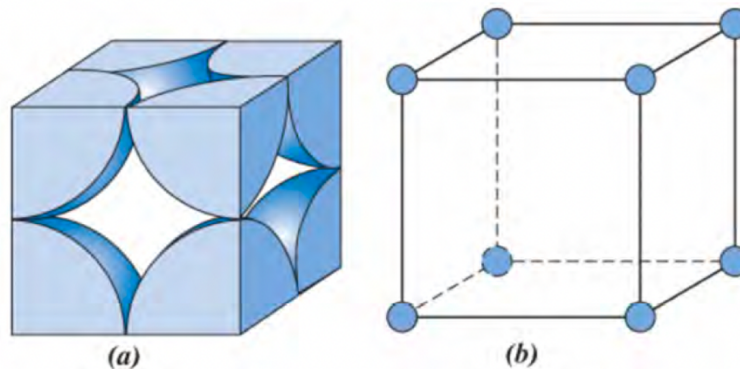


Fig. 1.6: Primitive cubic crystal structure, (a) a hard-ball (sphere) unit cell, and (b) a reduced-sphere unit cell.

1.6.2 BODY CENTERED CUBIC (BCC)

- **Atoms per unit cell:** $2 \text{ (8 corners} \times 1/8) + (1 \text{ center} \times 1) = 2$.

COORDINATION NUMBER (CN): 8.

- **Atomic Radius (r) & Lattice Parameter (a) relation:** $4r = \sqrt{3} a \rightarrow a = 4r/\sqrt{3}$.
- **APF: 68%.**
 - **Formula:** $APF = (2 \times 4/3\pi r^3) / (4r/\sqrt{3})^3 = (\pi\sqrt{3})/8 = 0.68$
- **Examples:** α -Fe, Cr, W, Mo, V.

Fig. 1.7: Body-Centered Cubic (BCC) Structure

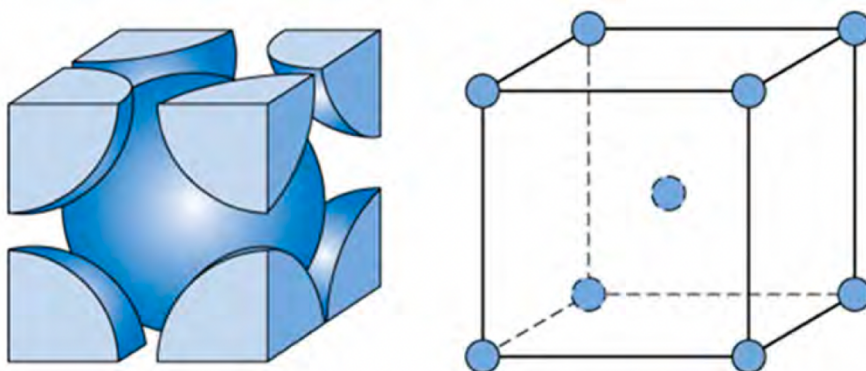


Fig. 1.7: Body-centered cubic crystal structure, (a) a hard-ball (sphere) unit cell, and (b) a reduced-sphere unit cell.

1.6.3 Face Centered Cubic (FCC)

- **Atoms per unit cell:** $4 \text{ (8 corners} \times 1/8) + (6 \text{ faces} \times 1/2) = 4$.

- **Coordination Number (CN): 12** (highest possible for equal-sized spheres).
- **Atomic Radius (r) & Lattice Parameter (a) relation:** $4r = \sqrt{2} a \rightarrow a = 4r/\sqrt{2}$.
- **APF: 74%** (highest possible, also called **Cubic Close-Packed (CCP)**).
 - **Formula:** $APF = (4 \times 4/3\pi r^3) / (4r/\sqrt{2})^3 = \pi/(3\sqrt{2}) = 0.74$
- **Examples:** Al, Cu, Ag, Au, Pt, Ni, Pb.
- **Stacking Pattern:** ABCABCABC...
- **Voids:** Tetrahedral voids (8 per cell) & Octahedral voids (4 per cell).

Fig. 1.8: Face-Centered Cubic (FCC) Structure

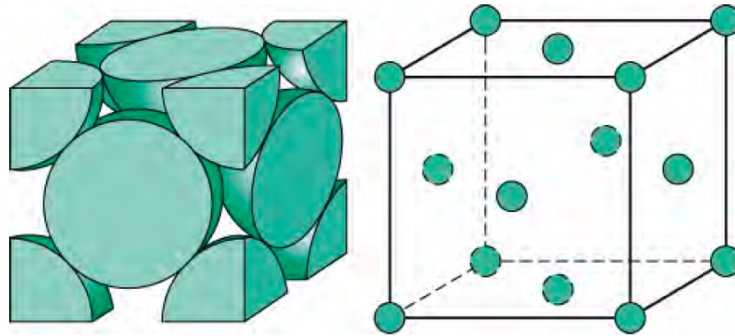


Fig. 1.8: Face-centered cubic crystal structure, (a) a hard-ball (sphere) unit cell, and (b) a reduced-sphere unit cell.

1.6.4 HEXAGONAL CLOSE-PACKED (HCP)

- **Atoms per unit cell:** 6.
- **Coordination Number (CN):** 12.
- **APF:** 74%.
- **Stacking Pattern:** ABABAB...
- **Examples:** Mg, Zn, Cd, Co, Zr, Be.

Fig. 1.9: Hexagonal Close-Packed (HCP) Structure

[A diagram of a hexagonal prism showing the ABAB stacking of atoms.]

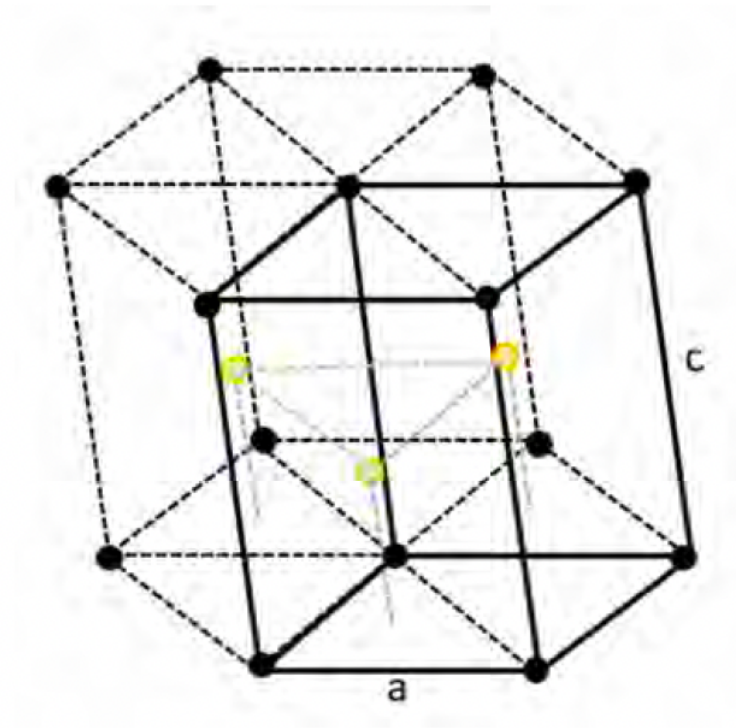


Fig. 1.9: Schematic showing hexagonal close-packed structure



Table 1.6: Crystal structure details of few elemental solids

Atomic Number	Pure Metal	Structure	Unit cell dimensions (nm)	
			a	b/c
4	Beryllium	HCP	0.229	0.358
12	Magnesium	HCP	0.321	0.521
13	Aluminium	FCC	0.405	-
22	Titanium	HCP	0.295	0.468
23	Vanadium	BCC	0.303	-
24	Chromium	BCC	0.289	-
25	Manganese	Cubic	0.891	-
26	Iron	BCC	0.287	-
27	Cobalt	HCP	0.251	0.409
28	Nickel	FCC	0.352	-
29	Copper	FCC	0.362	-
30	Zinc	HCP	0.267	0.495
39	Yttrium	HCP	0.365	0.573
40	Zirconium	HCP	0.323	0.515
41	Niobium	BCC	0.330	-
42	Molybdenum	BCC	0.315	-
45	Rhodium	FCC	0.380	-
46	Palladium	FCC	0.389	-
47	Silver	FCC	0.409	-
48	Cadmium	HCP	0.298	0.358
57	Lanthanum	HCP	0.376	0.606
72	Hafnium	HCP	0.320	0.506
73	Tantalum	BCC	0.331	-
74	Tungsten	BCC	0.317	-
77	Iridium	FCC	0.384	-
78	Platinum	FCC	0.392	-
79	Gold	FCC	0.408	-
81	Thallium	HCP	0.346	0.553
82	Lead	FCC	0.495	-

1.6.5 MILLER INDICES

A standardized notation system for describing crystallographic **directions** and **planes**.

MILLER INDICES FOR DIRECTIONS [UVW]

Procedure:

1. Find the coordinates of the start (x_1, y_1, z_1) and end (x_2, y_2, z_2) points of the direction vector.
2. Subtract: $(x_2 - x_1)$, $(y_2 - y_1)$, $(z_2 - z_1)$.
3. Clear fractions or reduce to the smallest integers.
4. Enclose in square brackets: $[uvw]$. A negative index is written with an overbar (e.g., $[1\bar{1}0]$).

Fig. 1.10: Important Crystallographic Directions

[Diagram of a cube showing directions like $[001]$, $[010]$, $[100]$, $[011]$, $[111]$, etc.]

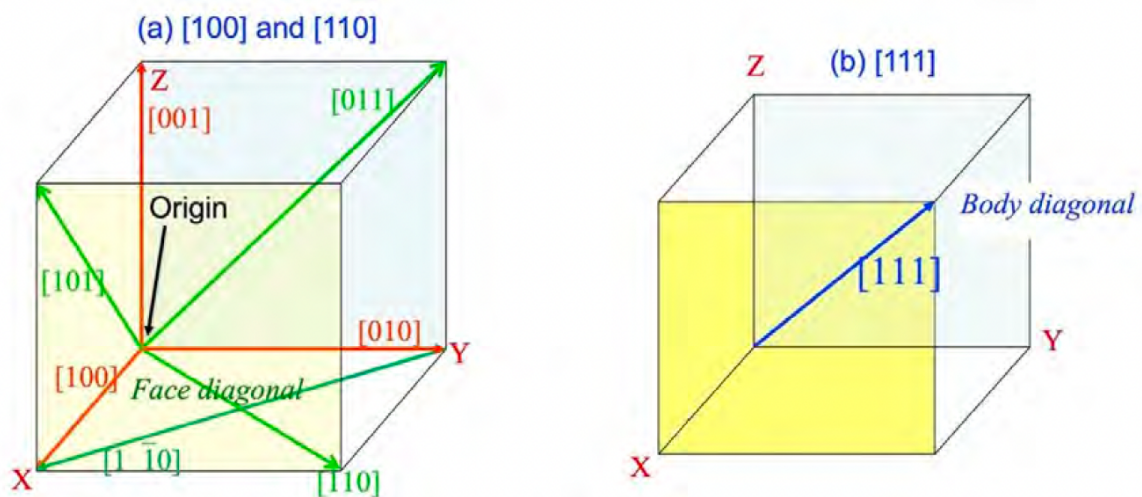


Fig. 1.10: Miller indices of important directions of cubic crystal

MILLER INDICES FOR PLANES (HKL)

Procedure:

1. Find the intercepts of the plane on the x, y, and z axes in terms of lattice parameters (a , b , c).
2. Take the reciprocals of these intercepts.
3. Clear fractions to get the smallest integers.
4. Enclose in parentheses: (hkl) .

Fig. 1.11: Important Crystallographic Planes

[Diagram of a cube showing planes like (100) , (110) , (111) .]

$$n\lambda = 2 d_{(hkl)} \sin\theta \quad [n=1, \text{ for first order diffraction}]$$

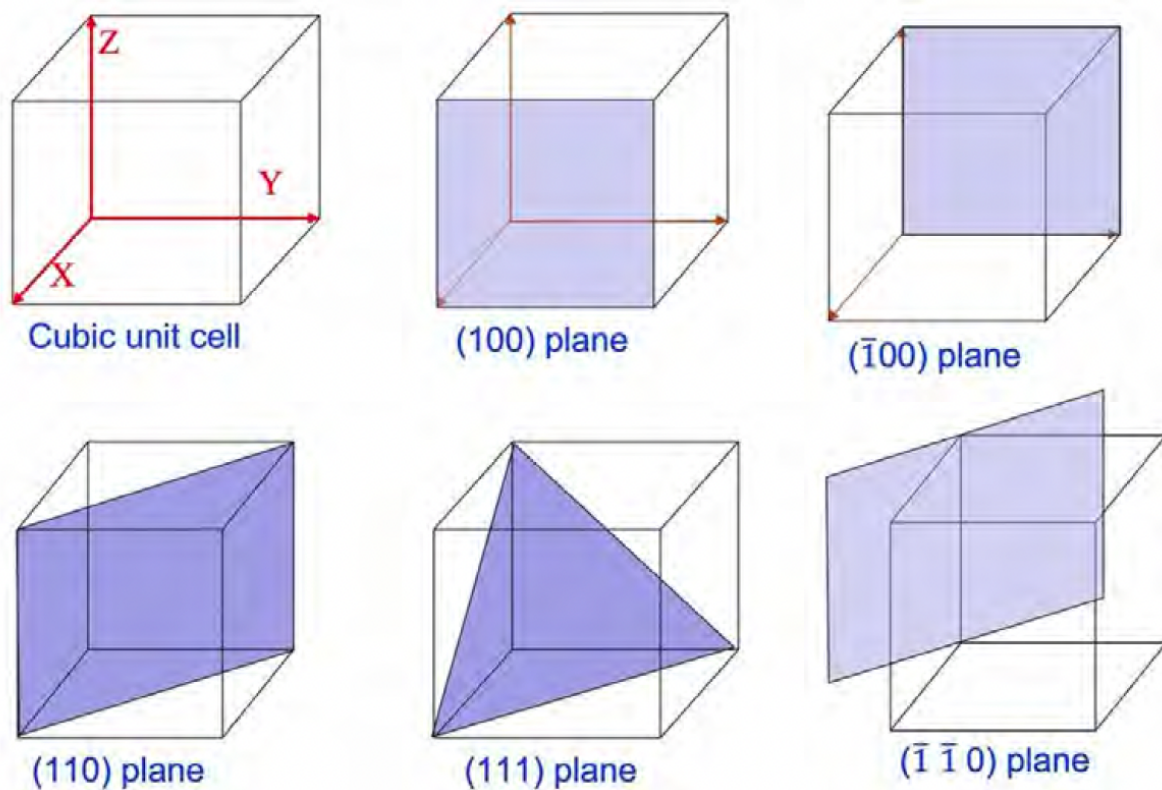


Fig. 1.11: Miller indices of planes in cubic crystal

- **Family of Directions:** $\langle uvw \rangle$ (e.g., $\langle 100 \rangle$ includes [100], [010], [001]).
- **Family of Planes:** $\{hkl\}$ (e.g., $\{100\}$ includes (100), (010), (001)).

1.6.6 CRYSTAL DEFECTS (IMPERFECTIONS)

Fig. 1.12: Classification of Crystallographic Defects

[A pyramid diagram: Top: Defects $\rightarrow$ Level 2: Point (0D), Line (1D), Surface/Interface (2D), Volume (3D)]

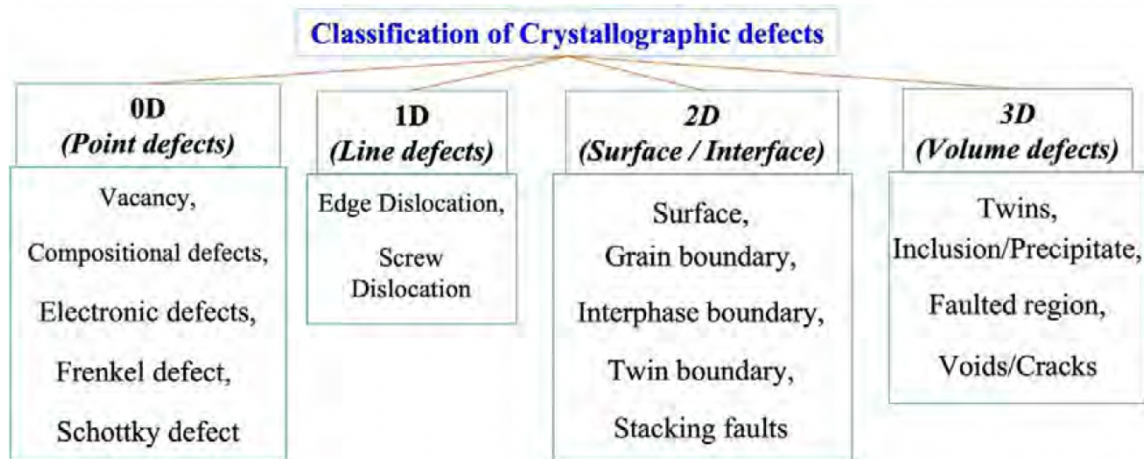


Fig. 1.12: Classification of crystallographic defects based on dimensionality

- **0D (Point Defects):**
 - **Vacancy:** An empty atomic site (equilibrium defect).
 - **Interstitial:** An atom squeezed into a normally empty space.
- **1D (Line Defects):**
 - **Dislocations:** Responsible for plastic deformation and strengthening.
 - **Edge Dislocation:** Extra half-plane of atoms.
 - **Screw Dislocation:** A spiral ramp-like distortion.
- **2D (Surface/Interface Defects):**
 - **Grain Boundaries:** Interfaces between two grains (crystals) of different orientation.
 - **Interphase Boundaries:** Interfaces between two different phases.
- **3D (Volume Defects):**
 - Pores, cracks, precipitates.

1.7 BONDS IN SOLIDS

Fig. 1.13: Classification of Chemical Bonding

[Flowchart: Bonding → Primary (Ionic, Covalent, Metallic) & Secondary (Van der Waals, Hydrogen)]

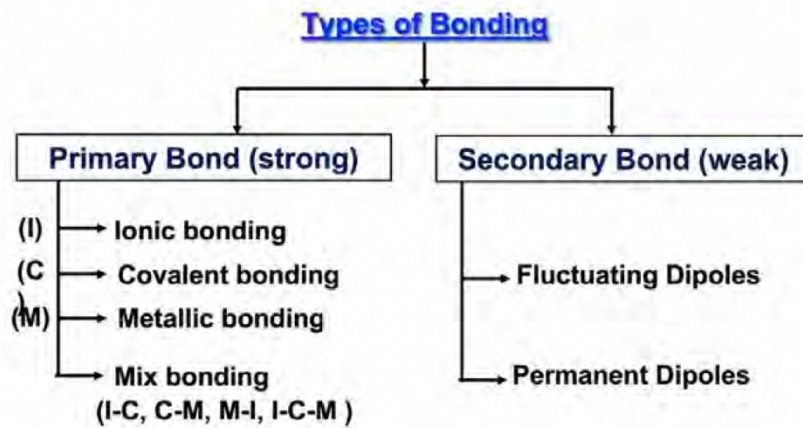
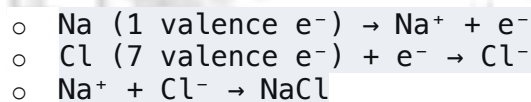


Fig. 1.13: Classification of chemical bonding.

PRIMARY BONDS (STRONG: 100-1000 KJ/MOL)

1. Ionic Bond

- **Mechanism:** Transfer of valence electrons from an electropositive metal (cation) to an electronegative non-metal (anion).
- **Force:** Electrostatic (Coulombic) attraction between oppositely charged ions.
- **Nature:** Non-directional.
- **Example:** NaCl (Table Salt).



- **Fig. 1.14: Ionic Bonding in NaCl**

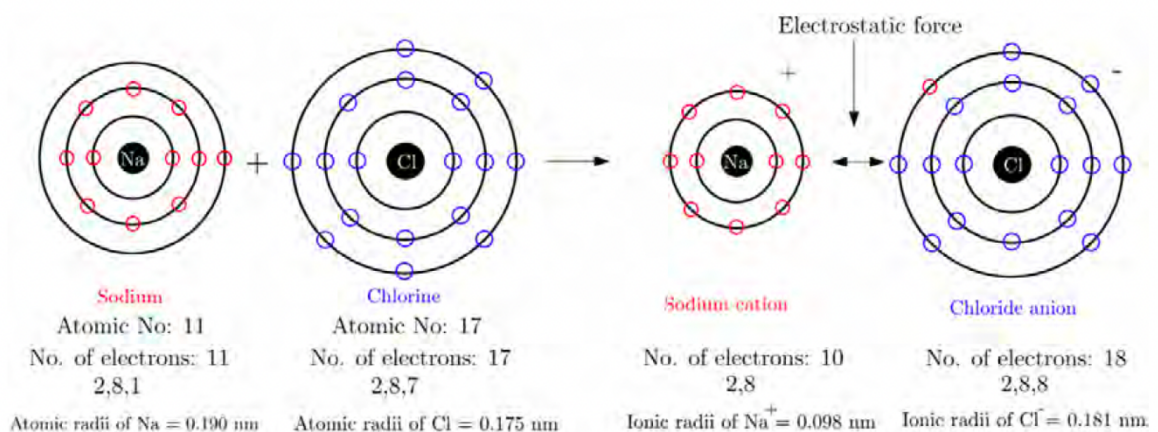


Fig. 1.14: Ionic bonding between sodium and chlorine atoms

2. Covalent Bond

- **Mechanism:** Sharing of valence electrons between two atoms to achieve stable noble gas configuration.

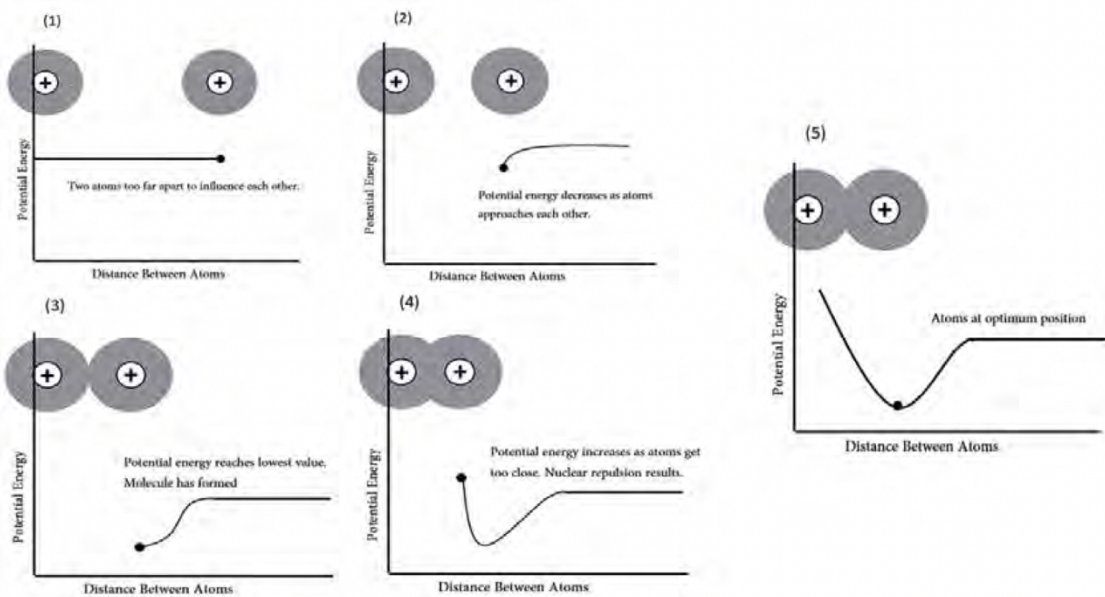


Fig. 1.15: Potential energy variation as a function of distance between two atoms

- **Nature:** Highly directional.
- **Example 1:** Oxygen molecule (O_2) – double bond.
- **Example 2:** Diamond – hardest known natural substance (3D network of carbon atoms).
- **Fig. 1.16: Covalent Bond in O_2 Molecule**

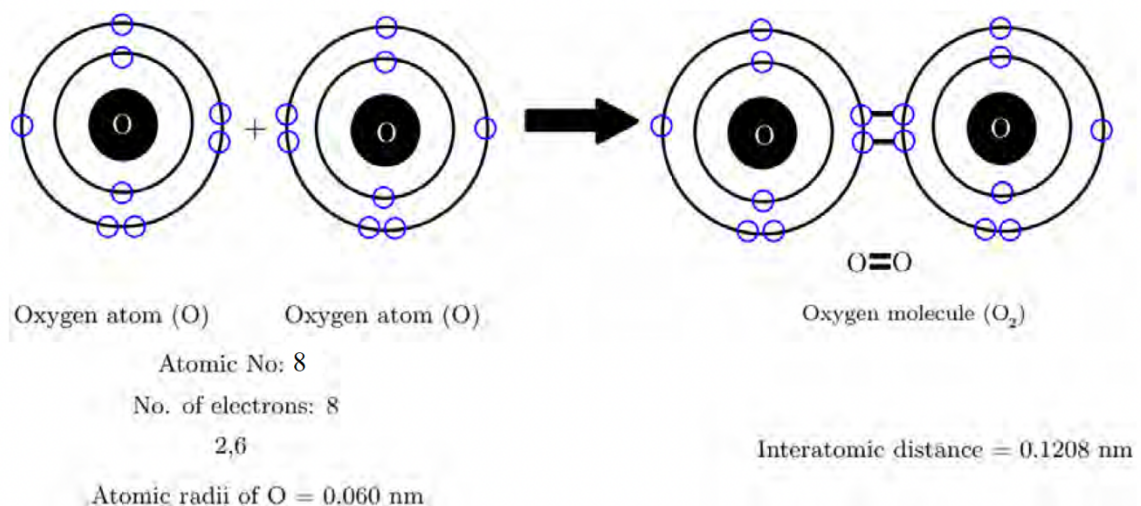


Fig. 1.16: Formation of covalent bond in oxygen molecule

3. Metallic Bond

- **Mechanism:** Positively charged metal ions (cations) held together by a "sea" of delocalized, mobile valence electrons.
- **Nature:** Non-directional.

- **Properties:** This "sea of electrons" explains high electrical and thermal conductivity, luster, and malleability/ductility.
- **Example:** Na, Fe, Cu, Al.
- **Fig. 1.17: Metallic Bonding**

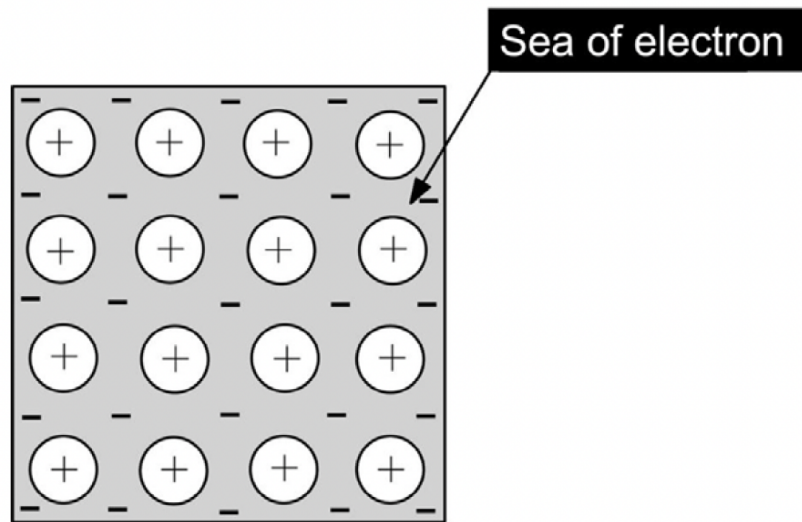


Fig. 1.17: A metallic crystal pictured as a lattice of +ve ions embedded in 'sea' of electrons.

SECONDARY BONDS (WEAK: 1-50 KJ/MOL)

1. Van der Waals Bonds

- **Origin:** Asymmetric distribution of electrical charge, creating temporary or permanent dipoles (positive and negative poles).
- **Weakest of all chemical bonds.**
- **Example:** Inert gases (Ar), between polymer chains.

2. Hydrogen Bond

- **Origin:** A special, strong type of dipole-dipole attraction between a hydrogen atom (bonded to F, O, or N) and an electronegative atom (F, O, N) in another molecule.
- **Stronger than Van der Waals, but weaker than primary bonds.**
- **Example:** Water (H₂O).
 - Explains why ice floats (less dense than water).

• **Fig. 1.18: Hydrogen Bonding in Water**

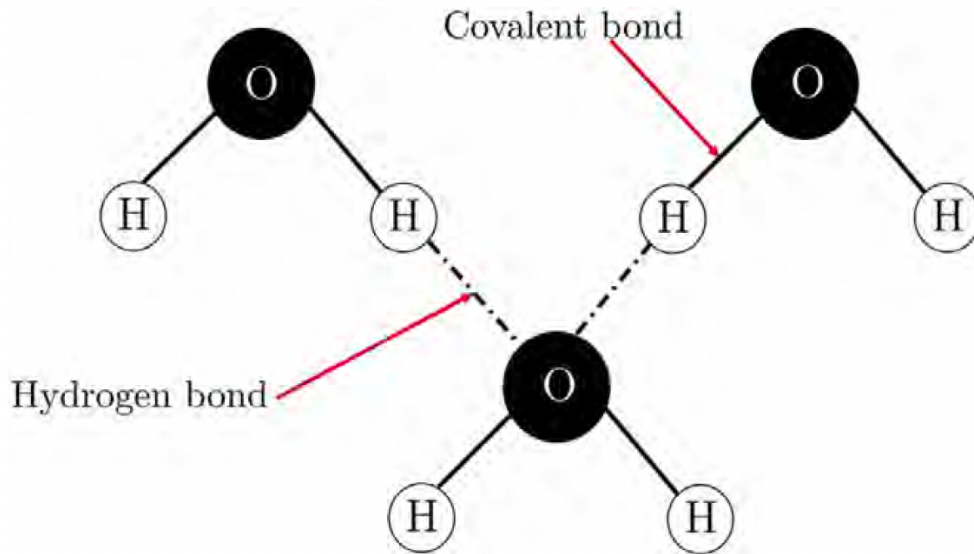


Fig. 1.18: Hydrogen bonding in water

Table 1.7: Summary of properties with respect to ionic, covalent and ionic bonds

Property	Bonding Type		
	Ionic Bonding	Covalent Bonding	Metallic Bonding
Nature of involved atoms	Metal and Non-metal atoms	Non-metal atoms only	Metal atoms only
Structure details	Form giant lattices that are brittle so are easy to crush	Form molecules with weak forces of attraction so are mainly gases and liquids	Forms a strong lattice structure
Melting point (MP) or boiling point (BP)	High melting and boiling point {Sodium Chloride (NaCl): MP: (800.7 °C) BP: (1,465 °C) Potassium Chloride (KCl): MP: (768 °C) BP: (1411 °C)}	Low melting and boiling point {Methane (CH ₄): MP: (-182.5 °C), BP: (-162 °C) Nitrogen (N ₂): MP: (-209.86 °C), BP: (-195.795 °C)}	High melting and boiling point {(Sodium (Na): MP: (97.794°C), BP: (882.940°C) Magnesium (Mg): MP: (650 °C), BP: (1,090 °C)}
Electrical conductivity	Will conduct electricity when molten or dissolved in water	Will not conduct electricity	Will conduct electricity when solid or molten
Magnetic property	Not magnetic	Not magnetic	Some are magnetic
Solubility issue in polar electrolyte (example: water)	Many are soluble in water	Are not soluble in water but are soluble in non polar solvents like ether	Are not soluble in water or any other solvent unless they undergo a reaction with them
Typical schematic example			
Typical examples	- Sodium Chloride (NaCl): Used to flavour food - Potassium iodide (KI) : to treat hyperthyroidism - Calcium oxide (CaO) : manufacturing of cement, paper, and high-grade steel.	- Water (H₂O) : drinking, cooking etc. - Oxygen (O₂) : necessary for human life - Ethylene (C₂H₄) : ripening fruit, making detergents etc.	- Copper (Cu): wiring electrical appliances - Diamond (C): cutting materials, as jewellery - Iron (Fe): to manufacture steel, for reinforcement in concrete etc.

UNIT SUMMARY (KEY POINTS FOR REVISION)

1. **Materials Science & Engg.** links **Structure, Properties, Processing, and Performance**.
2. **Crystalline** solids have long-range order; **Amorphous** solids have short-range order.
3. Main engineering materials: **Metals, Polymers, Ceramics, Composites, Electronic**.
4. **BCC** (68% APF, 8 CN), **FCC** (74% APF, 12 CN), **HCP** (74% APF, 12 CN).
5. **Miller Indices** $[uvw]$ for directions and (hkl) for planes are essential for describing crystal orientation.
6. **Crystal defects** (vacancies, dislocations, grain boundaries) control structure-sensitive properties.
7. **Primary Bonds** (Strong): Ionic (transfer), Covalent (sharing), Metallic (sea of electrons).
8. **Secondary Bonds** (Weak): Van der Waals (dipoles), Hydrogen (special dipole).



UNIT 2 - PHASE DIAGRAMS & FERROUS METALS

2.1 INTRODUCTION AND BASIC TERMINOLOGY

This unit provides a foundation for understanding the equilibrium relationships between phases in a material system as functions of temperature, composition, and pressure. It covers the Phase Rule, unary and binary phase diagrams, and their industrial applications, crucial for predicting the structure and properties of metallic systems. A brief introduction to the vast science and technology of steelmaking is also included.

What is a Phase Diagram?

A phase diagram is a graphical representation of the different phases present in a material system at various pressures, temperatures, and compositions. They are constructed using equilibrium conditions and are essential tools for scientists and engineers to predict:

- Phase transformations during processing.
- The resulting equilibrium microstructure.
- The stable states (phases) of an alloy, which have the minimum free energy under given conditions.

Key Terminology

To understand phase diagrams, we must first define some fundamental terms:

- **Grain:** A single crystal within which the atomic lattice and its orientation are continuous. All atoms in a grain are arranged in one specific pattern and orientation.
- **Grain Boundary:** The interface between two adjacent grains with different crystallographic orientations.
- **Microstructure:** The structure of a material's surface as revealed by an optical or electron microscope. It consists of grains, grain boundaries, and other defects. Grain sizes are typically on the order of microns (10^{-6} m) or nanometers (10^{-9} m).

- **DIAGRAM REFERENCE:** FIG. 2.1 - SCHEMATIC OF A MICROSTRUCTURE WITH GRAINS AND GRAIN BOUNDARIES.

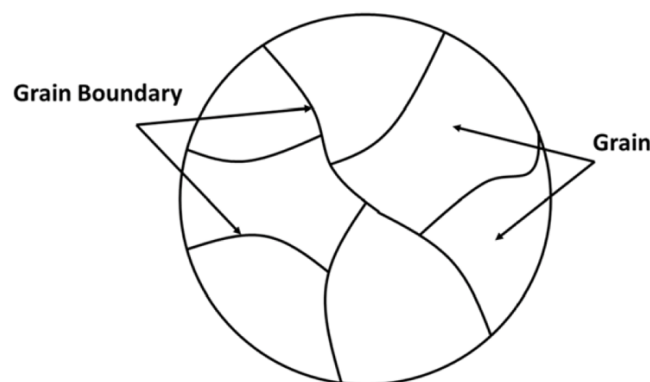


Fig 2.1: Schematic representation of a microstructure consisting of grains and grain boundaries.

- **Component:** The independent chemical species that make up a system (e.g., elements, ions, or compounds). A pure metal is a single-component system; a two-metal alloy is a two-component system. A component does not dissociate under the processing conditions (e.g., Fe_3C , cementite, is a component in steel).
- **Solid Solution:** A homogeneous, solid mixture of two or more substances where the atoms or molecules share a crystal lattice.

- **Types of Solid Solutions:**

1. **Substitutional Solid Solution:** Solute atoms replace solvent atoms in their lattice sites.
2. **Interstitial Solid Solution:** Solute atoms occupy the spaces (interstices) between solvent atoms.

▪ **EXAMPLE:** STEEL IS AN INTERSTITIAL SOLID SOLUTION OF CARBON IN IRON.

Phase: A physically distinct, chemically homogeneous, and mechanically separable portion of a system with a unique composition and/or microstructure. A system can be single-phase or multi-phase.

Phase Transformation: The process where the phases in a system change as a function of temperature and/or pressure. Controlling this process is key to achieving a material's desired final properties.

- **Equilibrium:** A state where a system's free energy is at a minimum under defined conditions of pressure, temperature, and composition. Its thermodynamic properties do not change with time.
 - **Metastable Equilibrium (State A):** A local minimum in free energy. The system is stable against small fluctuations but may transition to a more stable state.
 - **Stable Equilibrium (State B):** The global minimum in free energy. This is the most stable state.
 - **Unstable Equilibrium:** A short-lived state at a local maximum of free energy.
 - **DIAGRAM REFERENCE:** FIG. 2.2 - SCHEMATIC ILLUSTRATING DIFFERENT STATES OF EQUILIBRIUM.
 - **A system is in thermodynamic equilibrium** when mechanical, chemical, and thermal equilibrium coexist.

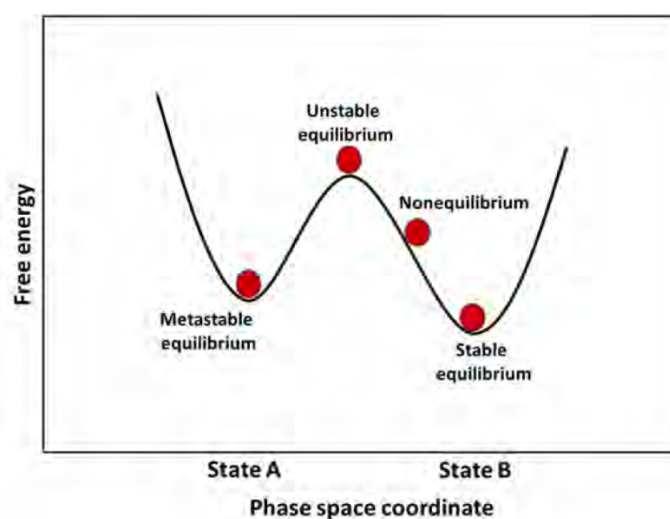


Fig. 2.2: Schematic illustrating the different states of equilibrium

2.2 THE PHASE RULE

Derived by J.W. Gibbs, the Phase Rule is a fundamental equation that determines the number of phases that can coexist in equilibrium in a system.

$$[P + F = C + 2]$$

Where:

- **P** = Number of phases present
- **F** = Number of degrees of freedom (the number of independent variables - T, P, composition - that can be changed without altering the number of phases)
- **C** = Number of components in the system
- **2** = Represents the two variables: temperature (T) and pressure (P)

Interpretation of Degrees of Freedom (F):

- **F = 0 (Invariant System):** No variables can be changed without causing a phase change.
- **F = 1 (Univariant System):** One variable can be changed independently within a limit.
- **F = 2 (Bivariant System):** Two variables can be changed independently.

EXAMPLE: THE WATER (H₂O) SYSTEM (C=1)

- **DIAGRAM REFERENCE:** FIG. 2.3 - PRESSURE-TEMPERATURE DIAGRAM FOR H₂O.

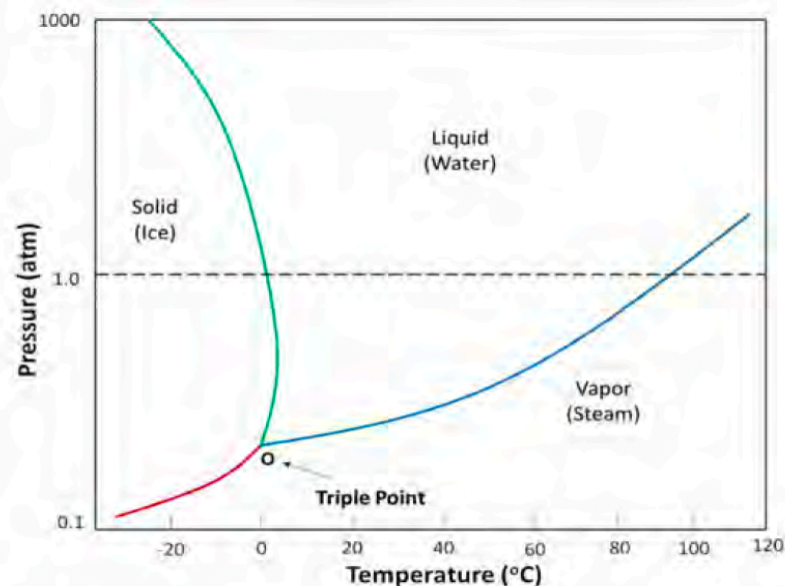


Fig 2.3: Pressure-temperature diagram of H₂O.

- **At the Triple Point (O):** Solid (ice), Liquid (water), and Vapor (steam) coexist. P=3.

$$3+F=1+2 \Rightarrow F=0(\text{Invariant})$$

- **Along the Freezing Curve (Green Line):** Solid and Liquid coexist. $P=2$.

$$2+F=1+2 \Rightarrow F=1(\text{Univariant})$$

- **In the Liquid Region:** Only Liquid phase exists. $P=1$.

$$1+F=1+2 \Rightarrow F=2(\text{Bivariant})$$

For Metallurgical Systems: Pressure is often constant (e.g., 1 atm). This reduces the variables by one, simplifying the phase rule to:

$$[P + F = C + 1]$$

2.3 UNARY PHASE DIAGRAM

A unary phase diagram describes a system with a single component (e.g., pure iron, pure carbon). The variables are pressure and temperature.

- Also known as a **Pressure-Temperature (P-T) Diagram**.

- **EXAMPLES:**

- **FIG. 2.4:** P-T DIAGRAM FOR PURE IRON. SHOWS PHASE CHANGES (BCC TO HCP) AT VERY HIGH PRESSURES.

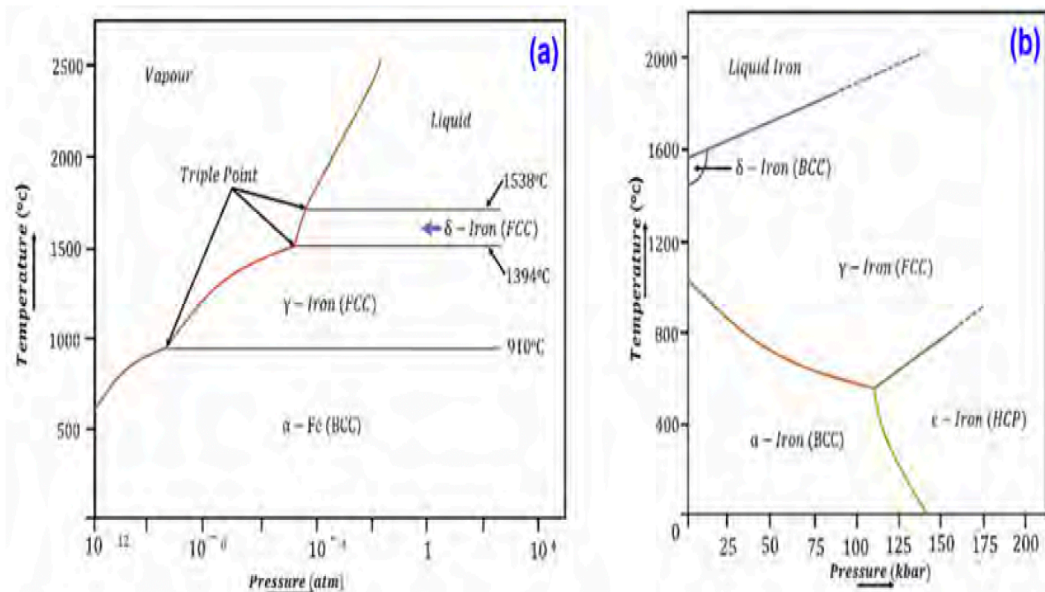


Fig. 2.4: Pressure-temperature diagram for pure Iron at (a) lower pressure range, and (b) higher pressure range (1 atm ~ 1.013 bar pressure).

- **FIG. 2.5:** P-T DIAGRAM FOR PURE CARBON. SHOWS TWO TRIPLE POINTS.

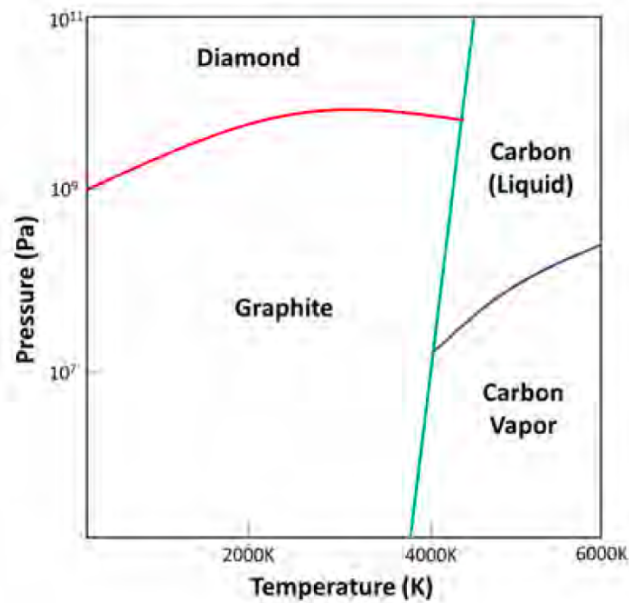


Fig. 2.5: Pressure-temperature diagram for pure carbon.

2.3.1 COOLING CURVES

A cooling curve is a plot of temperature vs. time for a material as it solidifies. It is used to determine phase transition temperatures.

- **DIAGRAM REFERENCE:** FIG. 2.6 - COOLING CURVE FOR A PURE METAL.

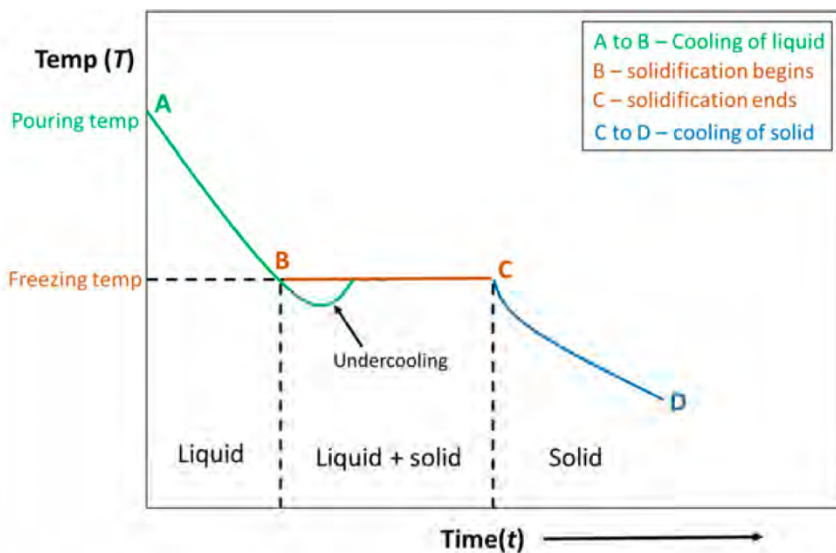


Fig. 2.6: Cooling curve of a pure metal

- **A-B:** Cooling of the liquid.
- **B:** Solidification begins (freezing point). Undercooling is often required to initiate nucleation.

- **B-C:** Solidification occurs. Temperature remains constant as the latent heat of fusion is released. The system is a mixture of solid and liquid.
- **C:** Solidification is complete.
- **C-D:** Cooling of the solid.

2.4 BINARY ISOMORPHOUS SYSTEM

A binary system has two components ($C=2$). An **isomorphous system** is one where the two components are completely soluble in each other in both the liquid and solid states, forming a single solid solution phase.

Phase Rule (at constant pressure): $P+F=C+1=3$

Constructing a Phase Diagram: Cu-Ni Example

- **DIAGRAM REFERENCE:** FIG. 2.7 - CONSTRUCTION OF A PHASE DIAGRAM FROM COOLING CURVES.

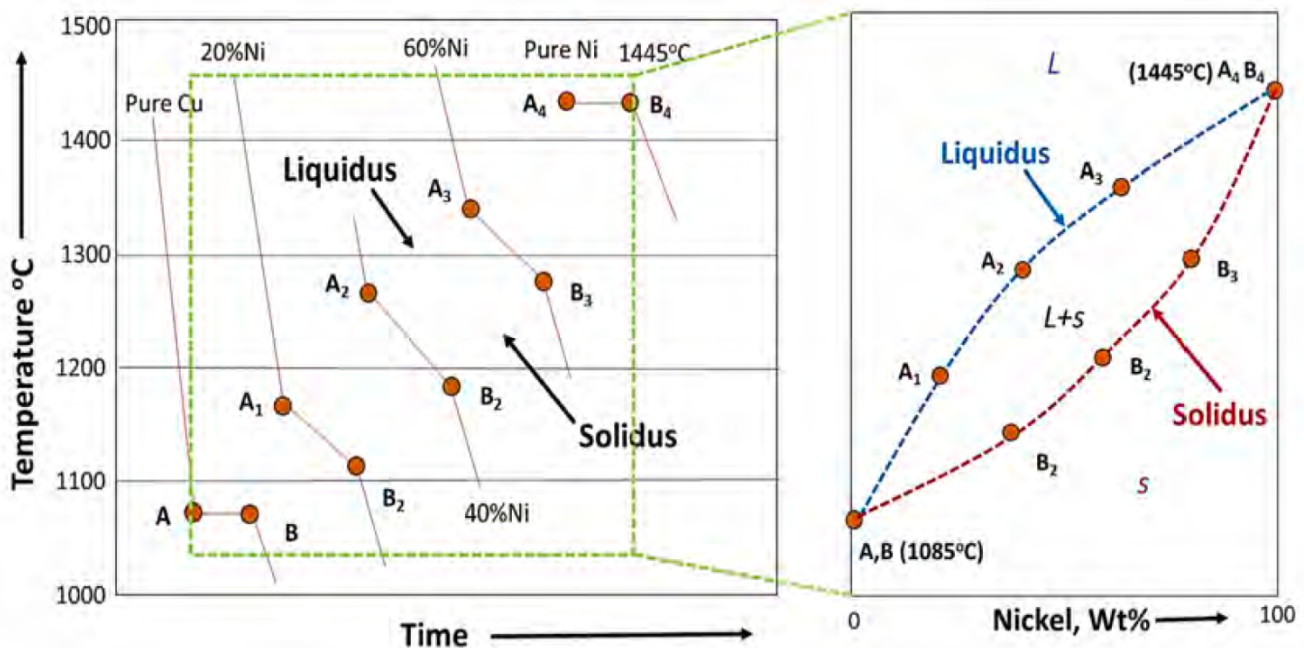


Fig 2.7: Phase diagram construction from the cooling curves

- Pure Cu and Pure Ni solidify at a constant temperature.
- Alloys solidify over a **range of temperatures**.
- **Liquidus Line:** The line (A-A₄) connecting the temperatures where solidification *begins*.
- **Solidus Line:** The line (B-B₄) connecting the temperatures where solidification *ends*.
- **Region above Liquidus:** Single-phase Liquid (L).
- **Region below Solidus:** Single-phase Solid Solution (α).

- **Region between Lines (Mushy Zone):** Two-phase region ($L + \alpha$).

DIAGRAM REFERENCE: FIG. 2.8 - COPPER-NICKEL (CU-NI) PHASE DIAGRAM.

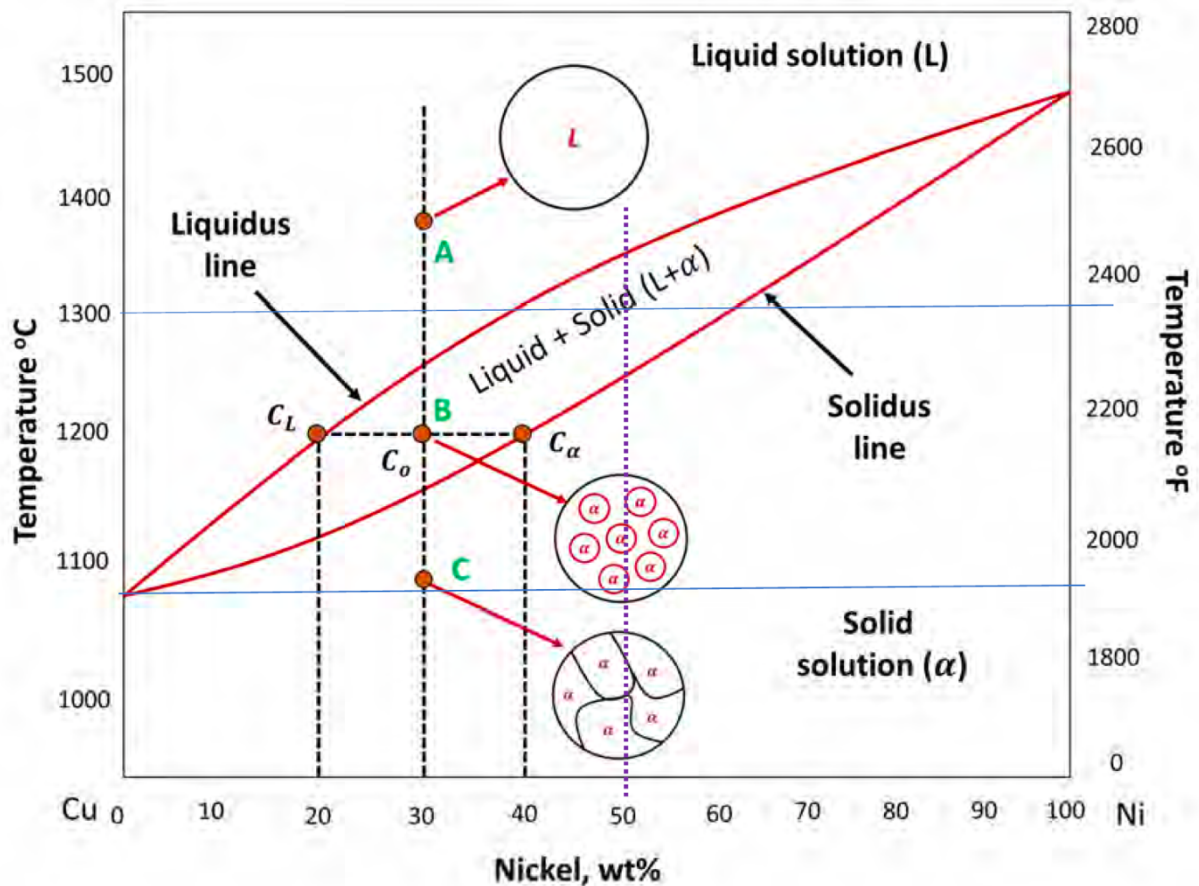


Fig 2.8: Copper-nickel phase diagram

- **X-axis:** Composition (0% Ni = 100% Cu; 100% Ni = 0% Cu)
- **Y-axis:** Temperature
- The melting points of pure Cu (1084°C) and pure Ni (1455°C) are invariant points ($F=0$).

Hume-Rothery Rules for Complete Solid Solubility:

For two elements to be completely soluble in the solid state (form an isomorphous system), they must satisfy:

1. **Atomic Size Difference:** $\leq 15\%$.
2. **Same Crystal Structure:** e.g., both FCC, both BCC.
3. **Similar Electronegativity:** To prevent compound formation.
4. **Same Valency.**

Cu and Ni satisfy all these rules (both FCC, similar radii and electronegativity).

2.4.1 PREDICTION OF PHASES

Locate the point on the diagram defined by the alloy's composition and temperature. The phase field in which the point lies tells you the phase(s) present.

- **EXAMPLE (FIG 2.8):** 30WT%NI-70WT%CU ALLOY.
 - At 1315°C (Point A): In Liquid (L) field → **All Liquid**
 - At 1190°C (Point B): In (L + α) field → **Mixture of Liquid and Solid**
 - At 1095°C (Point C): In Solid (α) field → **All Solid**

2.4.2 DETERMINING CHEMICAL COMPOSITIONS OF PHASES

- **Single-Phase Region:** The composition of the phase is the same as the overall alloy composition.
- **Two-Phase Region:**
 1. Draw a horizontal **tie line** at the temperature of interest.
 2. The intersections of the tie line with the phase boundaries give the compositions of the two phases.
 - Intersection with the **liquidus** gives the composition of the liquid phase (**C_L**).
 - Intersection with the **solidus** gives the composition of the solid phase (**C_α**).
- **EXAMPLE (FIG 2.8, POINT B):** FOR 30%NI ALLOY AT 1190°C.
 - C_L = 20% Ni (from liquidus intersection)
 - C_α = 40% Ni (from solidus intersection)

2.4.3 PREDICTION OF AMOUNTS OF PHASES: THE LEVER RULE

The Lever Rule is used to calculate the weight fraction or percentage of each phase in a two-phase region.

Procedure:

1. Draw the tie line at the temperature of interest.
2. Identify the three critical compositions on the tie line:
 - **C_o**: Overall composition of the alloy.
 - **C_L**: Composition of the liquid phase.
 - **C_α**: Composition of the solid phase.
3. Apply the lever rule equations:

$$\text{Weight Fraction of Liquid} = \frac{C_{\alpha} - C_L}{C_{\alpha} - C_o}$$

$$\text{Weight Fraction of Solid} = \frac{C_o - C_L}{C_{\alpha} - C_L}$$

Multiply the fractions by 100 to get **weight percentages**.

- **EXAMPLE (FIG 2.10):** FOR A 40WT%B ALLOY AT THE TEMPERATURE SHOWN.

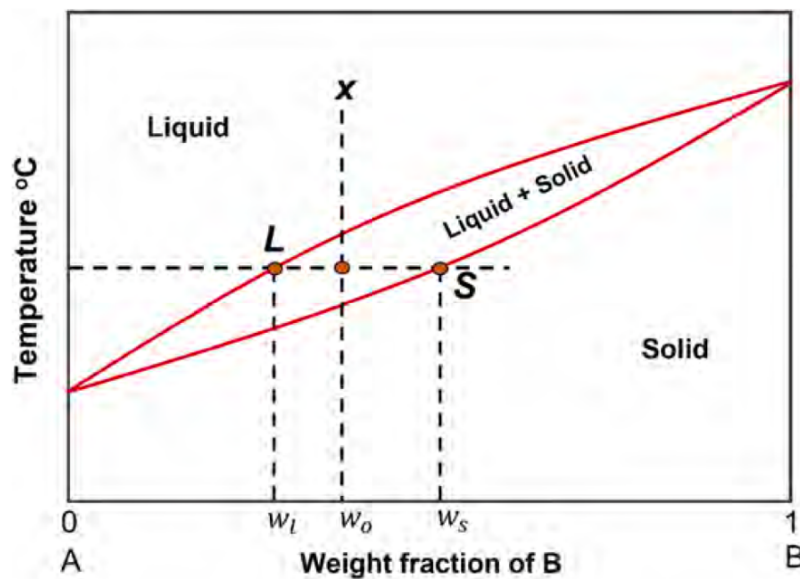


Fig. 2.10: A hypothetical phase diagram of two metals A and B completely soluble in each other.

- $C_O = 40\% \text{ B}$
- $C_L = 30\% \text{ B}$
- $C_\alpha = 55\% \text{ B}$
- $\text{Wt\% Liquid} = (55 - 40) / (55 - 30) * 100 = 60\%$
- $\text{Wt\% Solid} = (40 - 30) / (55 - 30) * 100 = 40\%$

Solved Problem Q 2.1 (Cu-Ni System):

- Alloy: 47% Cu, 53% Ni at 1300°C.
- **(1) Compositions:** From tie line in Fig 2.8:
 - Solid Phase (α) contains **38% Cu**
 - Liquid Phase (L) contains **62% Cu**
- **(2) Amounts:** Using lever rule on Ni composition:
 - $w_o = 53\% \text{ Ni}$, $w_l = 45\% \text{ Ni}$, $w_s = 58\% \text{ Ni}$
 - $\text{Wt\% Liquid} = (58 - 53) / (58 - 45) = 5/13 \approx 38\%$
 - $\text{Wt\% Solid} = (53 - 45) / (58 - 45) = 8/13 \approx 62\%$

Other Example: Fig. 2.9 shows a binary isomorphous phase diagram for the ceramic system $\text{Al}_2\text{O}_3 - \text{Cr}_2\text{O}_3$.

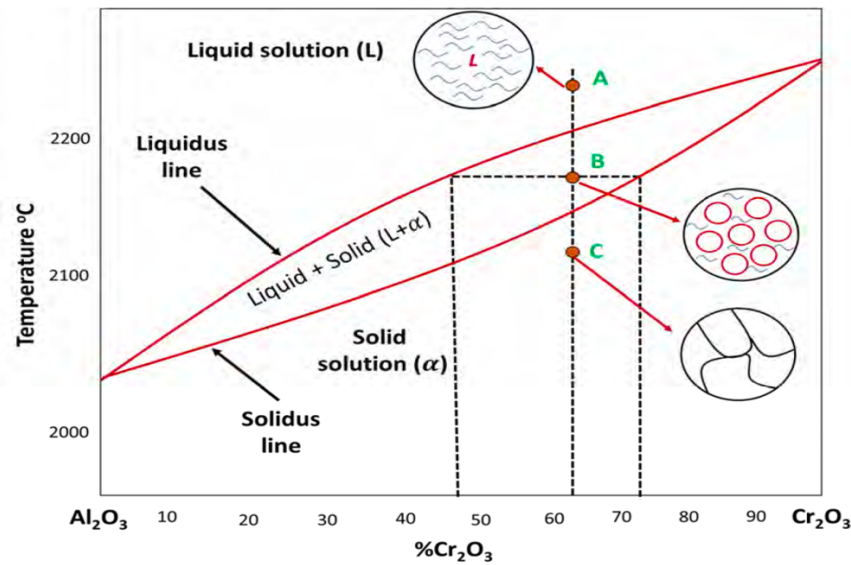


Fig. 2.9: $\text{Al}_2\text{O}_3 - \text{Cr}_2\text{O}_3$ phase diagram

2.5 EUTECTIC REACTION

A eutectic reaction is a three-phase invariant reaction where a single liquid phase transforms into two different solid phases upon cooling at a specific temperature and composition.

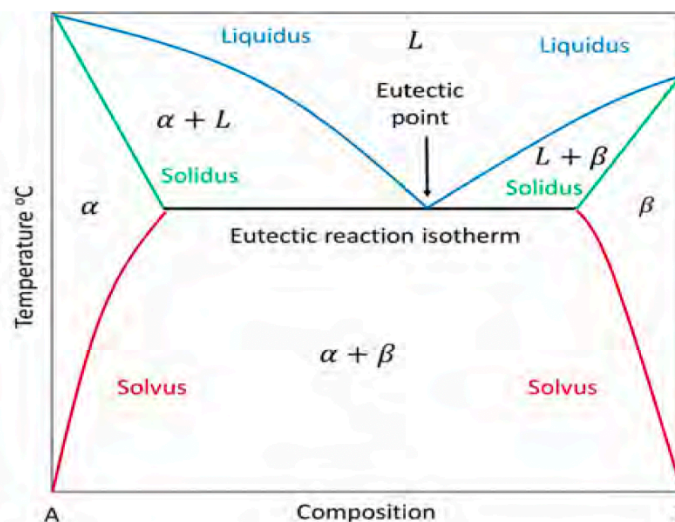
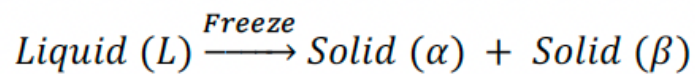


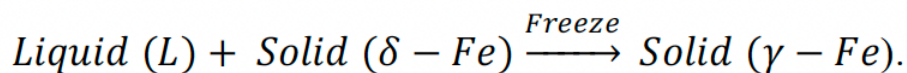
Fig 2.11: Phase diagram displaying eutectic reaction

- **Eutectic Point:** The specific composition and temperature where the eutectic reaction occurs. It is the point of lowest melting temperature in the system.
- **Eutectic Isotherm:** The horizontal line at the eutectic temperature.

- **Hypoeutectic Alloy:** Composition to the *left* of the eutectic point.
- **Hypereutectic Alloy:** Composition to the *right* of the eutectic point.
- **Proeutectic Phase:** The solid phase that forms *above* the eutectic temperature before the remaining liquid undergoes the eutectic reaction.

2.6 PERITECTIC REACTION

A peritectic reaction is a three-phase invariant reaction where a liquid phase and a solid phase react together upon cooling to form a single, new solid phase.



- **Difference from Eutectic:** Eutectic: $L \rightarrow \alpha + \beta$. Peritectic: $L + \alpha \rightarrow \beta$.
- **DIAGRAM REFERENCE:** FIG. 2.12 - PERITECTIC REACTION IN THE CARBON-STEEL SYSTEM.

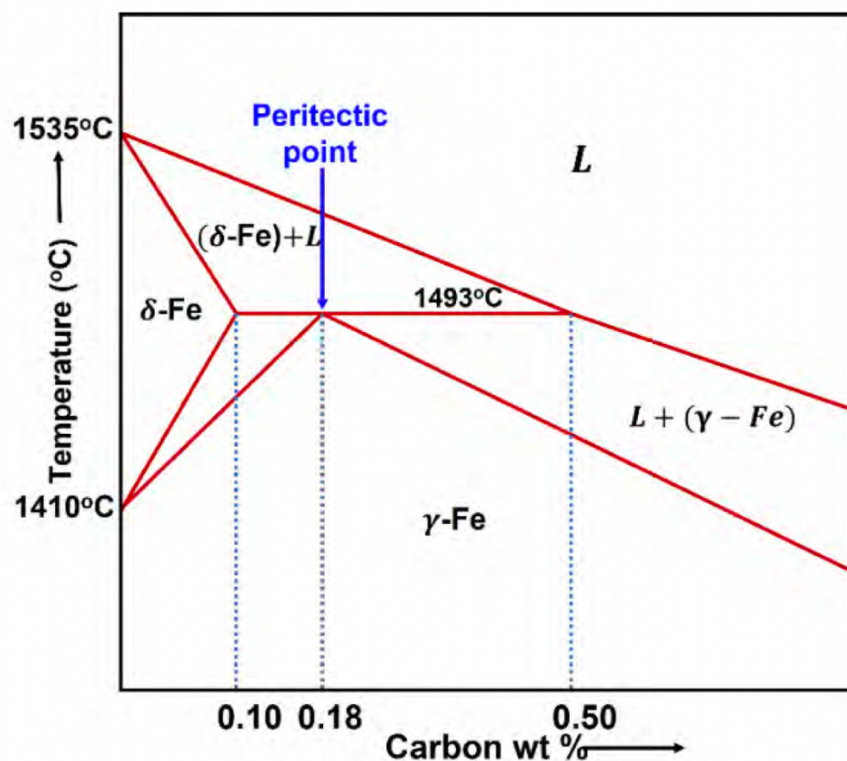


Fig. 2.12: Schematic of peritectic reaction for carbon steel

- This reaction occurs at 1493°C for a composition of ~0.18% Carbon.
- A common microstructural feature is **surrounding**, where the new product phase (γ-Fe) surrounds the parent solid phase (δ-Fe), isolating it from the liquid.

2.7 FERROUS METALS

2.7.1 TYPES OF IRON

Iron is the base for the most significant engineering alloys (steels and cast irons).

- **Commercially Pure Iron:** Not commonly used. Types include:
 - Ingot Iron
 - Electrolytic Iron
 - Hydrogen Purified Iron
 - Carbonyl Iron
- These are relatively soft. Their strength can be increased by:
 1. **Strain Hardening (Cold Working)**
 2. **Alloying** (especially with carbon).
- **Armco Ingot Iron** is a well-known trade name for commercially pure iron.

2.7.2 IRON-CARBON (Fe-Fe₃C) PHASE DIAGRAM

The Iron-Carbon phase diagram is the most important in engineering, forming the basis for understanding steels and cast irons. The metastable Fe-Fe₃C diagram is used because cementite (Fe₃C) forms more readily than graphite in most steels.

- **Components:** Fe and Fe₃C (Iron Carbide or Cementite)
- **X-axis:** Weight % of Carbon (0% to 6.67%)
- **Y-axis:** Temperature

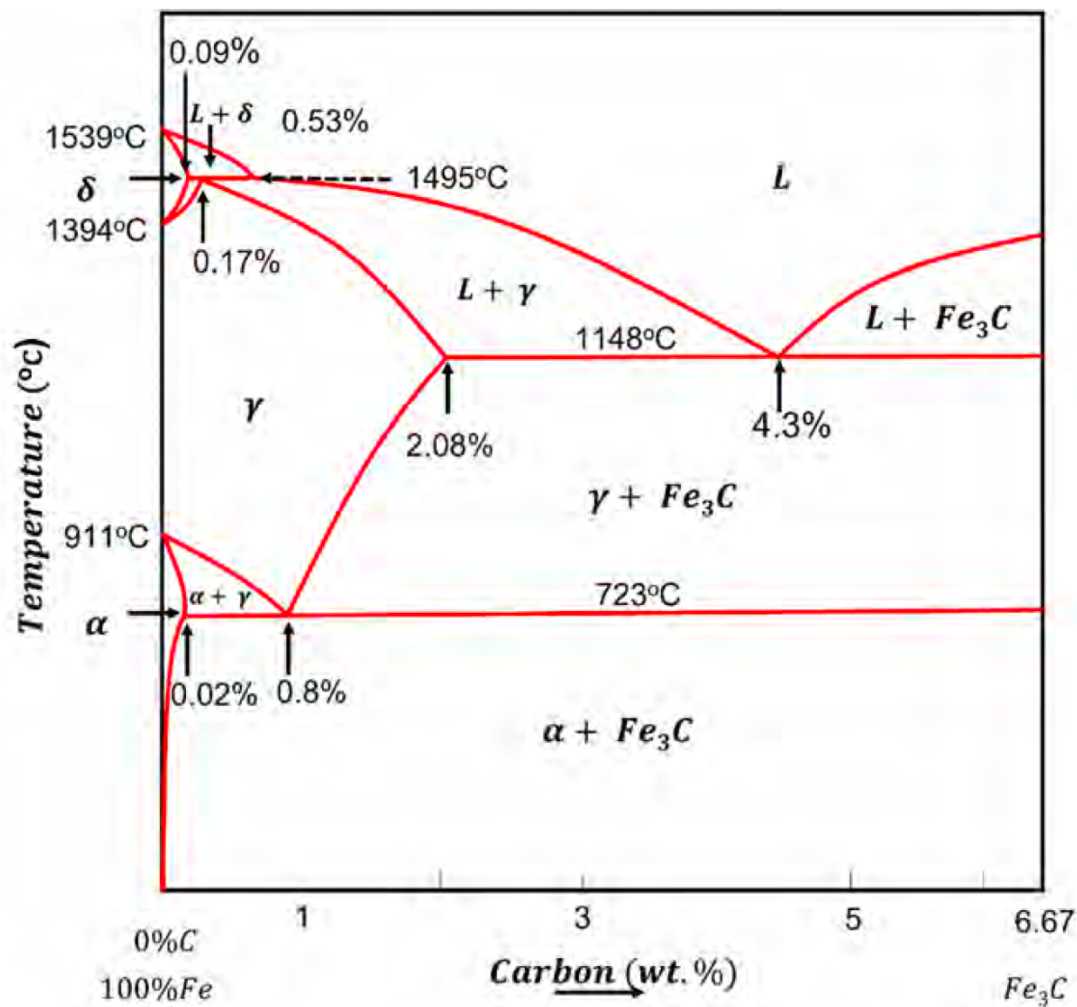


Fig 2.13: The iron-iron carbide phase diagram

DIAGRAM REFERENCE: FIG. 2.13 - THE IRON-IRON CARBIDE (FE-Fe₃C) PHASE DIAGRAM.

Four Key Solid Phases:

1. α -Ferrite:

- An interstitial solid solution of carbon in Body-Centered Cubic (BCC) iron.
- Very low solubility of carbon: max. **0.02 wt.%** at 723°C, decreasing to ~0.005% at room temperature.
- Relatively soft, ductile, and magnetic.

2. γ -Austenite:

- An interstitial solid solution of carbon in Face-Centered Cubic (FCC) iron.

- High solubility of carbon: max. **2.08 wt.%** at 1148°C, decreasing to 0.8% at 723°C.
- Non-magnetic. This is the phase in which most heat treatments of steel are performed.

3. **δ-Ferrite:**

- The high-temperature BCC phase of iron, stable above 1394°C.
- Maximum carbon solubility is **0.09 wt.%** at 1495°C.

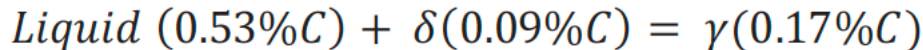
4. **Cementite (Fe₃C):**

- An intermetallic compound with a fixed composition of **6.67 wt.% C**.
- Orthorhombic crystal structure.
- Very hard, brittle, and metallic.

2.7.3 INVARIANT REACTIONS IN THE FE-Fe₃C DIAGRAM

Three crucial invariant (F=0) reactions occur:

1. **Peritectic Reaction (at 1495°C):**



- Occurs in low-carbon steels. The δ-ferrite phase reacts with the liquid to form austenite.

2. **Eutectic Reaction (at 1148°C):**



- The mixture of austenite and cementite formed is called **Ledeburite**.
- This reaction defines the boundary between steels (<2.08% C) and cast irons (>2.08% C).

3. **Eutectoid Reaction (at 723°C):**



- The lamellar mixture of α-ferrite and cementite formed is called **Pearlite**.
- **Eutectoid Steel:** Exactly 0.8% C.
- **Hypoeutectoid Steel:** <0.8% C (microstructure: proeutectoid ferrite + pearlite).

- **Hypereutectoid Steel:** >0.8% C (microstructure: proeutectoid cementite + pearlite).

2.7.4 COOLING OF PLAIN CARBON STEEL

- The cooling rate determines the fineness of the pearlite and thus the hardness.
 - **Furnace Cooling:** Coarse pearlite → Low Hardness (~5 Rc)
 - **Air Cooling:** Fine pearlite → Medium Hardness (20-25 Rc)
 - **Very Fast Cooling:** Very fine pearlite → High Hardness (~40 Rc)
- **Bainite:** A fine, non-lamellar mixture of **ferrite and cementite** formed by cooling austenite rapidly and holding it at a constant temperature.

Properties vs. Carbon Content:

- As carbon content increases, the amount of hard, brittle cementite increases.
- **Result:** Hardness and strength increase, while ductility and impact resistance decrease.

Applications of Plain Carbon Steels (Table 2.1):

Carbon %	Type	Typical Uses
0.0 - 0.1	Mild Steel	Car bodies, refrigerator bodies, rivets
0.1 - 0.3	Mild Steel	Ship hulls, structural components, bridges
0.4 - 0.5	Medium Carbon	Train axles and wheels
0.5 - 0.6	Medium Carbon	Rails
0.8 - 0.9	High Carbon	Hammers, saw cutters
1.0 - 1.1	High Carbon	Axes
1.1 - 1.2	High Carbon	Razor blades

Carbon %	Type	Typical Uses
1.3 - 1.4	High Carbon	Files, knives, scissors

Cast Irons (>2% C):

- **White Cast Iron:** Carbon is in the form of cementite. Very hard and brittle. Microstructure: Cementite + Pearlite.
- **Gray Cast Iron:** Carbon is in the form of **graphite flakes**. The fractured surface appears gray.
 - **DIAGRAM REFERENCE:** FIG. 2.14A - MICROSTRUCTURE OF GRAY CAST IRON (GRAPHITE FLAKES IN FERRITE MATRIX).
 - Excellent machinability and vibrational damping but brittle under tension due to stress concentration at flake tips.

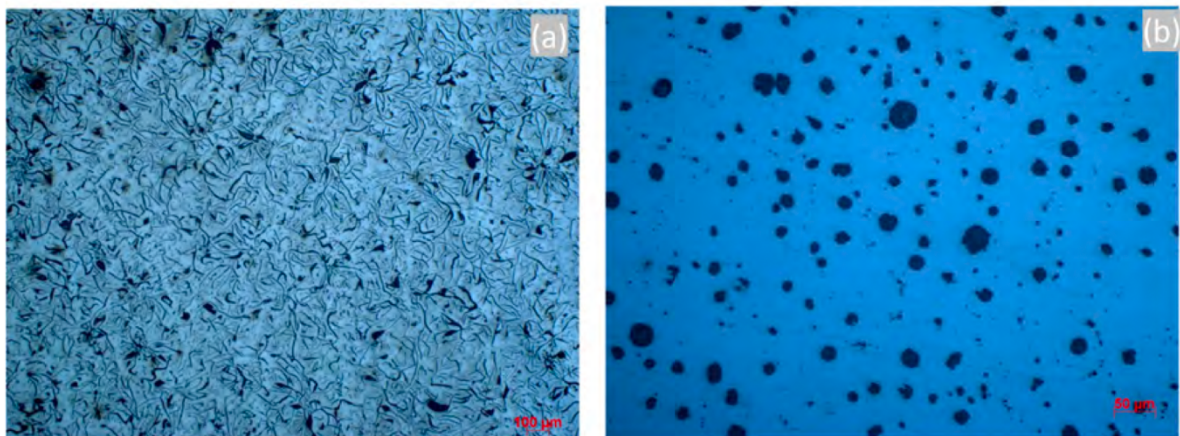


Fig. 2.14: Typical microstructure of (a) Gray cast iron, and (b) spheroidal graphite iron.

- **Malleable Cast Iron:** Produced by heat-treating white cast iron. Graphite forms as **clusters (temper carbon)**. Better ductility than gray iron.
- **Nodular (Ductile) Cast Iron:** Treated with Mg or Ce to make graphite form as **spheres (nodules)**.
 - **DIAGRAM REFERENCE:** FIG. 2.14B - MICROSTRUCTURE OF SPHEROIDAL GRAPHITE IRON.
 - Combines the castability of iron with good strength and ductility.

2.8 IRON AND STEEL MAKING

2.8.1 & 2.8.2 HISTORY

- **Early Sources:** Meteoric iron and native (telluric) iron were scarce.

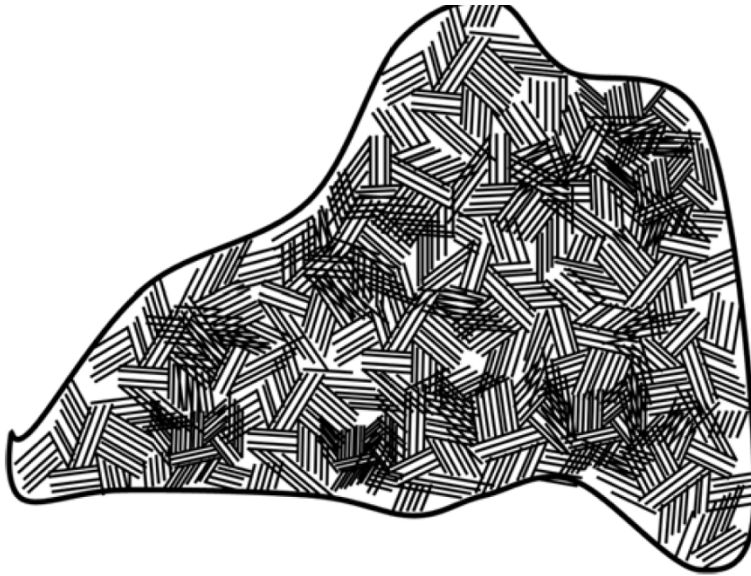


Fig. 2.15: Schematic of a heavily etched iron meteorite structure.

- **Smelting:** Developed around 2000 BC. Involved heating iron ore with charcoal for reduction.

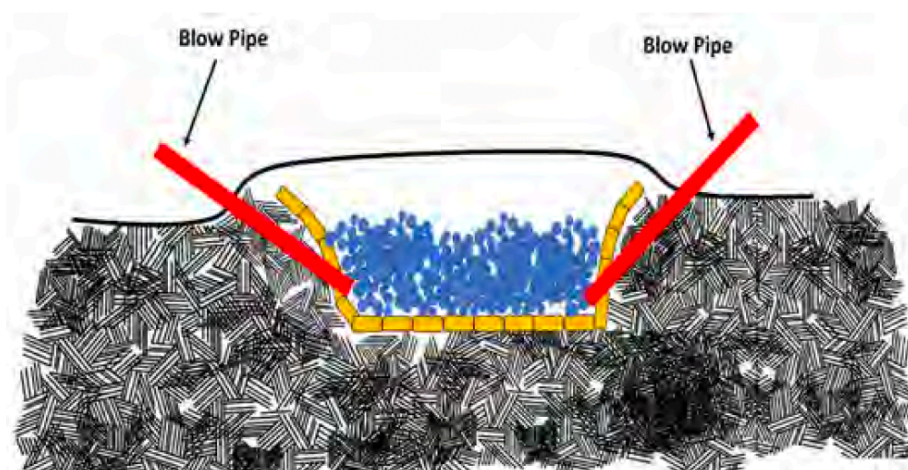


Fig. 2.16: An early open-pit iron furnace.

- **Wootz Steel:** A high-carbon crucible steel produced in India (~300 BC - 1700 AD). Famous for its use in **Damascus swords**, which had a characteristic wavy pattern from bands of carbide particles. The secret involved specific ores with V and Mo and a complex forging/decarburation process.

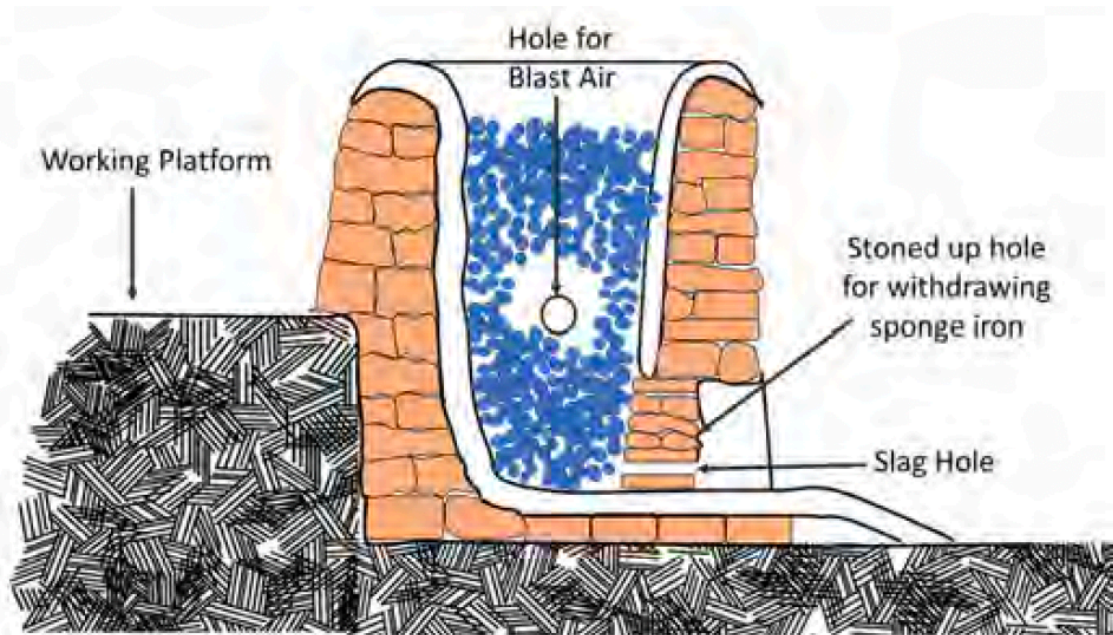


Fig. 2.17: An early shaft-type iron furnace.

- **Blast Furnace:** Evolved from early shaft furnaces. Use of coke (instead of charcoal) began in the 17th century.

2.8.3 MODERN FABRICATION PROCESS

The most common modern route is the **Blast Furnace - Basic Oxygen Furnace (BF-BOF)** process.

DIAGRAM REFERENCE: FIG. 2.18 - FLOWCHART FOR IRON AND STEEL PRODUCTION.



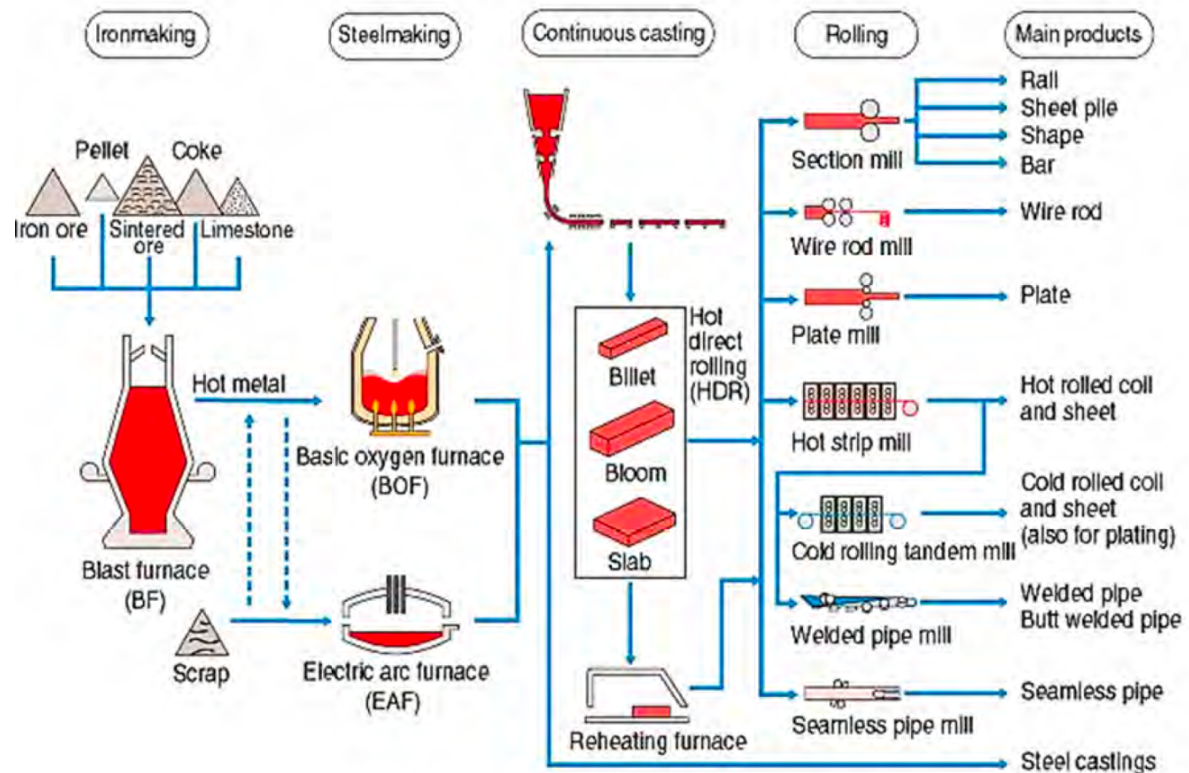


Fig. 2.18: Flow chart displaying production of Iron and Steel.

Key Steps:

1. **Blast Furnace (BF):** Iron ore (Fe_2O_3), coke (C), and limestone (flux) are fed in. Coke is oxidized to CO, which reduces the ore to impure molten **pig iron** ("hot metal") containing ~4% C.
2. **Basic Oxygen Furnace (BOF):** The hot metal is charged into the BOF along with scrap steel. Pure oxygen is blown in to oxidize and remove excess carbon (decarburization) and other impurities, producing molten steel of the desired composition.
3. **Secondary Steelmaking:** Alloying elements are added, and the steel is deoxidized (e.g., with Si or Al).
4. **Continuous Casting:** Molten steel is cast into semi-finished shapes like slabs, blooms, or billets.
5. **Forming:** The cast shapes are hot-rolled (and often cold-rolled) into final products like plates, sheets, bars, rods, and pipes.

Alternative Route: Electric Arc Furnace (EAF)

- Uses primarily **scrap steel** as the input.
- Melting is achieved using a powerful electric arc.
- More flexible and energy-efficient for recycling scrap.

2.8.4 PIG IRON

- The crude, impure iron (with ~4% C and other impurities) directly from the blast furnace.
- It is the basic raw material for producing all other ferrous products: cast iron, wrought iron, and steel.
- **Manufacturing Steps:** Dressing → Calcination/Roasting → Smelting in a Blast Furnace.

2.9 IRON AND STEEL HERITAGE OF INDIA

India has a rich and ancient history in iron and steel production.

- **1100 BC:** Evidence of iron objects from megalithic sites.
- **300 BC:** Crucible steel processes (precursor to Wootz steel) in South India.
- **AD 400:** The **Delhi Iron Pillar** (7 tons, 8m tall) was constructed. It is famous for its exceptional corrosion resistance, achieved through a protective passive layer and high phosphorus content.
- **17th Century:** Significant export of Wootz steel from Golconda to Persia.
- **Modern Era:** Establishment of major steel plants (TISCO - 1907, Bhilai, Rourkela, Durgapur - 1950s, Bokaro - 1972, SAIL - 1978).

TABLE REFERENCE: TABLE 2.3 - TIMELINE OF IRON AND STEEL IN INDIAN HISTORY.

Table 2.2 The three ages of civilization describing the Iron age evolution.

Stone Age	1,000,000 BC	Human beings on earth
Chalcolithic Age	8000 BC	Native copper, native gold
	6500 BC	Smelting of copper from malachite Arsenical Bronze- an accidental alloy
Bronze Age	4000 BC	Silver
	3000 BC	Tin Bronze
	2900 BC	First handmade iron object in the great pyramid of Giza
	2500 BC	Lead in Indus valley, India/Pakistan
	1750 BC	Tin
	1500 BC	Bronze by Shang dynasty in China Chinese princess discovers silk
	1200 BC	Smelting of iron by Hittites
Iron Age	1000-500 BC	Wrought and quenched high-tin beta bronze vessels in South Indian megalithic and iron age sites
	1000-700 BC	Greeks and Indians quench and temper iron to improve the cutting characteristics
	500 BC	Deepest old gold mine at Maksi, India
	500 BC	Gold, copper-gold, gold-platinum alloys
	500 BC	Reference to diamond in Indian Sanskrit texts
	300 BC	Crucible steel in South India, later known as wootz
	200 BC	Cast iron in China
	100 BC	Development of silk road
	AD400-420	Delhi Iron Pillar
	AD 1200	Zinc smelting at Zawar, India
	AD 1400	Blast furnace of iron making
	AD 1856	Bessemer steel

2.10 CAST IRONS (DETAILED)

Cast irons are ferrous alloys with $>2.08\%$ C, designed to be cast into shape.

2.10.1 WHITE CAST IRON

- **Composition:** 1.8–3.6% C, 0.5–1.9% Si.
- **Microstructure:** Cementite + Pearlite.
- **Properties:** Very hard, brittle, excellent wear resistance. Fractured surface appears white.
- **Use:** Wear-resistant applications, raw material for malleable iron.

2.10.2 GRAY CAST IRON

- **Composition:** 2.5–4.0% C, 1.0–3.0% Si.
- **Microstructure:** **Graphite flakes** in a ferrite/pearlite matrix.
- **Properties:** Easy to cast and machine, good damping capacity, brittle under tension.
- **Use:** Engine blocks, flywheels, cylinder heads.

2.10.3 MALLEABLE CAST IRON

- **Composition:** 2.0–2.6% C, 1.1–1.6% Si.
- **Microstructure:** **Temper carbon nodules** (clusters) in a ferrite matrix. Produced by heat-treating white iron.
- **Properties:** Good strength and ductility (elongation 10-15%).
- **Use:** Automotive crankshafts, chain links, brackets.

2.10.4 NODULAR (DUCTILE) CAST IRON

- **Composition:** 3.0–4.0% C, 1.8–2.8% Si. Treated with **Magnesium (Mg)**.
- **Microstructure:** **Spherical graphite nodules** in a ferrite/pearlite matrix ("bull's eye" structure).
- **Properties:** Excellent combination of strength, ductility, and castability.
- **Use:** Crankshafts, pipes, gears.

2.11 STEEL

2.11.1 STEEL SPECIFICATIONS

- **Indian Standard (IS):** e.g., **IS: C15** = Carbon steel with 0.15% C. **IS: 20Mn1** = 0.20% C, 1.0% Mn. **IS: T105Cr1Mn60** = Tool steel with 1.05% C, 1.0% Cr, 0.60% Mn.
- **AISI-SAE Standard (USA):** 4-digit number.
 - First two digits: Main alloying element(s).

- Last two digits: Carbon content in hundredths of a percent.
- **EXAMPLE: 1040** = PLAIN CARBON STEEL WITH 0.40% C. **4340** = NI-CR-MO STEEL WITH 0.40% C.
- **Other Standards:** British (En, BS), German (DIN), Russian (GOST), Japanese (JIS).

TABLE REFERENCE: TABLE 2.4 - AISI-SAE CLASSIFICATION OF STEELS (E.G., 10XX = PLAIN CARBON, 41XX = CR-MO STEEL).

2.11.2 PLAIN CARBON STEEL

Classified based on carbon content:

1. **Low Carbon Steel (Mild Steel):** <0.30% C
 - **Properties:** Inexpensive, soft, ductile, easily formed, weldable.
 - **Use:** Structural beams, car bodies, sheets, wires.
2. **Medium Carbon Steel:** 0.30% - 0.85% C
 - **Properties:** Higher strength, lower ductility, can be heat treated.
 - **Use:** Railway tracks, gears, shafts.
3. **High Carbon Steel:** 0.85% - 1.50% C
 - **Properties:** Very hard, strong, low ductility, difficult to weld.
 - **Use:** Springs, cutting tools, blades.

Limitations of Plain Carbon Steels:

- Low strength at high temperature.
- Low corrosion/oxidation resistance.
- Low hardenability (can't be hardened in thick sections).
- Soften rapidly during tempering.

2.12 ALLOY STEELS

Alloy steels contain intentional additions of other elements (Cr, Ni, Mo, V, etc.) to overcome the limitations of plain carbon steels.

- **Low Alloy Steel:** $\leq 5\%$ total alloying elements.
- **Medium Alloy Steel:** $> 5\%$ to $\leq 10\%$.
- **High Alloy Steel:** $> 10\%$ (e.g., stainless steels).

Purpose of Alloying:

- Increase hardenability.
- Improve strength and toughness.
- Enhance corrosion/oxidation resistance.
- Retain hardness at high temperatures (red hardness).
- Improve wear resistance.

2.12.1 SILICON STEEL

- **Key Feature:** Soft magnetic material.
- **Composition:** Up to $\sim 3.2\%$ Si, very low C ($< 0.01\%$).
- **Effect of Si:** Increases electrical resistivity (reduces eddy current losses), promotes grain growth.
- **Use:** Transformer cores, motor laminations, generator stator/rotor.

2.12.2 HIGH-SPEED STEEL (HSS)

- **Key Feature:** Retains hardness at high temperatures (Red-Hardness).
- **Composition:** High W, Mo, Cr, V, Co (e.g., 18%W-4%Cr-1%V).
- **Use:** Cutting tools (drills, taps, milling cutters), dies.
- **Types:** Tungsten-based (T-type) and Molybdenum-based (M-type).

2.12.3 HEAT RESISTING STEEL

- **Key Feature:** Resists oxidation and maintains strength at high temperatures.
- **Composition:** Typically, Fe-Cr-Ni austenitic stainless steels (e.g., 18-8, 25-20).

- **Use:** Furnace parts, heat treatment fixtures.

2.12.4 SPRING STEEL

- **Key Feature:** Very **high yield strength** and **elastic limit** (resilience).
- **Composition:** Medium to high carbon (0.5-0.65% C), often with Si (e.g., 55Si2Mn90) or Cr-V (e.g., 50Cr1V23).
- **Use:** Leaf springs, coil springs, saw blades.

2.12.5 MAGNET STEEL

- **Key Feature:** High **coercivity**.
- **Composition:** Historically high C, then W-steels, then high Co steels (e.g., 30-40% Co).
- **EXAMPLES:** CUNIFE (CU-NI-FE), VICALLOY (CO-FE-V). LARGELY REPLACED BY RARE-EARTH MAGNETS TODAY.

2.12.6 STAINLESS STEEL

Defined by a minimum of **~12% Chromium**, which forms a passive Cr-oxide layer for corrosion resistance.

Four Main Types:

1. **Ferritic (e.g., AISI 430):**
 - **Composition:** 12-30% Cr, low C.
 - **Properties:** Magnetic, moderate corrosion resistance, cannot be hardened by heat treatment.
 - **Use:** Construction, automotive trim.
2. **Martensitic (e.g., AISI 410, 440C):**
 - **Composition:** 12-17% Cr, higher C (0.15-1.0%).
 - **Properties:** Magnetic, can be hardened by heat treatment, lower corrosion resistance.
 - **Use:** Cutlery, tools, bearings.
3. **Austenitic (e.g., AISI 304, 316):**
 - **Composition:** 16-25% Cr, 7-20% Ni (Ni stabilizes austenite).

- **Properties:** Non-magnetic, excellent corrosion resistance, ductile, not heat treatable (but can be work-hardened).
 - **Use:** Chemical plants, food processing, architectural.
4. **Precipitation-Hardening (PH) (e.g., 17-4PH):**
- **Composition:** Cr, Ni, plus Al, Cu, Mo, Ti.
 - **Properties:** Can be strengthened to very high levels by a low-temperature aging heat treatment after hardening. Good corrosion resistance.
 - **Use:** Aerospace components, high-strength fittings.

End of Lecture Notes (Unit 2)



Lecture Notes: Unit 3 - Non-Ferrous Metals and Their Alloys

3.1 ALUMINIUM AND ITS ALLOYS

Aluminium is a lightweight (density: 2.7 g/cm^3), ductile, and malleable metal with excellent thermal and electrical conductivity. It forms a protective Al_2O_3 layer, providing superior corrosion resistance. Its melting point is 660°C . While pure aluminium has poor mechanical properties, alloying with elements like Cu, Si, Mg, Zn, Mn, and Ti significantly enhances its strength, weldability, workability, and corrosion resistance.

Key Phase Diagrams:

- **Al-Cu System (Fig. 3.1):** Maximum solubility of Cu in Al is 5.65 wt.% at 548°C , dropping to $<0.25\%$ at room temperature. This system is the basis for precipitation hardening.

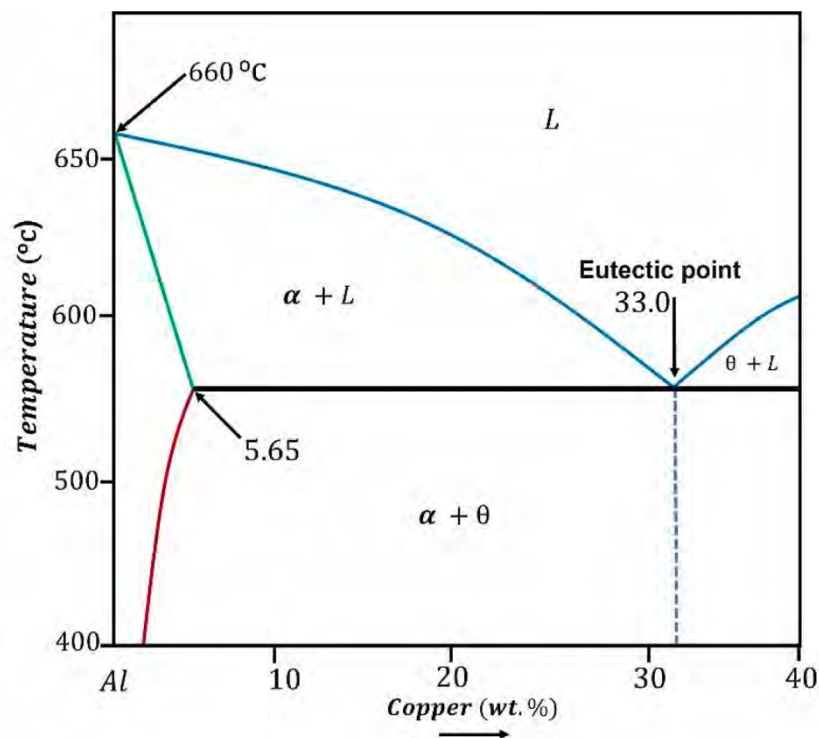


Fig. 3.1: Aluminium-rich end of the aluminium–copper equilibrium phase diagram

- **Al-Si System (Fig. 3.2):** Maximum solubility of Si in Al is 1.65 wt.% at 577°C . Silicon improves castability, fluidity, and reduces thermal expansion.

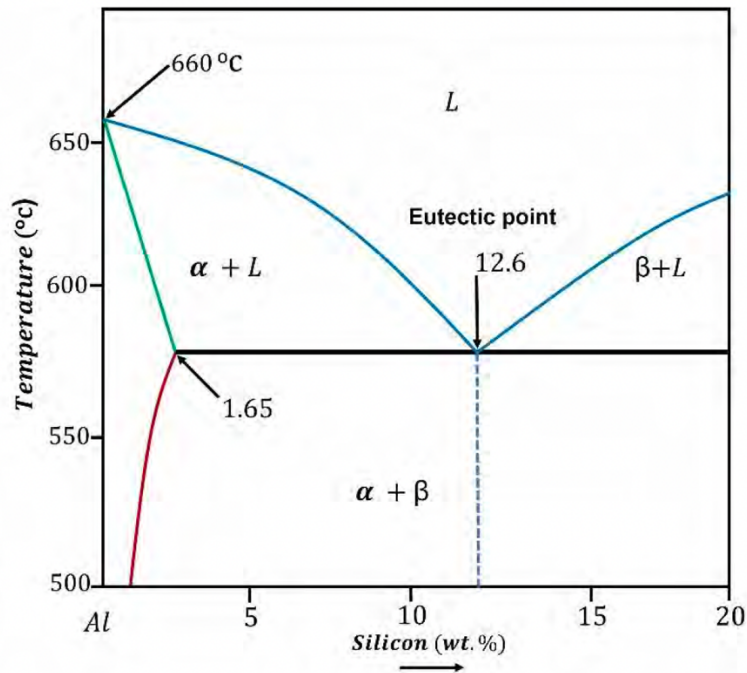


Fig. 3.2: Aluminium-rich end of the aluminium–silicon equilibrium phase diagram

3.1.1 DESIGNATION SYSTEM FOR WROUGHT ALUMINIUM ALLOYS

A four-digit code is used:

- **1xxx:** $\geq 99\%$ Al (Pure Aluminium)
- **2xxx:** Cu (Primary alloying element)
- **3xxx:** Mn
- **4xxx:** Si
- **5xxx:** Mg
- **6xxx:** Mg + Si (Forms Mg_2Si)
- **7xxx:** Zn
- **8xxx:** Other elements

Temper Designations (Suffix):

- **O:** Annealed
- **F:** As fabricated
- **H:** Strain-hardened (e.g., H14: strain-hardened to half-hard temper)
- **T:** Heat-treated (See Table 3.2 for specific T codes like T6 - Solutionized and artificially aged)

Table: 3.2 shows the designation used in the heat treatment of aluminium alloys.

Heat Treated (T)	Operation
T-1	Partial solution and natural ageing
T-2	Annealed cast product only
T-3	Solution and cold work
T-4	Solution and natural ageing
T-5	Artificial ageing only
T-6	Solution and artificial ageing
T-7	Solution and stabilizing
T-8	Solution, cold work, and artificial ageing

TABLE REFERENCE: TABLE 3.1 - MECHANICAL PROPERTIES AND APPLICATIONS OF COMMON ALUMINIUM ALLOYS (E.G., AA2024-T6 FOR AIRCRAFT STRUCTURES, AA6061-T6 FOR STRUCTURAL APPLICATIONS).

Table: 3.1: Mechanical properties and applications of Aluminium alloys.

Alloys Name	Composition	Condition /Heat treatment	Tensile Strength (MPa)	Yield strength (MPa)	% elongation	Applications
AA1100	99%Al+0.12%Cu	Annealed	89	24	25	Sheet metal work
AA2024	4.4 Cu+1.5Mg	Annealed	220	97	12	Aircraft structure
		T6	442	345	5	
AA3003	1.2 Mn	Annealed	117	34	23	Pressure vessels
AA5052	2.5 Mg+0.25 Cr	Annealed	193	65	18	Automobile
		H14	262	179	4	
AA6061	1Mg+0.6 Si+0.27 Cu	Annealed	152	82	16	Structural application
		T6	290	241	10	
AA7075	5.6Zn +2.5Mg+1.6Cu	Annealed	276	145	10	Aircraft
		T6	504	428	8	

3.1.2 SPECIAL ALUMINIUM ALLOYS

1. **Duralumin:** A famous trade name for a strong, heat-treatable Al-Cu (~4%) alloy with additions of Mg, Mn. Used in aircraft structures. Strengthened by precipitation hardening (CuAl_2 , Mg_2Si).
2. **Hiduminium (RR-58 / Y-alloy):** High-duty Al alloy for aircraft engines. Contains Cu (~4%), Ni (~2%), Mg (~1.5%). Excellent high-temperature strength and corrosion resistance.
3. **Hindalium:** A trade name for an Al-Mg-Mn-Si-Cr alloy. Strong, corrosion-resistant, scratch-resistant. Used for anodized utensils.
4. **Magnalium:** Al-Mg alloy (3-6% Mg). Lighter and stronger than pure Al. Used in aerospace, instruments, and pyrotechnics. High-Mg variants (>50% Mg) are brittle.

3.2 COPPER AND ITS ALLOYS

Copper (melting point: 1084°C) is known for its excellent electrical/thermal conductivity, corrosion resistance, and ease of fabrication.

3.2.1 BRASSES (CU-ZN ALLOYS)

DIAGRAM REFERENCE: FIG. 3.3 - CU-ZN PHASE DIAGRAM.

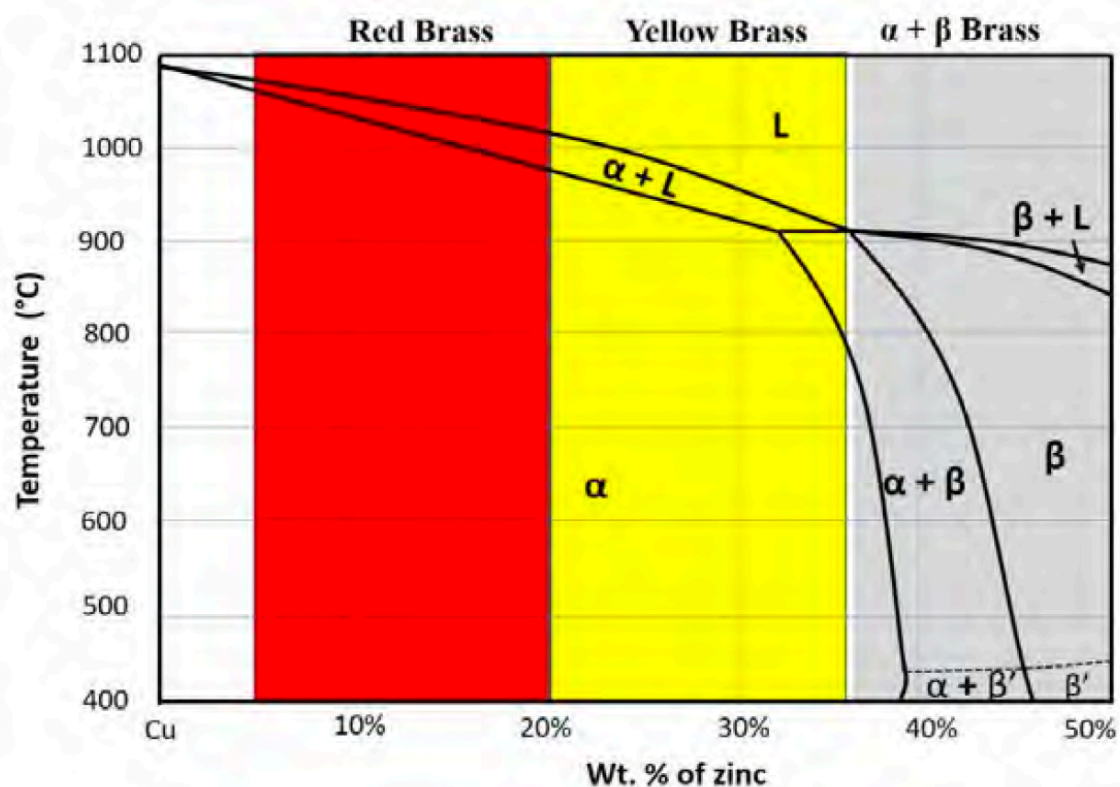


Fig. 3.3: Phase diagram of copper–zinc system.

- **Alpha (α) Brasses:** Zn < 36%. Single-phase, good cold workability.
 - **Red Brasses:** Zn 5-20% (e.g., Gilding metal: 95Cu-5Zn, Red Brass: 85Cu-15Zn). Excellent corrosion resistance, resist dezincification.
 - **Yellow Brasses:** Zn 20-36% (e.g., Cartridge Brass: 70Cu-30Zn). Best combo of strength and ductility.
- **Alpha-Beta ($\alpha+\beta$) Brasses:** Zn 36-45% (e.g., Muntz Metal: 60Cu-40Zn). Harder, better for hot working. Poor cold workability.

Season Cracking: Stress-corrosion cracking of cold-worked brasses in ammonia environments. Prevented by stress-relief annealing.

3.2.2 BRONZES

Originally Cu-Sn alloys, now refers to Cu alloys with Sn, Al, Si, or Be as the main alloying element (not Zn).

1. Tin Bronzes (Phosphor Bronzes):

- **DIAGRAM REFERENCE:** FIG. 3.4 - CU-SN PHASE DIAGRAM. COMPLEX WITH MULTIPLE EUTECTOID REACTIONS.

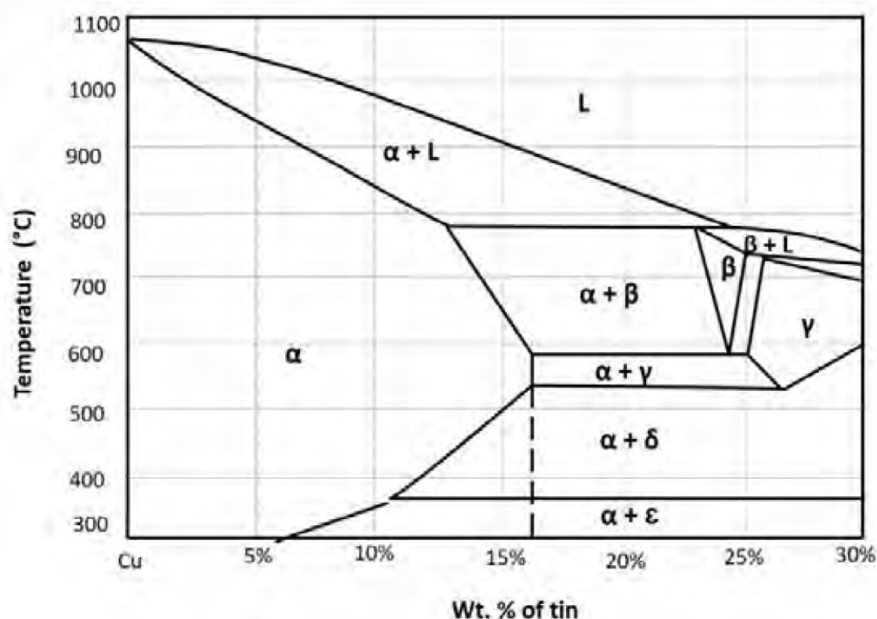


Fig. 3.4: Phase diagram of copper–tin system.

- Contain 1-11% Sn, with P as a deoxidizer.
- Excellent strength, toughness, corrosion resistance, low friction. Used for springs, bearings, bushings.

2. Silicon Bronzes:

- **DIAGRAM REFERENCE:** FIG. 3.5 - CU-SI PHASE DIAGRAM.

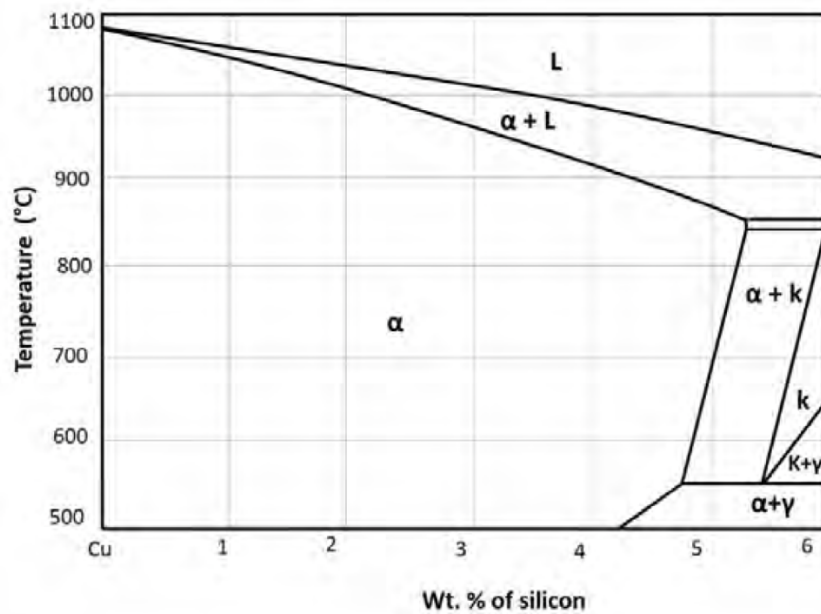


Fig. 3.5: Phase diagram of copper–silicon system.

- ~95% Cu, ~3-5% Si. Strongest work-hardenable Cu alloys. Properties similar to mild steel. Used in tanks, marine structures.

3. Aluminium Bronzes:

○ **DIAGRAM REFERENCE:** FIG. 3.6 - CU-AL PHASE DIAGRAM.

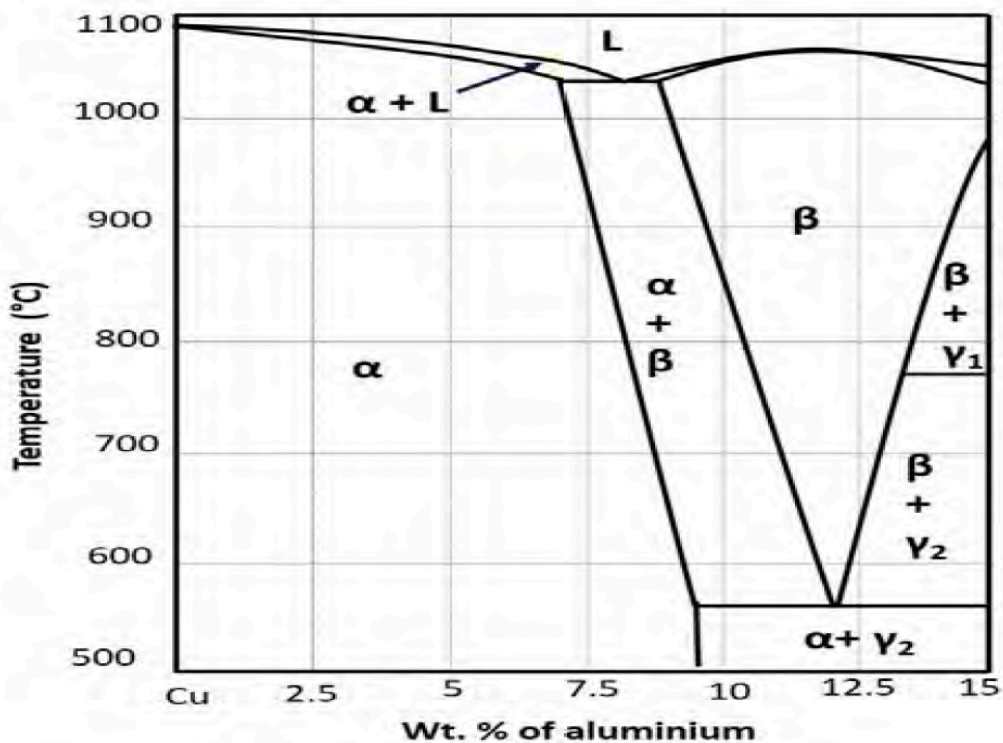


Fig. 3.6: Phase diagram of copper–aluminium system.

- Contain 4-11% Al. Can be heat-treated. Excellent corrosion resistance, especially in seawater. Used in pumps, valves, gears, non-sparking tools.

4. Beryllium Bronzes:

○ **DIAGRAM REFERENCE:** FIG. 3.7 - CU-BE PHASE DIAGRAM.

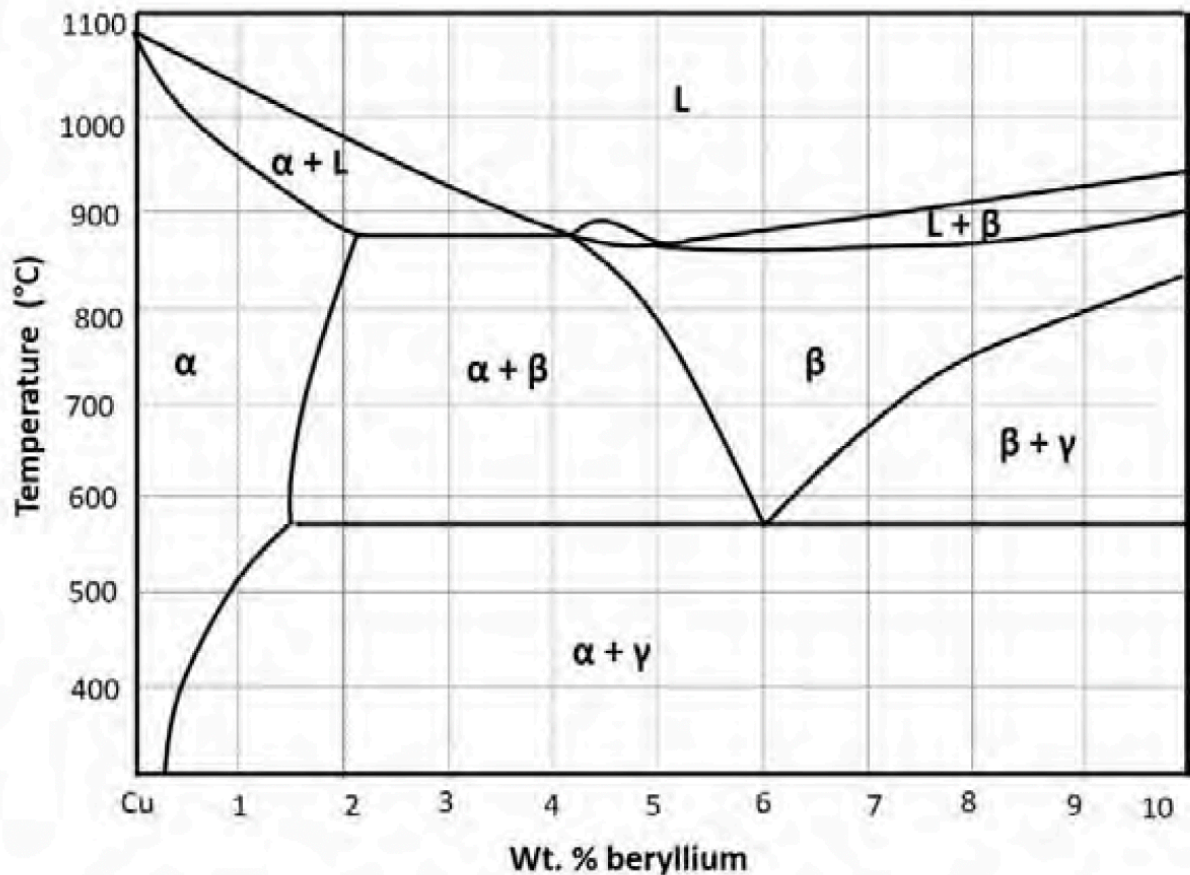


Fig. 3.7: Phase diagram of copper–beryllium system.

- Contain 0.5-3% Be. Can be precipitation hardened to very high strength. Excellent fatigue resistance, non-sparking. Used for springs, diaphragms, explosion-proof tools.

3.2.3 OTHER COPPER ALLOYS

- **Cupro-Nickels:** Single-phase alloys (Cu-Ni system, complete solubility). Excellent corrosion resistance in seawater. Used for condenser tubes, heat exchangers.
- **Nickel Silvers:** Cu-Ni-Zn alloys. Silvery appearance, good corrosion resistance. Used for decorative items, nameplates, zippers.

3.2.4 DESIGNATION (CDA SYSTEM)

TABLE REFERENCE: TABLE 3.3 & 3.4 - CDA DESIGNATION AND PROPERTIES.

- C1xxx: Pure Cu
- C2xxx: Zn (Brasses)

- C3xxx: Zn + Pb (Leaded Brasses)
- C4xxx: Zn + Sn (Tin Brasses)
- C5xxx: Sn (Phosphor Bronzes)
- C6xxx: Al, Si (Aluminium/Silicon Bronzes)
- C7xxx: Ni (Nickel Silvers)
- C8xxx, C9xxx: Cast Cu alloys

Table 3.3: The CDA designation system of copper alloys.

C1	Pure copper
C2	Brasses
C3	Lead brasses
C4	Tin brasses
C5	Phosphor bronze
C6	Aluminium and silicon bronze
C7	Nickel silvers
C8	Cast copper alloys
C9	Cast copper tin alloys

Table 3.4: Typical mechanical properties of copper alloys

Alloy No.	Chemical composition	Condition	Tensile strength (MPa)	Elongation %
C10100	99.99Cu	Annealed	220	45
		Cold worked	345	6
C26000	70Cu+30Zn	Annealed	325	62
		Cold worked	525	8
C28000	60Cu+40Zn	Annealed	370	45
		Cold worked	485	10
C17000	99.5Cu+1.7Be+0.2 Co	Solution treated	410	60
		Cold worked	1240	4
C61400	91Cu+7Al+2Fe	Annealed	550	40
		Cold worked	615	32
C71500	70Cu+30Ni	Annealed	380	36
		Cold worked	580	3
C80500	99.75Cu	As cast	172	40
C90300	88Cu+8Sn+4Zn	As cast	310	30

3.3 MAGNESIUM AND ITS ALLOYS

Magnesium is the lightest structural metal (density: 1.7 g/cm^3). It has an HCP structure, leading to poor room-temperature ductility. Melting point is 650°C . It is difficult to cast due to high oxidation tendency. Alloying improves strength and corrosion resistance.

3.3.1 DESIGNATION SYSTEM

A code like **AZ31B-F**:

- **First two letters:** Main alloying elements (A: Al, Z: Zn, K: Zr, E: Rare Earth, H: Th).
- **Numbers:** Approximate percentages of those elements.
- **Final letter:** Purity/variant (A, B, C...).
- **Temper suffix:** e.g., F (as fabricated), T5 (artificially aged).

3.3.2 MAGNESIUM ALLOY SYSTEMS

DIAGRAM REFERENCE: FIG. 3.8 - APPLICATIONS OF MG ALLOYS (AEROSPACE, ELECTRONICS).

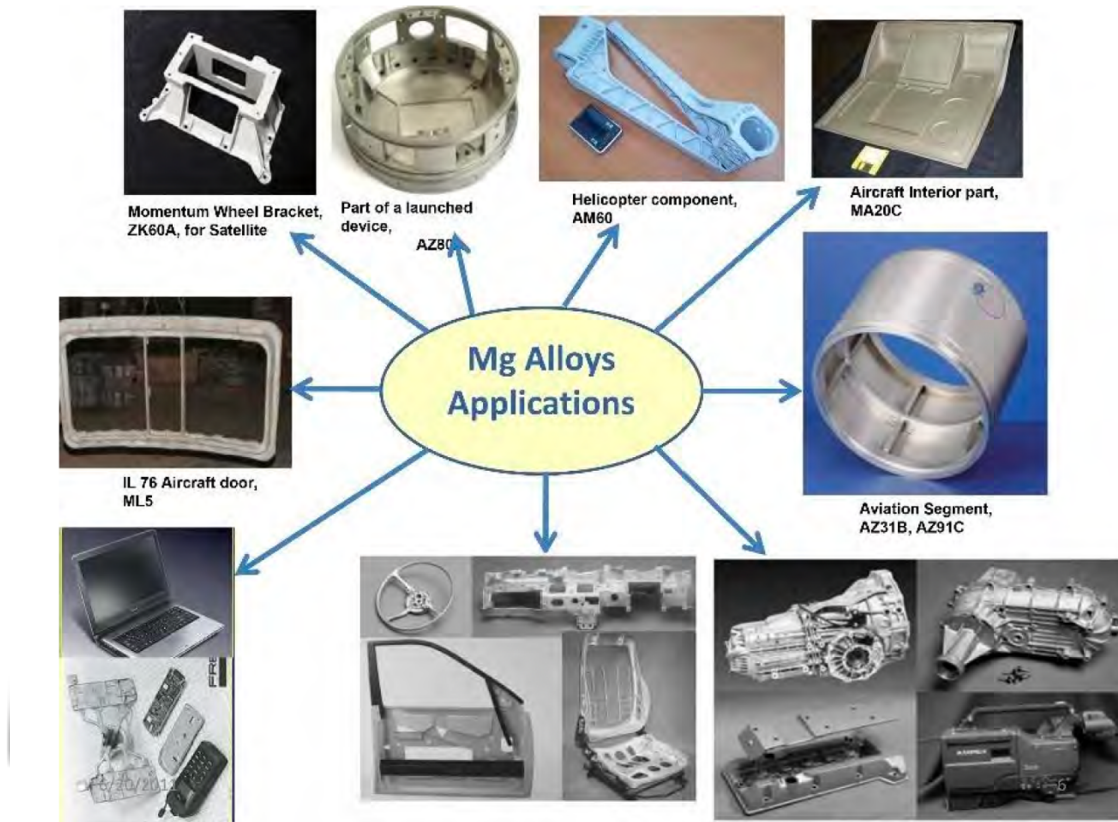


Fig. 3.8: Typical applications of magnesium alloys

TABLE REFERENCE: TABLE 3.5 - PROPERTIES OF MG ALLOYS.

Table 3.5: Typical mechanical properties of the magnesium alloys

Alloy Name	Composition (balanced by Mg)	Condition/ Treatment	Tensile strength (MPa)	Yield strength (MPa)	% of Elongation
AZ31B	3Al + 1 Zn	Annealed	228		11
HM21A	2Th + 0.8Mn	T8	228	138	6
AZ63A	6Zn + 3Al	cast	179	76	4
AZ91C	9Al + 1Zn	T6	275	131	5
ZK60	6Zn + 0.5Zr	T5	310	235	5

1. **Mg-Al-Zn (AZ) & Mg-Al-Mn (AM):** Most common. Good strength, castability. (e.g., AZ91, AM100). Used in automotive, consumer electronics.
2. **Mg-Zn-Zirconium (ZK):** Zirconium is a powerful grain refiner. High strength alloys (e.g., ZK60). Used for extrusions and forgings.
3. **Mg-Rare Earth (EK, EZ):** Excellent high-temperature creep resistance (up to 260°C). Used in aircraft engines.
4. **Mg-Thorium (HK, HZ):** Superior high-temperature strength (up to 371°C). Used in aerospace applications.

3.4 NICKEL AND ITS ALLOYS

Nickel (m.p. 1455°C) has excellent corrosion/oxidation resistance, high toughness, and good high-temperature strength.

TABLE REFERENCE: TABLE 3.6 - PROPERTIES OF NI ALLOYS.

Table 3.6 Mechanical properties of Ni based alloys

Alloys	Composition	Condition/ treatment	Tensile strength (MPa)	Yield strength (MPa)	% elongation
Monel	66.15 Ni+31.3Cu	Annealed	517	241	40
		Cold rolled	758	690	5
Inconel	72.85Ni+15.15Cr+6.8 Fe	Annealed	692	344	50
Hastelloy A	Ni+22Mo+22Fe	As cast	503	303	10
Hastelloy D	Ni+10Si+3Cu	Sand cast	813	813	2

1. **Nickel-Copper Alloys (Monel):** ~67Ni-33Cu. Excellent corrosion resistance in acids, alkalis, seawater. Used in marine, chemical processing.
2. **Nickel-Chromium-Iron Alloys:**
 - **Nichrome (80Ni-20Cr):** Heating elements.
 - **Inconel (e.g., 76Ni-16Cr-8Fe):** Retains strength at high temperatures. Forms a protective Cr-oxide layer. Used in gas turbines, heat exchangers, aerospace.
3. **Nickel-Molybdenum-Iron Alloys (Hastelloy B):** Resistant to reducing acids (HCl). Used in chemical industry.

4. **Nickel-Chromium-Molybdenum Alloys (Hastelloy C):** Resistant to both oxidizing and reducing acids. Used in severe chemical environments.

5. **Nickel-Silicon-Copper Alloys (Hastelloy D):** Excellent resistance to hot sulfuric acid. Used in chemical plant equipment.

3.5 TITANIUM AND ITS ALLOYS

Titanium (m.p. 1668°C, density: 4.5 g/cm³) has an excellent strength-to-weight ratio and outstanding corrosion resistance.

Alloying Elements:

- **Alpha (α) Stabilizers:** Raise the $\alpha \rightarrow \beta$ transus temperature (e.g., Al, O, N, C).
- **Beta (β) Stabilizers:** Lower the $\alpha \rightarrow \beta$ transus temperature (e.g., V, Mo, Cr, Fe, Mn).

3.5.1 TYPES OF TI ALLOYS

TABLE REFERENCE: TABLE 3.7 - PROPERTIES OF TI ALLOYS.

Table 3.7 Typical mechanical properties of different Ti based alloys.

Alloys	Compositions	Condition	Tensile strength (MPa)	Yield strength (MPa)	% elongation
Pure Ti	Ti-99	Annealed	545	434	27
Alpha Ti	Ti-5Al-2.5Sn	Annealed	862	827	18
	Ti-6Al-4Zr-1V	Annealed	985	951	17
	Ti-8Al-1Mo-1V	Annealed	1013	930	16
Alpha-Beta Ti	Ti-8Mn	Annealed	951	862	15
	Ti-4Al-4Mn	Heat treated	1116	965	9
	Ti-6Al-4V	Annealed	930	827	111
	Ti-6Al-4V	Heat treated	1172	1034	7
Beta Ti	Ti-3Al-13V-11Cr	Heat treated	1241	1206	6

1. **Alpha (α) Alloys:** Contain α -stabilizers (e.g., Ti-5Al-2.5Sn). Good weldability and creep resistance at high temperatures. Not heat-treatable.

2. **Alpha-Beta (α - β) Alloys:** Contain both stabilizers (e.g., **Ti-6Al-4V** - the workhorse alloy). Can be heat-treated. Excellent overall strength. Used in aerospace compressors, biomedical implants.
3. **Beta (β) Alloys:** Contain high % of β -stabilizers (e.g., Ti-3Al-13V-11Cr). Can be solution treated and aged to very high strength. Good formability.

3.6 BEARING ALLOYS

Bearings require high fatigue strength, wear resistance, conformability, and corrosion resistance.

3.6.1 BABBITT (WHITE METAL) ALLOYS

Table 3.8: Chemical composition and mechanical properties of bearing materials

Alloy	Nominal compositions (wt%)				Mechanical properties		Applications
	Pb	Sn	Sb	Cu	Tensile strength (MPa)	Hardness (BHN)	
Lead babbitts:							
SAE 13	85	5	10	-	69	19	Light loads: car journal bearings
SAE 14	75	10	15	-	72	22	Moderate loads: pumps, blowers
SAE 15	83	1	15	-	71	20	High loads: diesel engine bearings
Tin babbitt	-	91	4.5	4.5	64	17	Automotive applications

TABLE REFERENCE: TABLE 3.8 - COMPOSITION AND PROPERTIES OF BEARING ALLOYS.

- **Lead-Based Babbitt:** Contains Pb, Sn, Sb, (As). Good embeddability and conformability. Used in automotive engines. Environmental concerns limit use.
- **Tin-Based Babbitt:** >80% Sn, with Sb and Cu. Hard SnSb cubes in a soft Sn matrix. Superior wear and corrosion resistance. Used for high-speed, heavy-load bearings.

3.6.2 ALUMINIUM-BASED BEARING ALLOYS

- **Al-Si Alloys:** High strength, good thermal conductivity. Si provides hardness and wear resistance.

- **Al-Sn Alloys:** Sn (10-20%) acts as a solid lubricant, preventing seizure under poor lubrication. Excellent combination of strength and anti-friction properties. Used in modern internal combustion engines.

3.6.3 BEARING BRONZES

Various bronze alloys (Phosphor, Aluminium, etc.) are used for their good machinability, wear resistance, and low friction. Yield strengths range from 138–414 MPa.

4.1 INTRODUCTION TO FAILURE ANALYSIS

Definition: Failure analysis is the process of investigating the root cause of the failure of an engineering component and identifying measures to prevent its recurrence.

Importance of Failure Analysis:

- **Safety:** Prevents threats to human life.
- **Economics:** Avoids economic losses and operational breakdowns.

Common Causes of Failure:

1. Improper material selection and processing.
2. Inadequate component design.
3. Misuse of the component.

The Problem-Solving Model for Root Cause Analysis (Fig. 4.1):

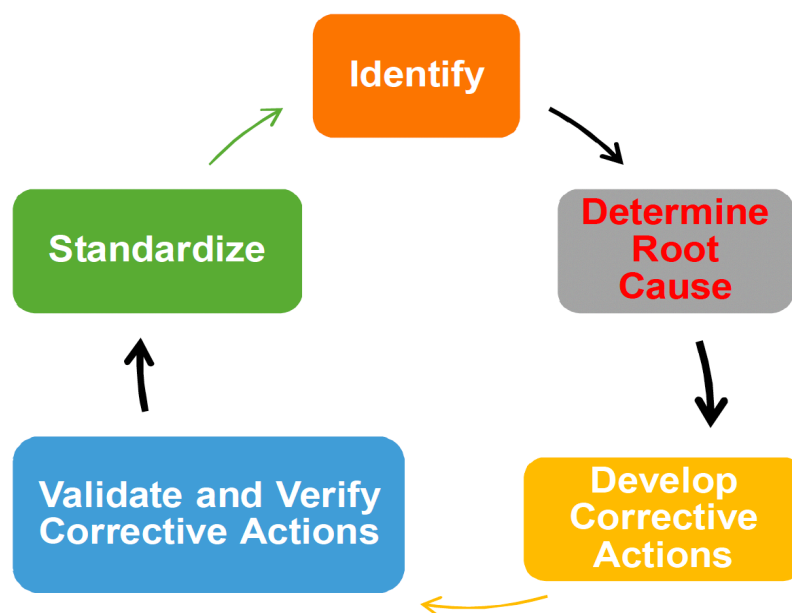


Fig. 4.1: Problem-solving model for root cause failure analysis

A systematic, five-step approach:

1. **Identify:** Describe the current situation, define the deficiency of the failed component, and collect data on its impact.
2. **Determine Root Cause:** Analyze the problem and perform relevant tests to identify the underlying causes.

3. **Develop Corrective Actions:** List possible solutions to mitigate and prevent recurrence. Generate alternatives and an implementation plan.
4. **Validate and Verify Corrective Actions:** Test the proposed solutions in a pilot study. Measure the effectiveness of the changes and validate improvements.
5. **Standardize:** Incorporate the successful corrective action into the company's standards and documentation to prevent recurrence in similar products or systems.

4.2 FRACTURE

Definition: Fracture is the failure of a material under load, resulting in it breaking into two or more pieces. The applied stress can be tensile, compressive, shear, or torsional.

Classification of Fracture

Fractures are primarily classified into two major categories based on the ability of a material to undergo plastic deformation:

1. **Ductile Fracture**
2. **Brittle Fracture**

Comparison between Ductile and Brittle Fracture:

Feature	Ductile Fracture	Brittle Fracture
Plastic Deformation	Substantial	Little or none
Energy Absorption	High	Low
Crack Propagation	Slow, requires increasing stress	Very fast, spontaneous
Crack Stability	Stable (resists extension)	Unstable (propagates spontaneously)

Feature	Ductile Fracture	Brittle Fracture
Warning	Gives warning via deformation	Sudden and catastrophic
Appearance	Dull, fibrous	Bright, granular
Crystallographic Mode	Shear	Cleavage

Why Ductile Fracture is Preferred:

1. It provides warning through plastic deformation, allowing for preventive measures.
2. It requires more strain energy, meaning the material is generally tougher.

The Fracture Process involves two steps:

1. Crack formation
2. Crack propagation

4.2.1 DUCTILE FRACTURE

Definition: Fracture accompanied by large amounts of plastic deformation.

- **Common in:** Face-centered cubic (FCC) metals and their alloys.
- **Mechanism (Cup and Cone Fracture):**
 1. A material under uniaxial tensile stress undergoes plastic deformation, leading to **necking** (localized reduction in cross-section). (**Fig. 4.2a**)
 2. At the neck, a triaxial stress state develops. Fine cavities form and coalesce into voids in the central part of the neck.
 3. These voids grow and coalesce to form a crack perpendicular to the stress direction.
 4. The crack grows outwards towards the surface at approximately a **45° angle** (the angle of maximum shear stress) until final fracture occurs, creating the characteristic "cup and cone" appearance. (**Fig. 4.2b**)

- **Microstructure:** The fractured surface exhibits **dimples** under a scanning electron microscope (SEM). (**Fig. 4.2c**)

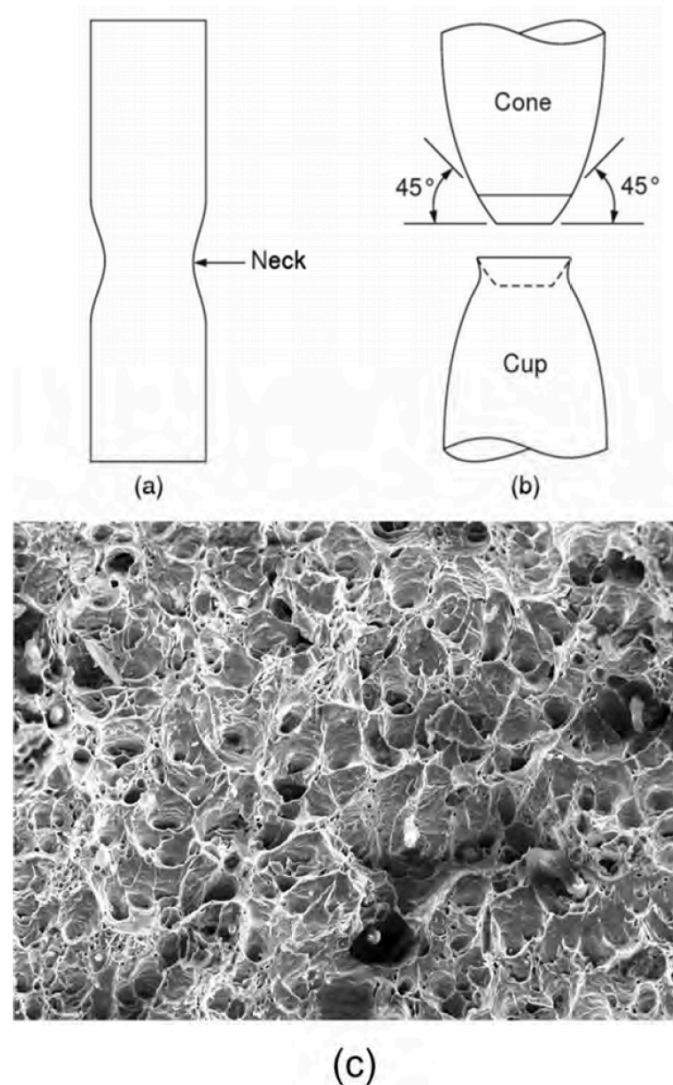


Fig. 4.2: (a) Neck formation at maximum tensile load in a ductile material, (b) Schematic representation of a ductile tensile failure characterising cup-cone like fracture, (c) Scanning electron micrograph of a low carbon steel exhibiting ductile fracture.

4.2.2 BRITTLE FRACTURE

Definition: Fracture that occurs after little or no plastic deformation.

- **Common in:** High-strength metals with low ductility, white and grey cast iron.
- **Mechanism (Cleavage):** Crack propagation corresponds to the successive breaking of atomic bonds along specific crystallographic planes.

Griffith Theory of Brittle Fracture

Griffith postulated that all brittle materials contain pre-existing microcracks. Stress concentrates at the tips of these cracks. When the concentrated stress exceeds the theoretical fracture strength, the crack propagates.

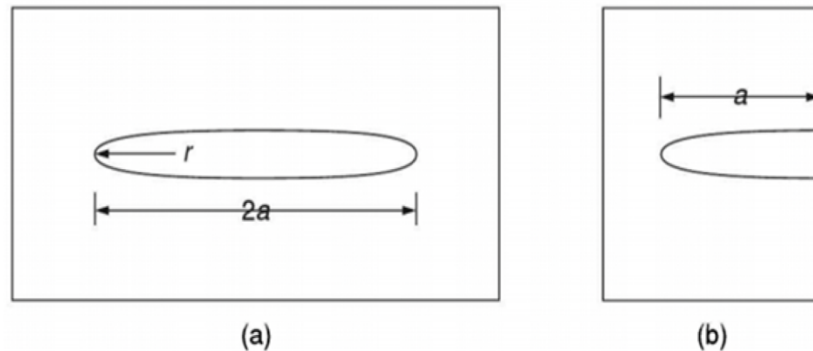


Figure 4.3: Illustration of (a) An interior elliptical or lens shape crack, (b) A surface crack.

- For an elliptical crack of length $2a$ and tip radius r , the maximum stress at the tip is:

$$\sigma_{\max} = 2\sigma\sqrt{\frac{a}{r}} \quad (4.1)$$

where σ is the applied tensile stress.

- The **Griffith Criterion** states that a crack will propagate when the decrease in elastic strain energy is at least equal to the increase in surface energy required to create the new crack surfaces.

- Elastic Strain Energy (per unit volume): $U_E = \frac{\pi a^2 \sigma^2}{E}$ (4.2)

- Surface Energy (for a crack of unit width): $U_s = 4\gamma_s a$ (4.3)

- Applying the criterion $\frac{dU_E}{da} = \frac{dU_s}{da}$ gives the critical stress for crack propagation:

$$\sigma = \sqrt{\frac{2\gamma_s E}{\pi a}} \quad (4.5)$$

Orowan-Irwin Modification (Modification for Metals)

For metallic materials, which undergo some plastic deformation at the crack tip, the equation is modified to account for the plastic deformation energy (γ_p):

$$\sigma = \sqrt{\frac{(2\gamma_s + \gamma_p)E}{\pi a}} \quad (4.6)$$

4.2.3 FATIGUE

Definition: The progressive and localized structural damage that occurs when a material is subjected to cyclic or fluctuating loads. Failure occurs at stresses much lower than the tensile or yield strength of the material.

- **Key Characteristic:** Lack of gross plastic deformation; failure is brittle-like.
- **Importance:** The most common cause of failure in structures and machines (e.g., shafts, springs, blades, axles).

Necessary Conditions for Fatigue:

1. Cyclic Stress
2. Tensile Stress (to open the crack)
3. Plastic Strain (localized at the crack tip)

4.2.3.1 CYCLIC STRESSES (FIG. 4.4)

- **Reversed Stress Cycle (Fig. 4.4a):** Stress alternates symmetrically between equal maximum tensile ($\sigma_{\max}$) and minimum compressive ($\sigma_{\min}$) stresses.

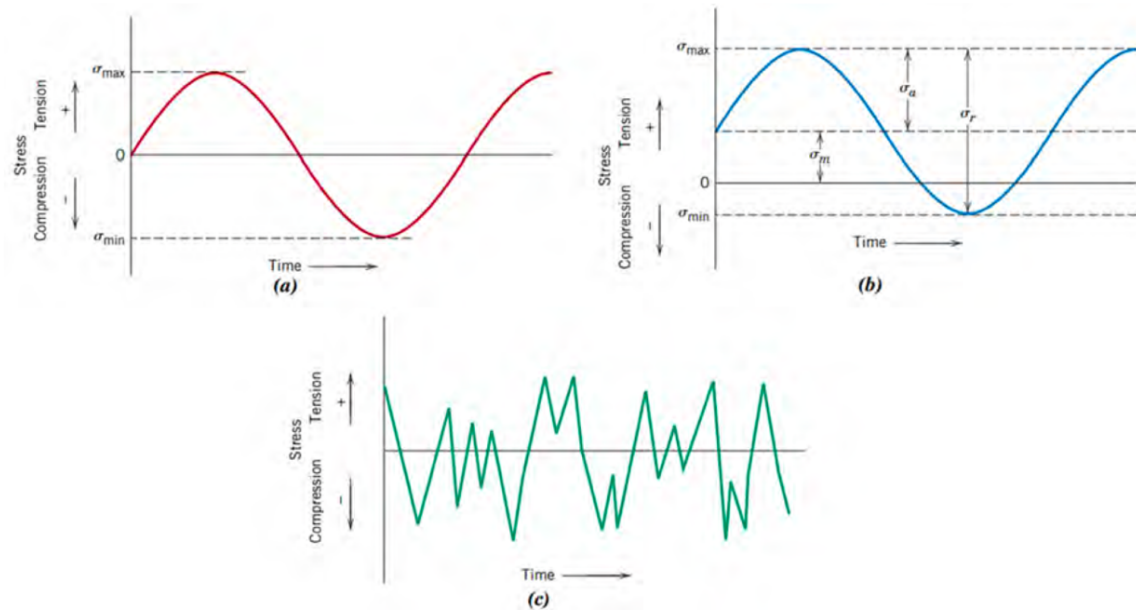


Fig. 4.4: Variation of stress with time that accounts for fatigue failures. (a) Reversed stress cycle, (b) Repeated stress cycle, and (c) Random stress cycle.

- **Repeated Stress Cycle (Fig. 4.4b):** Maxima and minima are asymmetrical relative to the zero-stress level.
- **Random Stress Cycle (Fig. 4.4c):** Stress varies randomly in amplitude and frequency.

Stress Cycle Parameters:

- **Mean Stress:** $\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2}$ (4.7)
- **Stress Range:** $\sigma_r = \sigma_{\max} - \sigma_{\min}$ (4.8)
- **Stress Amplitude:** $\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2}$ (4.9)
- **Stress Ratio:** $R = \frac{\sigma_{\min}}{\sigma_{\max}}$ (4.10)

4.2.3.2 THE S-N CURVE (FIG. 4.5)

- **Definition:** A plot of Stress (S) versus the Number of cycles to failure (N), typically with a logarithmic scale for N.
- **Fatigue Strength:** The maximum stress a material can withstand for a specified number of cycles without failure.

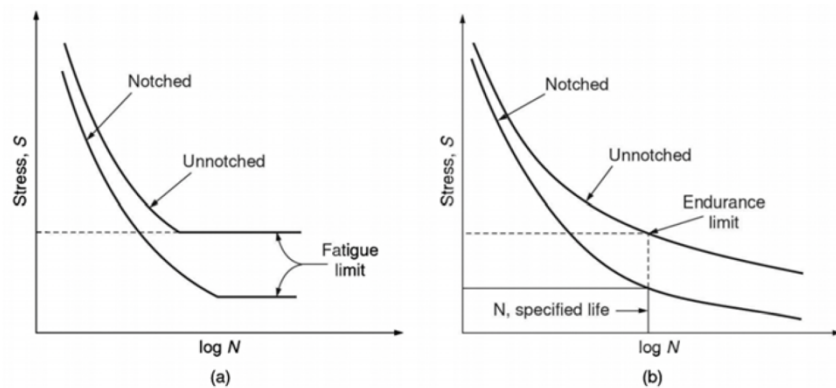


Fig. 4.5: Nature of the fatigue curves for notched and unnotched specimens. Number of stress cycles is plotted as $\log N$. (a) Fatigue limit, (b) Endurance limit for a given number of stress cycles.

- **Fatigue/Endurance Limit:** A limiting stress below which a material can endure an indefinitely large number of cycles without fracturing. Not all materials have a fatigue limit (e.g., Aluminum).
- **Effect of Notch:** A notch acts as a stress concentrator, significantly reducing the fatigue life, as shown by the lower S-N curve for notched specimens.

Types of Fatigue:

- **Low-Cycle Fatigue:** High stress ($> \sigma_y$), low cycles ($< 10^3$).
- **High-Cycle Fatigue:** Low stress ($< \sigma_y$), high cycles (10^5 to 10^6 and above).

4.2.3.3 FACTORS AFFECTING FATIGUE

1. **Alloy Composition:** Elements that increase tensile strength generally improve fatigue strength (e.g., Carbon in steel).
2. **Stress Concentration:** Notches, holes, keyways, and surface irregularities are preferential sites for crack initiation. **Polishing** the surface improves fatigue life.
3. **Size of the Specimen:** Larger components have a higher probability of containing a critical flaw and thus a lower fatigue life.
4. **Surface Condition:**
 - **Finish:** Smoother surfaces (buffed) have longer fatigue life than rough surfaces (machined).
 - **Hardness:** A harder surface resists crack initiation. **Case hardening** improves fatigue life.
 - **Residual Stresses:**

- **Compressive Residual Stresses** (introduced by shot peening, carburizing) are **beneficial** as they inhibit crack opening.
- **Tensile Residual Stresses** (introduced by electroplating, welding) are **detrimental**.

5. Metallurgical Structure:

- **Stacking Fault Energy (SFE):** Low SFE makes cross-slip difficult, delaying the formation of slip bands (intrusions/extrusions) that nucleate fatigue cracks.
- **Grain Size:** Fine grain structure improves fatigue properties.
- **Heat Treatment:** Austempered structures often provide superior fatigue properties compared to quenched and tempered structures of the same hardness.

4.2.4 CREEP

Definition: The time-dependent, permanent deformation of a material under a constant load (or stress) at elevated temperatures.

- **Significant above:** $\sim 0.4T_m$ (where T_m is the melting point in Kelvin). E.g., Lead creeps at room temperature.
- **Creep Strength:** The stress that produces a specified creep strain in each time at a constant temperature.
- **Creep Rupture Strength:** The stress that causes fracture in each time at a constant temperature.

4.2.4.1 CREEP CURVE (FIG. 4.6)

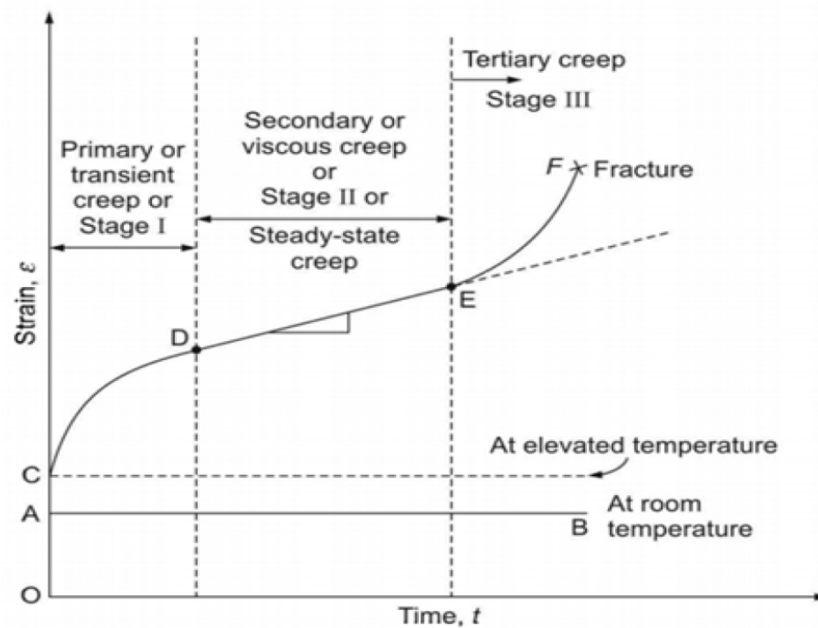


Fig. 4.6: An ideal creep curve showing three stages of creep.

A plot of strain vs. time under constant load and temperature shows three distinct stages:

1. **Primary (Transient) Creep:** The creep rate (slope) decreases with time due to **strain hardening**.
2. **Secondary (Steady-State) Creep:** The creep rate is constant. This is the longest stage, where a balance is achieved between strain hardening and **recovery** (softening).
3. **Tertiary Creep:** The creep rate accelerates rapidly, leading to **rupture**. This is caused by necking (in tension), internal crack formation, cavitation, and grain boundary separation.

4.3 DESTRUCTIVE TESTING

4.3.1 TENSILE TESTING

A uniaxial tensile load is applied to a standardized specimen (**Fig. 4.7**) at a slow strain rate until fracture.

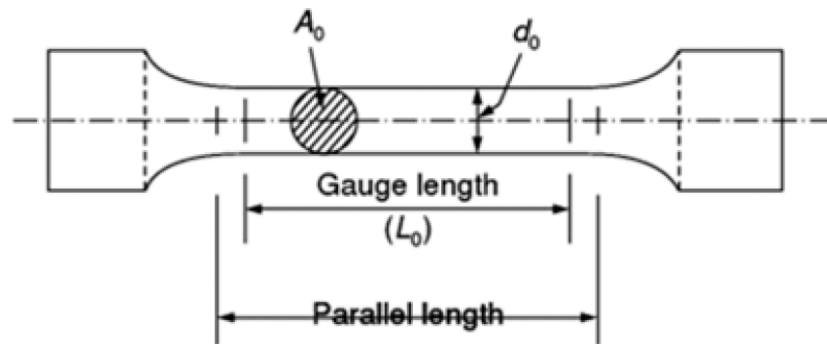


Fig. 4.7: Geometry of tensile specimen

- **Engineering Stress:** $\sigma = \frac{P}{A_0}$ (4.11, 4.12)
- **Engineering Strain:** $\epsilon = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0}$ (4.13, 4.14)

Analysis of a Stress-Strain Curve for Mild Steel (Fig. 4.8):

1. Elastic Region (O-A-B):

- **Hooke's Law:** Stress is proportional to strain. The constant of proportionality is **Young's Modulus (E)**.
- **Proportional Limit (A):** The highest stress at which stress is proportional to strain.
- **Elastic Limit (B):** The maximum stress from which the specimen will return to its original dimensions upon unloading.

2. Yielding (C-D):

- **Yield Point (C):** The point where a marked increase in strain occurs without an increase in stress (Upper Yield Point).
- **Lower Yield Point (D):** The relatively constant stress at which appreciable plastic deformation occurs.
- For materials without a sharp yield point, **Proof Stress** (e.g., 0.2% offset yield strength) is used.

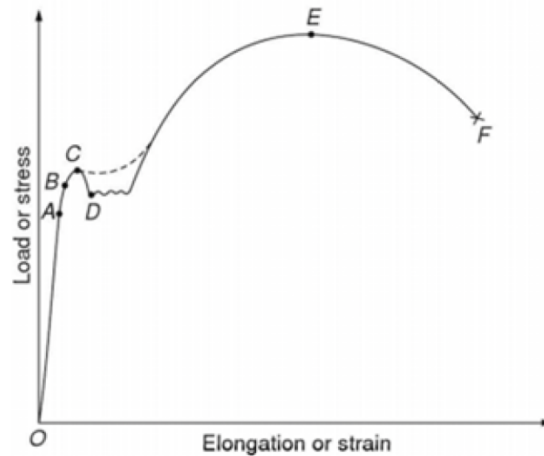


Fig. 4.8: Typical engineering stress-engineering strain curve for mild steel,

3. **Strain Hardening (D-E):** Deformation requires a continuously increasing stress.
4. **Necking (E-F):**
 - **Ultimate Tensile Strength (UTS) (E):** The maximum stress on the curve. After this point, **necking** begins.
 - The stress decreases after UTS because the decrease in cross-sectional area (reducing load capacity) dominates over the effect of strain hardening.
 - **Fracture (F):** The point of final failure.

Ductility Measures:

- **Percent Elongation:** $\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100$ (4.15)
- **Percent Reduction in Area:** $\%RA = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$ (4.16)

PROBLEM 4.1:

(a) **Modulus of Elasticity (E):** Calculated as the slope of the linear portion.

$$E = \frac{\Delta\sigma}{\Delta\epsilon} = \frac{(150 - 0) \text{ MPa}}{(0.0016 - 0)} = 93.8 \text{ GPa}$$

(b) **Yield Strength (at 0.002 offset):** Approximately 250 MPa.

(c) **Maximum Load (at UTS=450 MPa, $d_0=12.8$ mm):**

$$F = \sigma \times A_0 = 450 \times 10^6 \text{ Pa} \times \pi \times \left(\frac{12.8 \times 10^{-3}}{2}\right)^2 \text{ m}^2 = 57,900 \text{ N}$$

(d) **Change in Length (for $\sigma=320$ MPa, $l_0=250$ mm):** Strain $\epsilon \approx 0.06$.

$$\Delta l = \epsilon \times l_0 = 0.06 \times 250 \text{ mm} = 15 \text{ mm}$$

4.3.2 HARDNESS TESTING

Hardness is a material's resistance to permanent (plastic) deformation. We focus on **Indentation Hardness**.

4.3.2.1 BRINELL HARDNESS TEST

A hardened steel ball (10 mm diameter) is pressed into the material under a known load (P , typically 3000 kgf). The **Brinell Hardness Number (BHN or HB)** is calculated as:

$$BHN = \frac{P}{A} \quad (4.17)$$

Where A is the surface area of the spherical indentation. Measuring the impression diameter (d) and using geometry (Figure 4.9/4.10), the formula becomes:

$$BHN = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})} [\text{in kgf/mm}^2] \quad (4.21)$$

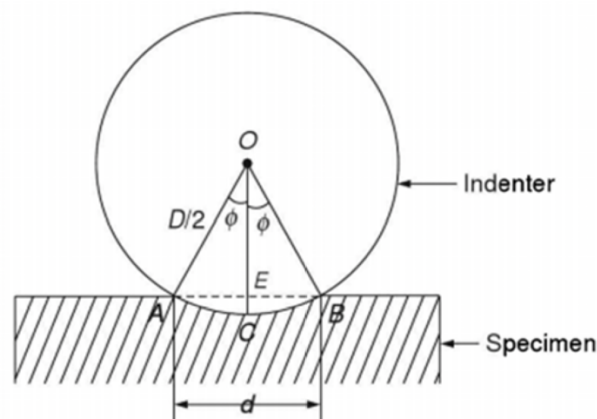


Fig. 4.10: Determination of area of spherical indentation ACB. The angle subtended by the edge of the indentation at the centre 'O' of the indenter is 2ϕ .

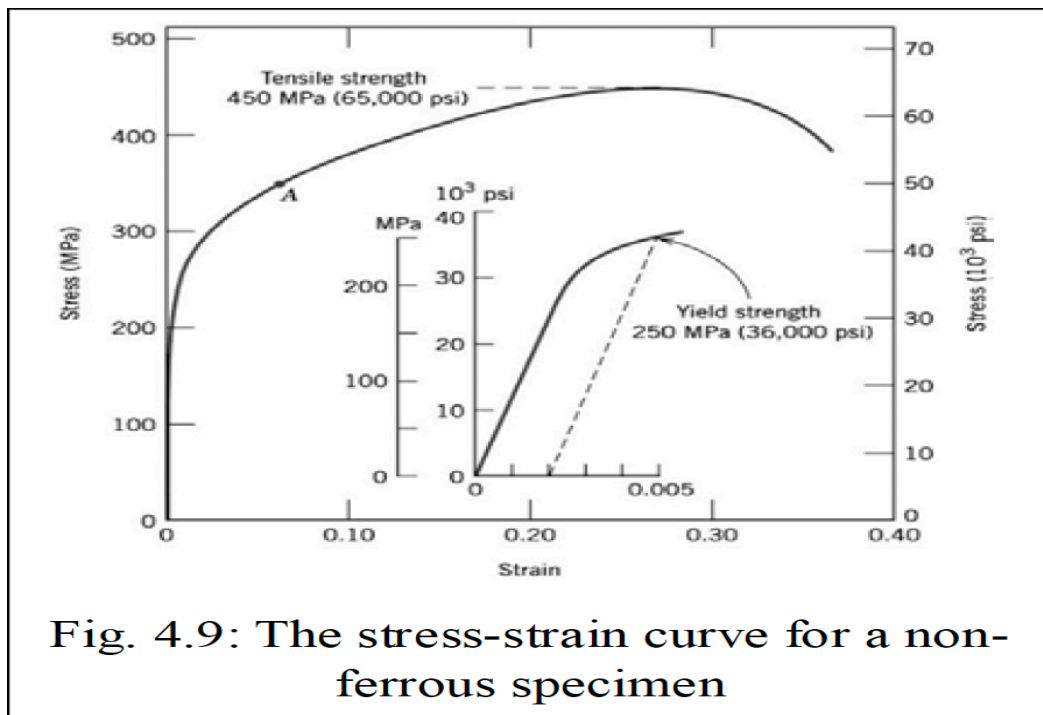


Fig. 4.9: The stress-strain curve for a non-ferrous specimen

For reliable results, geometrically similar indentations are needed, requiring a constant P/D^2 ratio:

$$\frac{P_1}{D_1^2} = \frac{P_2}{D_2^2} = \frac{P_3}{D_3^2} \quad (4.22)$$

Advantages: Averages local heterogeneities; less sensitive to surface scratches.

Disadvantages: Large impression; not suitable for small/thin parts or very hard materials.

4.3.2.2 ROCKWELL HARDNESS TEST

- **Principle:** Measures the **depth** of indentation under a major load.
- **Procedure:** A **minor load** (10 kgf) is applied first to seat the indenter, then the **major load** (60, 100, or 150 kgf) is applied. The hardness is read directly from the machine dial.
- **Indenters:**
 - Hardened steel ball (**1/16**-inch diameter).
 - Diamond cone (Brale indenter, **120°** apex angle).
- **Scales:** The scale (e.g., B, C) is denoted by a letter prefixing the hardness number (e.g., HRC, HRB), which specifies the indenter and load combination.
- **Advantages:** Very rapid, direct reading, non-destructive to finished surfaces.

4.3.3 BEND TEST

Used for evaluating materials under bending loads, especially for **brittle materials** (ceramics, glass) where tensile tests are difficult.

- **Setup:** A specimen is supported as a simple beam and loaded at one or two points.

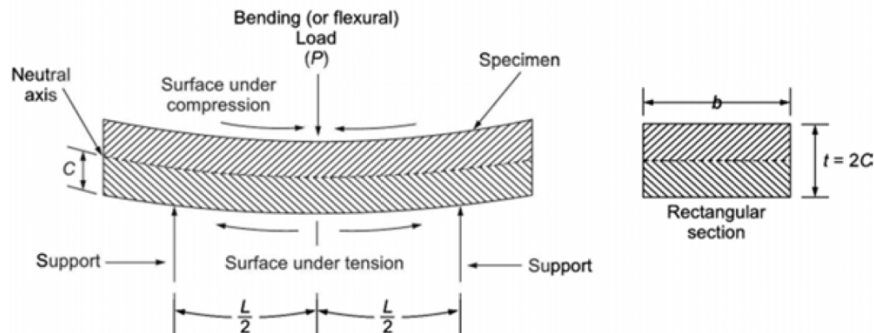


Fig. 4.11: Schematic representation for bend test. The specimen used is supported beam like.

- **Flexural Strength (Modulus of Rupture):**

- For a rectangular specimen: **Flexural Strength** = $\frac{3 PL}{2 bt^2}$
- For a cylindrical specimen: **Flexural Strength** = $\frac{8PL}{\pi D^3}$

4.3.4 TORSION TEST

Used to determine shear properties like modulus of elasticity in shear and torsional yield strength.

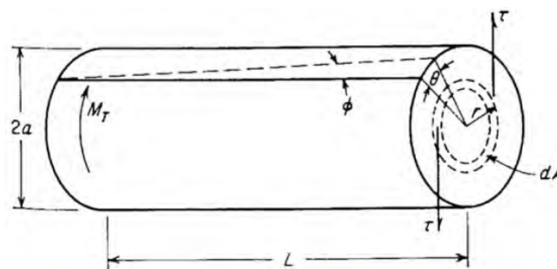


Fig. 4.12: Torsion of a solid bar

- **Setup:** A specimen is twisted by a torque (M_T).
- **Shear Stress (τ):** For a solid cylindrical bar, the maximum shear stress (at the surface) is:

$$\tau_{max} = \frac{16M_T}{\pi D^3} \quad (4.26)$$

where $J = \pi D^4/32$ is the polar moment of inertia.

- **Shear Strain (γ):** $\gamma = \frac{r\theta}{L}$ (4.28)

where θ is the angle of twist in radians, and L is the gauge length.

4.3.5 FATIGUE TEST

- **Objective:** To generate an S-N curve.
- **Common Machine: Rotating Bending Machine.** A specimen (Fig. 4.13) is rotated while a constant bending load is applied, subjecting the surface to fully reversed stress cycles.

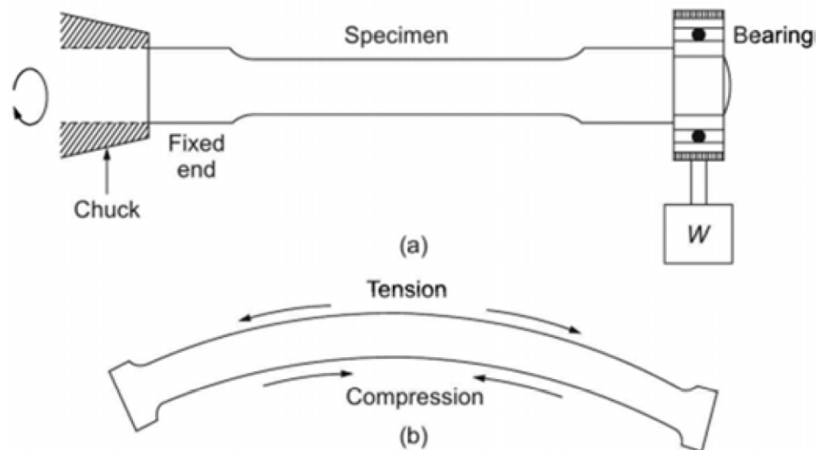


Fig. 4.13: Arrangement of fatigue specimen in the testing machine.

- **Stress Calculation:** The maximum tensile and compressive stresses on the surface are:

$$\sigma_t = \frac{32WL}{\pi d^3} \text{ and } \sigma_c = -\frac{32WL}{\pi d^3} \quad (4.29, 4.30)$$

- The test continues until the specimen fractures, and the number of cycles is recorded.

4.4 NON-DESTRUCTIVE TESTING (NDT)

Definition: A class of inspection techniques used to evaluate the properties of a material, component, or system without causing damage. The goal is to detect defects that could lead to premature failure.

4.4.1 VISUAL INSPECTION

- **Principle:** Illuminating the test specimen with visible light and examining it with the eye or optical aids.
- **Aids:** Magnifying glass, borescope, endoscope, and increasingly, **AI-powered intelligent visual inspection** for automation.
- **Applications:** Detecting surface cracks, corrosion, weld defects, porosity.

4.4.2 MAGNETIC PARTICLE INSPECTION (MPI)

- **Principle:** A ferromagnetic component is magnetized. At surface or near-surface flaws, magnetic flux leaks out, creating local poles. When iron particles are applied, they are attracted to this leakage field, outlining the flaw. (**Fig. 4.14**)

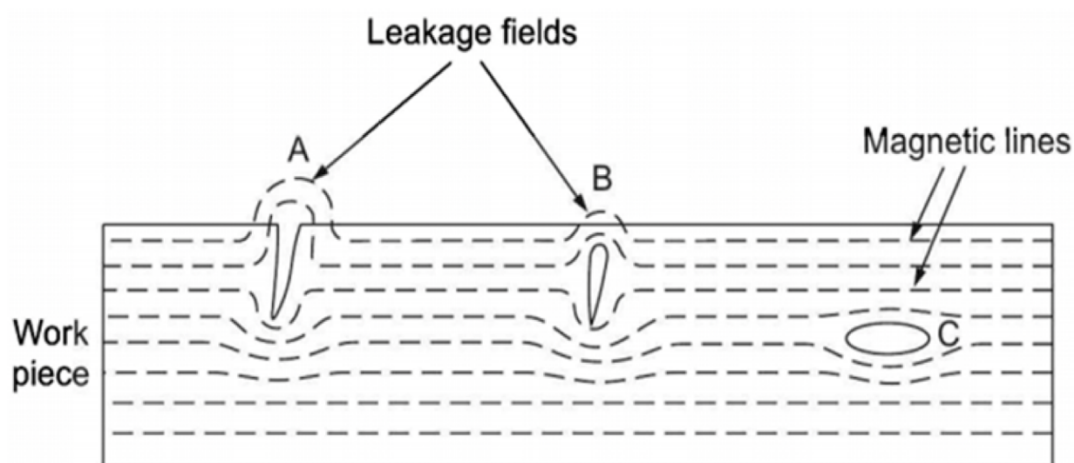


Fig. 4.14: Localised leakage of magnetic flux at flaws A and B.

- **Applicable to:** Only ferromagnetic materials (Iron, Nickel, Cobalt, and their alloys).
- **Sensitivity:** Can detect very fine surface cracks ($\sim 1 \mu\text{m}$). The flaw must be oriented roughly perpendicular to the magnetic field for clear detection.

4.4.3 LIQUID PENETRANT INSPECTION

- **Principle:** A low viscosity, brightly coloured or fluorescent liquid is applied to the surface. It seeps into surface-breaking flaws by capillary action. Excess penetrant is removed, and a developer is applied to draw the penetrant out, creating a visible indication.
- **Applicable to:** Any non-porous material.
- **Limitation:** Only detects flaws open to the surface.

4.4.4 ULTRASONIC TESTING (UT)

- **Principle:** High-frequency sound waves are introduced into the material. Reflections (echoes) from internal flaws or the back surface are detected and analyzed to determine the flaw's location and size.
- **Transducer:** A piezoelectric crystal converts electrical energy to ultrasonic waves and vice versa. A **couplant** is used for efficient sound transmission.
- **Common Methods:**

1. **Pulse-Echo (Fig. 4.15):** Uses one transducer as both sender and receiver. The screen shows the initial pulse, back-wall echo, and any intermediate echoes from defects.

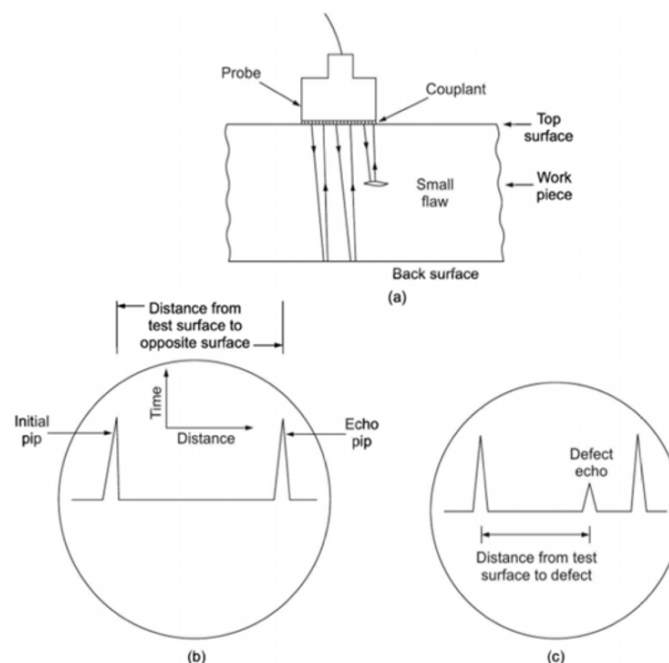


Fig. 4.15: Illustration of pulse-echo method. (a) the probe acts both as transmitter and receiver, (b) display of reflection of ultrasonic waves from the top and back surface, (c) intermediate pip showing presence of defect in the workpiece.

2. **Through-Transmission (Fig. 4.16):** Uses two transducers on opposite sides. A reduction in the transmitted signal indicates the presence of a defect.

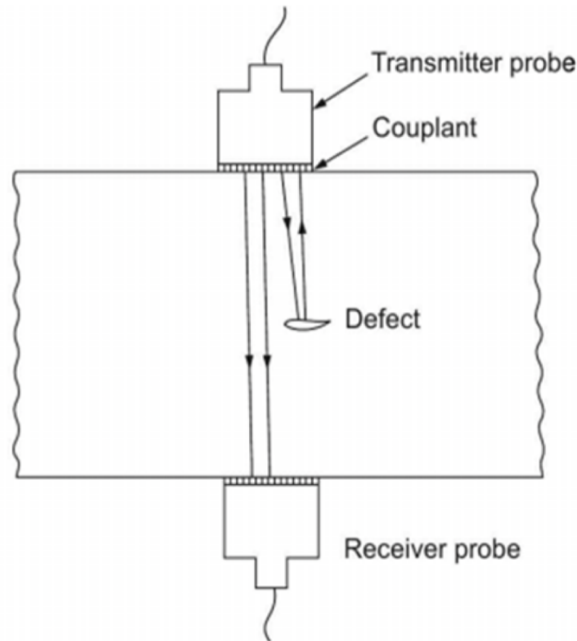


Fig. 4.16: Illustration of normal probe transmission method of ultrasonic testing

4.4.5 RADIOGRAPHIC INSPECTION

- **Principle:** Short-wavelength radiation (X-rays or γ -rays) is passed through a component. Denser areas and thicker sections absorb more radiation. The transmitted radiation is recorded on a film (**radiograph**), where dark areas indicate less absorption (e.g., voids, pores) and light areas indicate more absorption (e.g., dense inclusions). (**Fig. 4.17**)

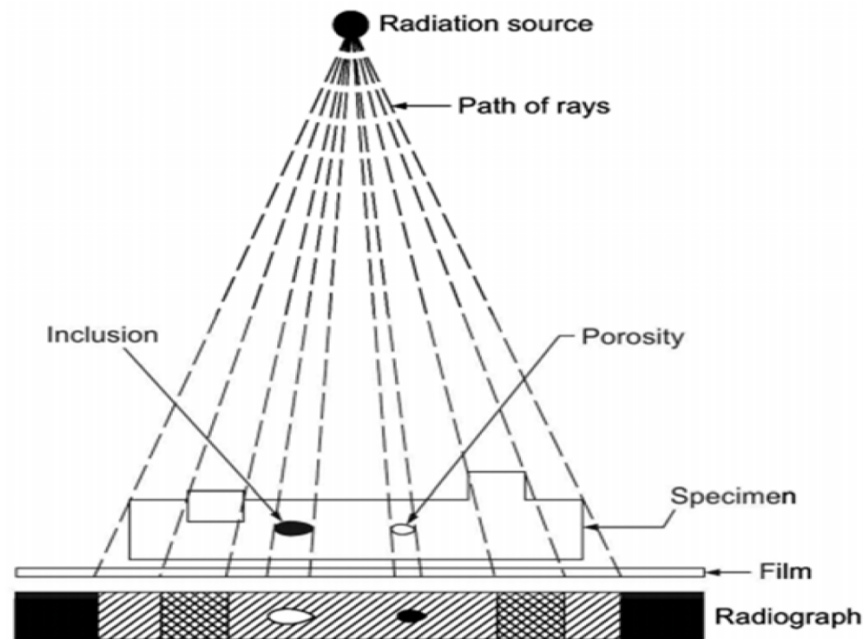


Fig. 4.17: Radiograph showing differential absorption.

- **Applications:** Inspecting welds, castings for internal defects like porosity and inclusions.

UNIT SUMMARY

1. Failure analysis uses a systematic model (Identify, Root Cause, Corrective Actions, Validate, Standardize) to prevent failures.
2. **Ductile Fracture** involves significant plastic deformation (necking, cup-cone), while **Brittle Fracture** is sudden and involves cleavage. Griffith's theory explains brittle fracture.
3. **Fatigue** is failure under cyclic stresses, characterized by the S-N curve. It is influenced by stress concentration, surface finish, residual stresses, and microstructure.
4. **Creep** is time-dependent deformation at high temperatures, showing primary, secondary, and tertiary stages on a creep curve.
5. **Destructive Tests** (Tensile, Hardness, Bend, Torsion, Fatigue) measure mechanical properties but render the component unusable.
6. **Non-Destructive Tests** (Visual, MPI, Liquid Penetrant, Ultrasonic, Radiography) are used to inspect components for defects without causing damage.

UNIT 5: CORROSION AND SURFACE ENGINEERING

Lecture Notes

5.1 NATURE OF CORROSION AND ITS CAUSES

Definition: Corrosion is the destruction or deterioration of a material due to its reaction with the environment. It is a natural process that converts a refined metal into a more chemically stable form, such as oxide, hydroxide, or sulfide.

Economic Impact: Corrosion is a massive global economic issue. Recent reports estimate global economic losses at **\$2.5 trillion**, accounting for approximately **3% of the global GDP**. Industries like petroleum, oil & gas, and construction are major contributors to this cost.

The Corrosion Cell: For corrosion to occur, four essential components must be present, forming an electrochemical cell:

1. **Anode:** The site where oxidation (metal loss) occurs. $M \rightarrow M^{n+} + ne^{-}$
2. **Cathode:** The site where reduction occurs, consuming the electrons produced at the anode.
3. **Electrolyte:** An electrically conductive solution (e.g., water, moist soil) that allows ion movement.
4. **Metallic Path:** An electrical connection between the anode and cathode that allows electron flow.

(Fig. 5.1): Schematic of a corrosion cell, showing the anode (corroding area), cathode (non-corroding area), electrolyte, and electron/current flow.

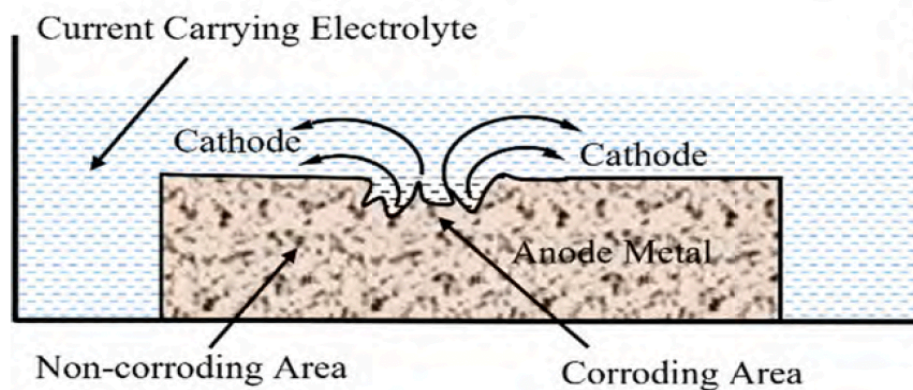


Fig. 5.1: Schematic of a corrosion cell.

Classification of Corrosion:

- **Wet Corrosion:** Occurs in the presence of a liquid electrolyte (e.g., corrosion of steel in water).
- **Dry Corrosion:** Occurs at high temperatures in the presence of vapors and gases, above the dew point (e.g., oxidation of steel by furnace gases).

Common Corrosion Environments:

1. **Atmosphere:** The most significant cause of corrosion by tonnage. Moisture with dissolved oxygen is the primary agent. Marine atmospheres (with NaCl) and industrial atmospheres (with acid rain, H_2SO_4) are highly corrosive. Common metals: Al-alloys, Cu-alloys, galvanized steel.
2. **Aqueous Solutions:**
 - **Freshwater:** Contains dissolved O_2 and minerals. Common metals: Cast iron, steel, Al, Cu, brass, some stainless steels.
 - **Seawater:** Contains ~3.5% salt (NaCl). Highly corrosive, causing pitting and crevice corrosion. Common metals: Ti, brass, bronzes, Cu-Ni alloys, Ni-Cr-Mo alloys.
3. **Soils:** Wide range of compositions. Variables include moisture, O_2 , salt, pH, and bacteria. Common metals: Cast iron and carbon steels, often with protective coatings.

5.2 ELECTROCHEMICAL REACTIONS

Corrosion is an **electrochemical** process involving the transfer of electrons.

- **Oxidation (Anodic Reaction):** The loss of electrons by a metal atom.
 $\text{M} \rightarrow \text{M}^{n+} + n\text{e}^-$ (e.g., $\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$, $\text{Al} \rightarrow \text{Al}^{3+} + 3\text{e}^-$)
- **Reduction (Cathodic Reaction):** The gain of electrons by another species. Common reactions include:
 - **Hydrogen Evolution (in acids):** $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2(\text{g})$
 - **Oxygen Reduction (in acids):** $\text{O}_2 + 4\text{H}^+ + 4\text{e}^- \rightarrow 2\text{H}_2\text{O}$
 - **Oxygen Reduction (in neutral/basic sol.):** $\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^-$

Overall Reaction: The sum of the oxidation and reduction half-reactions. There can be no net charge accumulation.

- Example (Zinc in Acid):
 - Oxidation: $\text{Zn} \rightarrow \text{Zn}^{2+} + 2\text{e}^-$
 - Reduction: $2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2$
 - **Overall:** $\text{Zn} + 2\text{H}^+ \rightarrow \text{Zn}^{2+} + \text{H}_2$

(Fig. 5.2): The electrochemical reactions associated with the corrosion of zinc in an acid solution

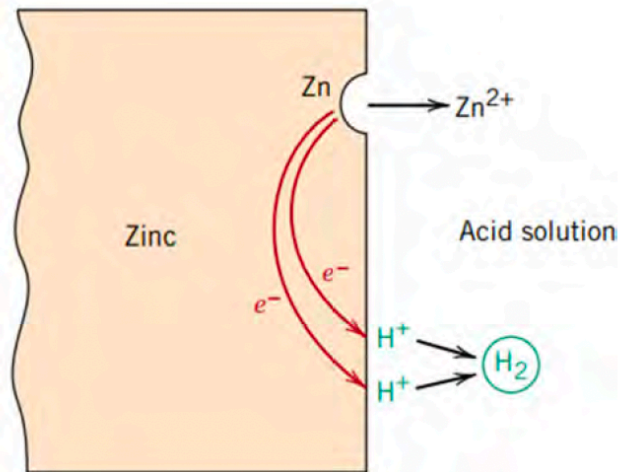
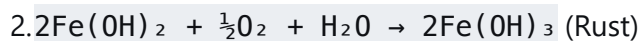
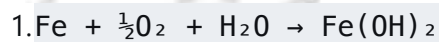


Fig. 5.2: The electrochemical reactions associated with the corrosion of zinc in an acid solution.

Rusting of Iron (a two-step process):



5.3 FACTORS AFFECTING CORROSION

5.3.1 ENVIRONMENTAL FACTORS

1. Oxidizing/Reducing Power (Fig. 5.3):

- **Strongly Oxidizing:** (e.g., conc. HNO_3 , wet Cl_2) promote oxidation of most metals.
- **Strongly Reducing:** (e.g., deaerated HCl) have a lesser tendency to oxidize metals.
- The graph shows the approximate oxidizing power of common environments on a potential-pH diagram.

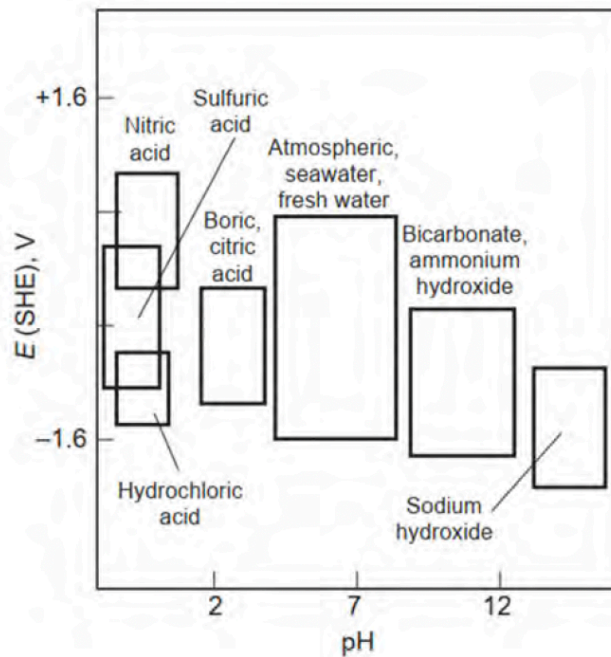


Fig. 5.3: Approximate locations of several common environments on a potential-pH diagram. SHE, standard hydrogen electrode

2. Temperature:

- Corrosion rate **increases** with temperature (it's an activation-controlled process).
- A rule of thumb: corrosion rate **doubles for every 10°C (18°F) increase**.
- EXCEPTION: Stability of passive films or solubility of gases can sometimes cause reversals.

3. Presence of Detrimental Species:

- Chloride ions (Cl^-):** Extremely detrimental; they break down passive films on metals like stainless steel, leading to pitting and stress corrosion cracking.
- Ammonia (NH_3):** Attacks copper alloys by forming soluble complexes.

4. Effect of Velocity:

- Beneficial:** Flow can prevent localized attack by ensuring a uniform supply of oxygen, helping maintain passivity (e.g., 316 SS in moving vs. stagnant seawater).
- Detrimental:** High velocity can cause **erosion-corrosion** and **impingement** by mechanically wearing away protective surface films.

5.3.2 METALLURGICAL FACTOR

- Cold Working:** Increases strength but also increases susceptibility to corrosion. Cold-worked areas (e.g., the head and point of a nail) become **anodic** to the annealed shank.

5.4 FORMS OF CORROSION

There are eight primary forms of corrosion:

1. Uniform Attack

- **Description:** Corrosion occurs at the same rate over the entire exposed surface (e.g., general rusting of steel, tarnishing of silver).
- **Prevention:** Proper material selection, coatings, inhibitors, cathodic protection.
- **(Fig. 5.4):** Uniform corrosion of a metal roof.



Fig. 5.4: UNIFORM CORROSION OF METAL ROOF

2. GALVANIC CORROSION

- **Description:** Occurs when two **dissimilar metals** are electrically coupled in an electrolyte. The less corrosion-resistant (more active) metal becomes the **anode** and corrodes faster. The more resistant (more noble) metal becomes the **cathode** and is protected.
- **Key Factor:** The **anode-to-cathode area ratio** is critical. A **small anode + large cathode** is a very dangerous combination.
- **Prevention:**
 1. Choose metals close together in the galvanic series.
 2. Avoid a small anode/large cathode ratio.
 3. Electrically insulate dissimilar metals.
 4. Use a sacrificial anode (cathodic protection).
- **(Fig. 5.5):** Galvanic corrosion in an oil and gas pipeline.

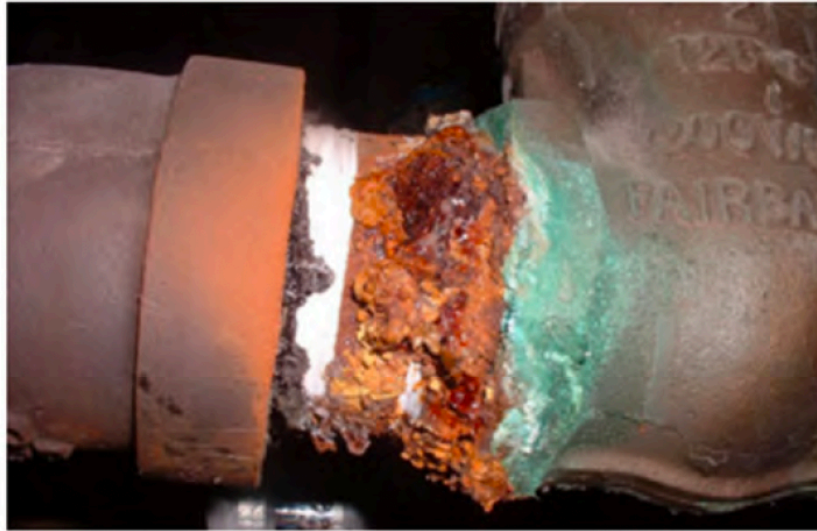


Fig. 5.5: An example of galvanic corrosion in oil and gas pipelines

3. CREVICE CORROSION

- **Description:** Localized attack within shielded areas (crevices) under gaskets, bolts, deposits, etc. It results from a **difference in ion concentration** inside vs. outside the crevice.
- **Mechanism:** Oxygen is depleted inside the crevice. This area becomes anode. The area outside, with ample oxygen, becomes cathode. A highly corrosive, acidic environment (high H^+ , Cl^-) develops inside the crevice.
- **Prevention:** Use welded instead of riveted joints, use non-absorbent gaskets, avoid stagnant areas, ensure complete drainage.
- **(Fig. 5.6 & 5.7):** Crevice corrosion in a pipeline and its mechanism between riveted joints.



Fig. 5.6: Oil and gas pipeline under crevice corrosion

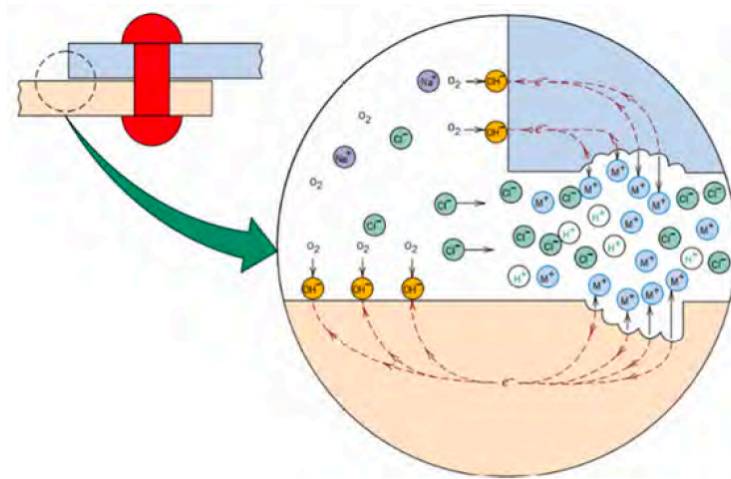


Fig. 5.7: Schematic illustration for mechanism of crevice corrosion between two riveted joints.

4. PITTING CORROSION

- **Description:** Highly localized, forming small pits or holes that penetrate inward. It is extremely insidious and dangerous because it causes sudden failure with little overall weight loss.
- **Mechanism:** Like crevice corrosion, but the pit itself acts as the crevice.
- **Prevention:** Use polished surfaces, alloy with Molybdenum (e.g., in 316 SS).
- **(Fig. 5.8):** Pitting corrosion on pipelines.

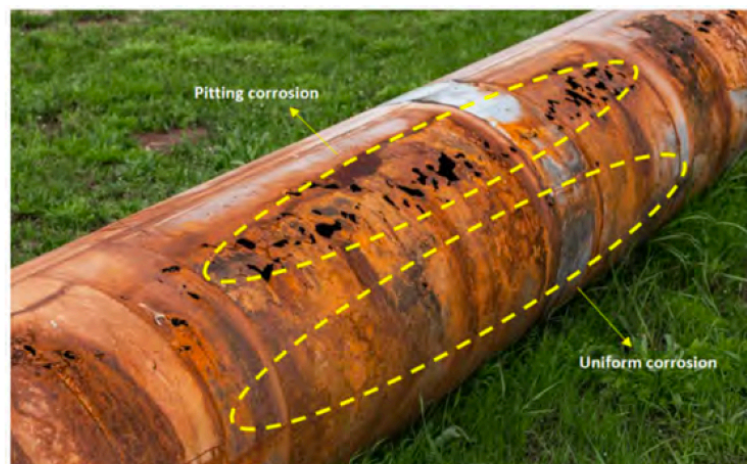


Fig. 5.8: Pitting corrosion on pipelines

5. INTERGRANULAR CORROSION

- **Description:** Preferential corrosion along grain boundaries.
- **Cause in Stainless Steels: Sensitization.** Heating between 500-800°C causes chromium carbide (Cr_{23}C_6) to precipitate along grain boundaries. This depletes chromium in adjacent zones, making them susceptible to corrosion.
- **Prevention:**

1. Solution heat treatment to redissolve carbides.
2. Use low-carbon grades (<0.03% C, e.g., 304L, 316L).
3. Stabilize with Ti or Nb (which form carbides preferentially over Cr, e.g., 321, 347).

- **(Fig. 5.9 & 5.10):** Schematic of Cr-depletion and photo of "weld decay."

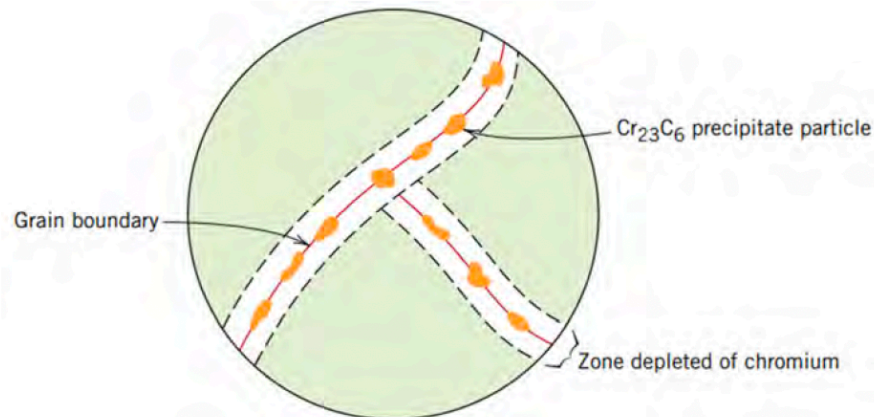


Fig. 5.9: Schematic illustration of chromium carbide particles that have precipitated along grain boundaries in stainless steel.

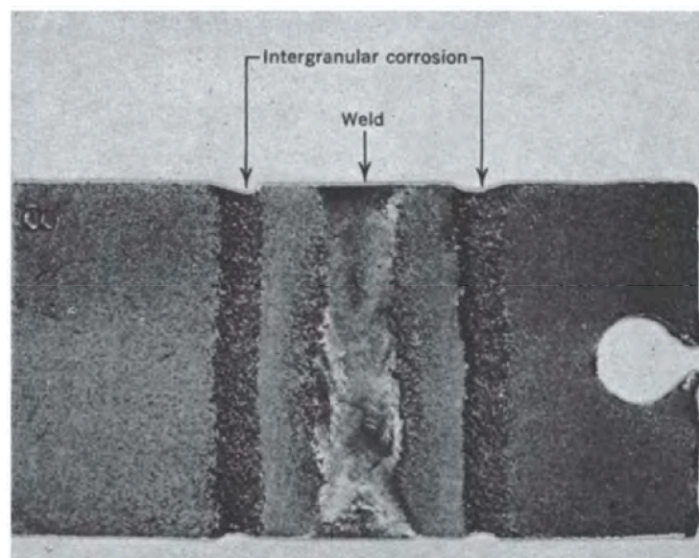


Fig. 5.10: Weld decay in a stainless steel. The regions along which the grooves have formed were sensitized as the weld cooled.

6. Selective Leaching

- **Description:** The selective removal of one element from a solid alloy.
- **Most Common Example: Dezincification** of brass (Cu-Zn alloy). Zinc is leached out, leaving a weak, porous copper structure. The part changes from yellow to red.
- **(Fig. 5.11):** Dezincification of a brass valve.

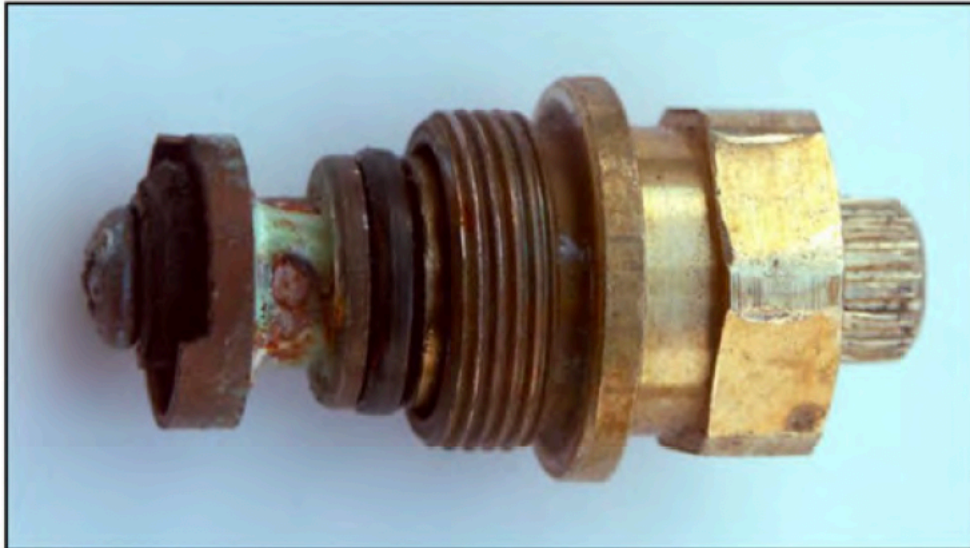


Fig. 5.11: Dezincification of a brass valve

7. Erosion-Corrosion

- **Description:** Acceleration of corrosion by the abrasive action of a moving fluid. It combines chemical attack and mechanical wear.
- **Common Locations:** Pipe bends, elbows, valves, pumps, impellers.
- **Prevention:** Change design to minimize turbulence, use harder/more resistant materials, remove particulates from fluid.
- **(Fig. 5.12):** Impingement failure of an elbow fitting.



Fig. 5.12: Impingement failure of an elbow that was part of a steam condensate line.

8. Stress Corrosion Cracking (SCC)

- **Description:** Cracking caused by the **combined action** of a **tensile stress** and a **specific corrosive environment**. The metal fails in a brittle manner, even though it is ductile.
- **Stress Source:** Can be applied or residual (from welding, cold working, thermal contraction).
- **Prevention:** Reduce stress (heat treat to relieve stress, reduce load), change environment, select resistant material.
- **(Fig. 5.13):** SCC cracks on a bent steel bar in seawater.

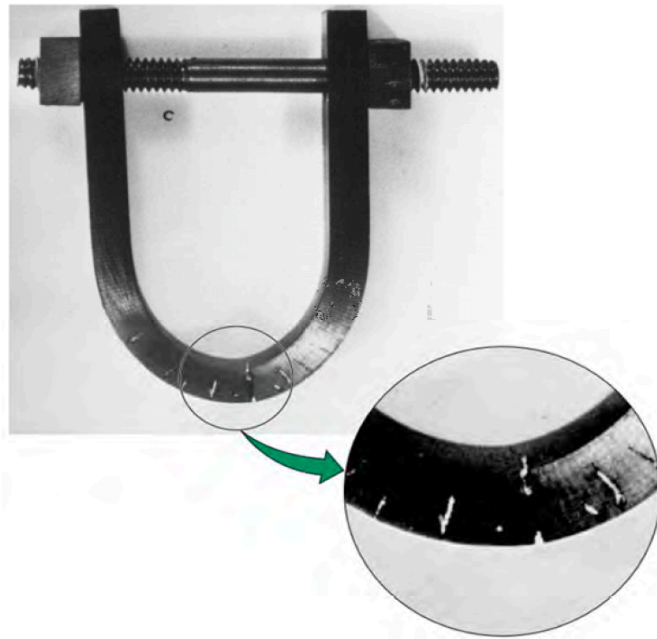


Fig. 5.13: A bar of steel bent into a horseshoe shape using a nut and-bolt assembly. While immersed in seawater, stress corrosion cracks formed along the bend at those regions where the tensile stresses are the greatest.

5.5 CORROSION CONTROL

1. Materials Selection

- Choose the right material for the specific environment.
- **Natural Combinations:**
 - Stainless Steels → Nitric Acid
 - Nickel Alloys → Caustic
 - Lead → Dilute Sulfuric Acid
 - Titanium → Hot Oxidizing Solutions
 - **Steel → Concentrated Sulfuric Acid** (it passivates)

2. DESIGN

- **Weld**, don't rivet, to avoid crevices.
- Design for **easy drainage and cleaning**.
- Avoid **stress concentrations** and **contact between dissimilar metals**.
- Avoid **sharp bends** in piping.
- Avoid **localized heating (hot spots)**.

3. INHIBITORS

Chemicals added in small concentrations to reduce corrosion rate.

- **Adsorption Type:** Organic amines that form a protective film on the surface.
- **Hydrogen Evolution Poisons:** As, Sb ions; retard H_2 evolution in acids.
- **Scavengers:** Remove corrosive agents (e.g., Na_2SO_3 , N_2H_4 remove dissolved O_2).
- **Vapor-Phase Inhibitors:** Volatile compounds (e.g., in packaging) that condense on metal surfaces.

4. COATINGS

- **Metallic Coatings:**
 - **Cathodic Coating (Noble):** e.g., Tin on steel (Tinplate). Must be pore-free, else it accelerates pitting of the underlying steel.
 - **Anodic Coating (Sacrificial):** e.g., Zinc (Galvanizing) or Aluminium on steel. The coating corrodes preferentially and protects the steel even if scratched.
- **Non-Metallic Coatings:** Paints, enamels, oils, tars. They act as a barrier. **Surface preparation** (cleaning, roughening) is critical for adhesion.

5. CATHODIC PROTECTION

Forcing the metal to be protected to become a **cathode**.

- **Sacrificial Anode:** Connect the structure to a more active metal (e.g., Mg, Zn anodes). The anode corrodes sacrificially.
- **Impressed Current:** Use an external DC power source. The negative terminal is connected to the structure. An inert anode (e.g., graphite) is connected to the positive terminal.
- **(Fig. 5.14):** Diagrams of both cathodic protection methods for underground structures.

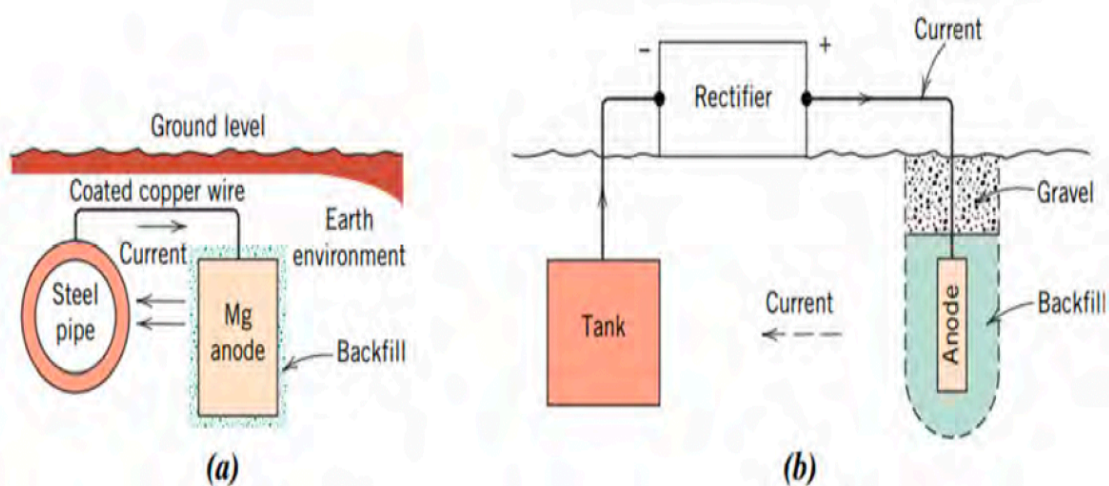


Fig. 5.14: Cathodic protection of (a) an underground pipeline using a magnesium sacrificial anode and (b) an underground tank using an impressed current.

5.6 SURFACE ENGINEERING AND HARDENING TREATMENTS

Definition: Treating the surface of a material to perform functions distinct from the bulk material (e.g., improve corrosion resistance, wear resistance, fatigue strength, appearance).

Thermochemical Treatments (Modify Surface Composition)

- **Carburizing:** Diffuse carbon into low-carbon steel surface at 850-950°C. Quenching creates a hard, wear-resistant martensitic case.
- **Nitriding:** Diffuse nitrogen into steel surface at ~500°C. Creates an extremely hard case without quenching. Excellent wear resistance.
- **Carbonitriding:** Diffuse both carbon and nitrogen. Allows lower processing temperatures.
- **Nitrocarburizing:** Done at ~570°C on plain carbon steels. Forms a thin, porous compound layer good for wear and corrosion resistance (porosity can hold oil).

(Table 5.1): Summary of thermochemical treatments, including process, temperature, case depth, and hardness.

Table 5.1: List of thermomechanical treatments based on carbon and nitrogen.

Process	Description	Typical treatment temp. (°C)	Typical case depth (mm)	Typical surface hardness (HV)
Carburizing	A process in which a steel surface is enriched with carbon, at a temperature above the ferrite/austenite transformation. On subsequent quenching, an essentially martensitic case formed	850-950	0.25-4.0	700-900
Carbonitriding	Similar to carburizing, but involving nitrogen as well as carbon enrichment.	700-900	0.05-0.75	600-850
Nitrocarburizing	A process in which a steel or cast-iron surface is enriched with nitrogen, carbon and possibly sulphur at a temperature below the ferrite/austenite transformation	570	0.02-1.0	500-650
Nitriding	A process in which a steel surface is enriched with nitrogen, at a temperature below the ferrite/austenite transformation.	500-525	0.4-0.6	800-1050

5.6.1 ORGANIC COATINGS

- **Paints, Plastisols, Powder Coatings:** Act as a barrier. Application methods include spraying, electrostatic spray, fluidized bed.
- **Linings:** Hand-lay-up fiberglass, rubber linings (prevulcanized/postvulcanized).
- **Key Factors:** Surface preparation (blasting, degreasing), primer selection, topcoat selection.

5.6.2 ELECTROPLATED COATINGS

- **Definition:** Deposition of a metal coating via electrolysis in an aqueous solution.
- **Applications:** Decoration, corrosion protection, wear resistance.
- **EXAMPLES:**
 - **Nickel + Chromium:** Decorative trim (autos, appliances).
 - **Hard Chromium:** Wear resistance (pistons, hydraulic cylinders).
 - **Zinc/Cadmium:** Galvanic protection for steel. (Cadmium is toxic, preferred for marine; Zinc for industrial).

- **Drawbacks:** Risk of hydrogen embrittlement, throwing power (ability to coat complex shapes uniformly) can be an issue.

5.6.3 ELECTROLESS NICKEL PLATING

- **Definition:** Autocatalytic chemical reduction process (no external current required).
- **Types:**
 - **Ni-P (Nickel-Phosphorus):** Excellent, uniform corrosion resistance. Amorphous structure. Resistance increases with P content in acidic/neutral environments.
 - **Ni-B (Nickel-Boron):** Excellent wear resistance, but more expensive and less corrosion resistant than Ni-P.

5.6.4 THERMAL SPRAY COATINGS

- **Definition:** A group of processes where melted or semi-molten material is sprayed onto a surface.
- **Processes:** Flame spray, arc spray, plasma spray, HVOF (High Velocity Oxy-Fuel), cold spray.
- **Principle:** Particles impact the surface, flatten, and form a lamellar (layered) coating.
- **Applications:** Corrosion protection, wear resistance, thermal barriers (e.g., on aerospace components).
- **(Fig. 5.15 & Table 5.2):** Temperature-velocity map and parameters for different thermal spray processes.

Table 5.2: Thermal spray process parameters

Process	Temperature (°C)	Velocity (m/s)
Oxyacetylene gas flame spraying	3000	150
Atmospheric plasma spraying	12000	900
Low-pressure plasma spraying	1200	900
Detonation gun spraying	300	1000
Hypersonic plasma spraying, high velocity oxyfuel	3000	800
Arc metallization, wire spraying	1500	200

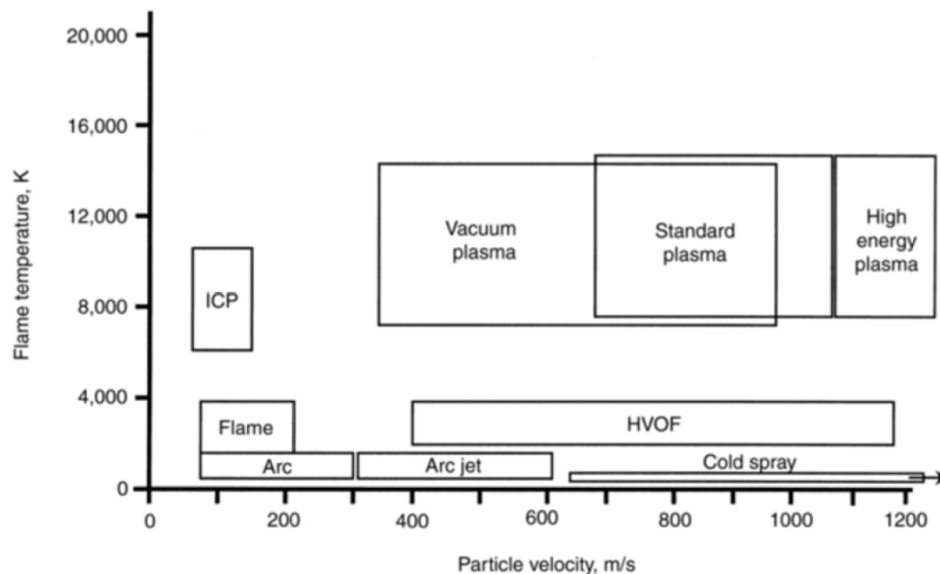


Fig. 5.15: The temperature-velocity distribution envelope of thermal spray processes. HVOF (high velocity oxyfuel); ICP (induction coupled plasma).

5.6.5 CONVERSION COATINGS

• Phosphate Coatings:

- **Iron Phosphate:** Lightweight, amorphous. Used as a paint base.
- **Zinc Phosphate:** Medium-weight, crystalline. Excellent paint adhesion and corrosion resistance with oil/wax.
- **Manganese Phosphate:** Heavy coating. Excellent for wear resistance and oil retention.

• Chromate Coatings:

- Formed by treating metals in solutions containing Cr^{6+} .
- Provide excellent corrosion resistance and paint adhesion for Al, Zn, Mg, Cd.
- **Major Drawback:** Hexavalent chromium (Cr^{6+}) is highly toxic and carcinogenic. Waste disposal is expensive and heavily regulated, driving the search for alternatives.

5.6.6 VAPOR DEPOSITION PROCESSES

• Physical Vapor Deposition (PVD - Sputtering):

- **Process:** A target material is bombarded with gas ions (Ar^+) in a vacuum chamber. Atoms are ejected from the target and deposit on the substrate.
- **Advantages:** Excellent quality, uniformity, and adhesion. Can deposit a wide range of materials.
- **Disadvantages:** Line-of-sight process, requires vacuum, high cost, limited thickness.
- **(Fig. 5.16):** Schematic of the sputtering process.

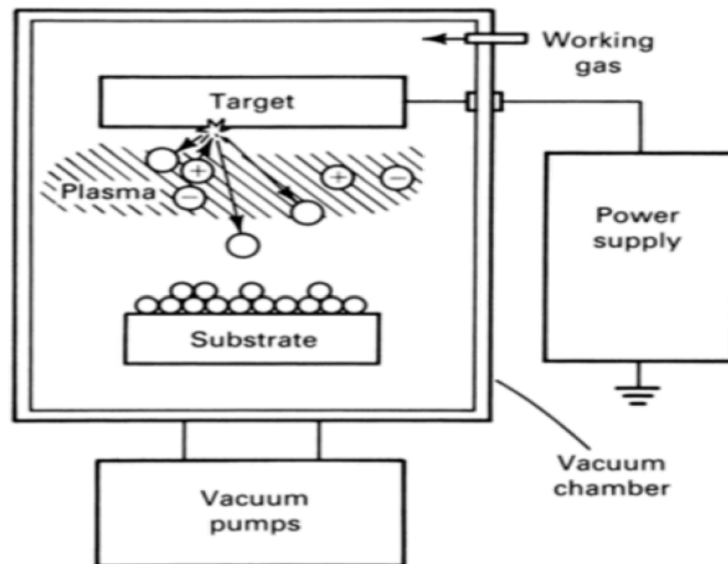


Fig. 5.16: Basic sputtering process

- **Chemical Vapor Deposition (CVD):**

- **Process:** Gaseous reactants decompose or react on a heated substrate to form a solid coating.
- **Advantages:** Can deposit very thick, dense, high-quality films. Excellent adhesion.
- **Disadvantages:** Very high process temperatures ($\sim 1000^\circ\text{C}$) limit substrate choice. Can cause dimensional changes and thermal stress.
- **(Fig. 5.17):** Schematic of a thermal CVD reactor.

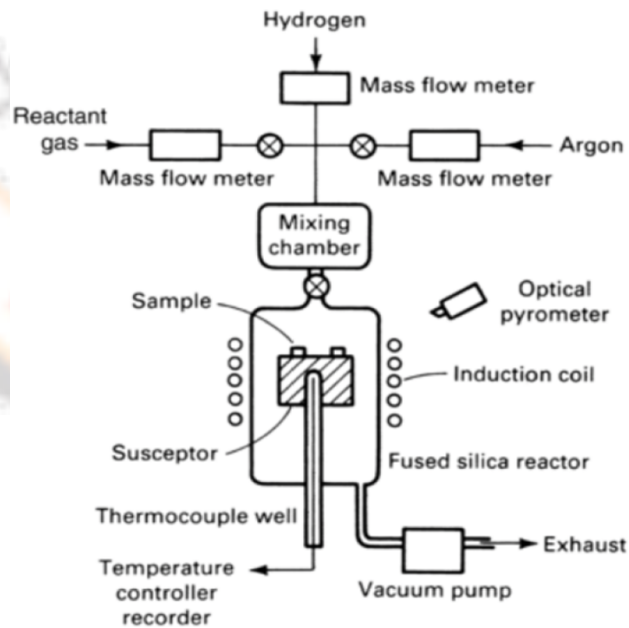


Fig. 5.17: Thermal CVD reactor