GUJARAT TECHNOLOGICAL UNIVERSITY

BE-3 SEMESTER – OLD PAPER – S22 TO S25 – QUESTION BANK ANSWER

Subject Name & Code:

Material Science and Metallurgy (3131904)

Unit 1 – Introduction to Material Science and Metallurgy

Question 1.1: Classify engineering materials.
(Appeared in: W22 (Q1b, 04 marks), S25 (Q1b, 04 marks), S24 (Q1a, 03 marks))
Answer:
Engineering materials are broadly classified into the following categories:

1. **Metals and Alloys:**
   - **Ferrous Metals:** Contain iron as the base element (e.g., steels, cast irons).
   - **Non-Ferrous Metals:** Do not contain iron (e.g., aluminum, copper, titanium, zinc).
2. **Polymers (Plastics):**
   - **Thermoplastics:** Can be reshaped on heating (e.g., polyethylene, PVC).
   - **Thermosets:** Permanently set on heating and cannot be remelted (e.g., epoxy, bakelite).
   - **Elastomers:** Exhibit high elasticity (e.g., natural rubber, silicone).
3. **Ceramics:**
   - **Traditional Ceramics:** Clay-based products (e.g., bricks, pottery).
   - **Advanced/Engineering Ceramics:** High-performance materials (e.g., alumina, silicon carbide, zirconia).
4. **Composites:**
   - Consist of two or more distinct phases (matrix and reinforcement).
   - **Types:** Polymer Matrix Composites (PMCs), Metal Matrix Composites (MMCs), Ceramic Matrix Composites (CMCs).
5. **Semiconductors:**
   - Materials with electrical conductivity between conductors and insulators (e.g., silicon, germanium). Crucial for electronics.
6. **Other Advanced Materials:**
   - **Biomaterials:** Used in medical implants.
   - **Smart/Nanomaterials:** Designed for specific functions and at the nanoscale.

Question 1.2: Explain/Define material properties: Ductility, Creep, Hardness, Strength, Elasticity.
(Appeared in: W22 (Q1a, 03 marks), W23 (Q1a, 03 marks), S25 (Q1a, 03 marks), W24 (Q1a, 03 marks))
Answer:

- **Ductility:** The ability of a material to undergo **significant plastic deformation** before fracture when subjected to tensile force. It is measured by **percentage elongation** or **percentage reduction in area**. Example: Gold and copper are highly ductile.

- **Creep:** The **slow, progressive, and permanent deformation** of a material under a constant stress (below its yield strength) at high temperatures over a long period. Critical for turbine blades and boilers.
- **Hardness:** The **resistance of a material to localized plastic deformation**, typically induced by **indentation, scratching, or wear**. Common tests: Brinell, Rockwell, Vickers.
- **Strength:** The **ability of a material to withstand an applied load without failure or plastic deformation**.
    - **Tensile Strength:** Maximum tensile stress it can withstand.
    - **Yield Strength:** Stress at which plastic deformation begins.
    - **Compressive Strength:** Resistance to being crushed.
- **Elasticity:** The **ability of a material to regain its original shape and size** after the removal of the deforming force. The stress is proportional to strain (Hooke's Law), and the constant of proportionality is the **Modulus of Elasticity**.

Question 1.3: Explain criteria for selection of materials for engineering applications.
(Appeared in: W23 (Q1c, 07 marks), S24 (Q1c, 07 marks))
Answer:
The selection of an engineering material is a critical multi-criteria decision-making process. The primary factors are:

1. **Functional Requirements (Performance):**
    - **Mechanical Properties:** Strength, hardness, toughness, fatigue resistance, and creep resistance as required by the service conditions.
    - **Physical Properties:** Density, melting point, thermal/electrical conductivity, magnetic properties.
    - **Chemical Properties:** Corrosion and oxidation resistance for the specific environment.
2. **Manufacturability (Processability):**
    - Can the material be easily **cast, formed, machined, welded, or heat-treated** into the desired shape?
    - Poor manufacturability increases cost and defects.
3. **Reliability and Durability:**
    - The material must perform safely and predictably over its intended **service life** under expected loads, temperatures, and environments (e.g., fatigue, wear, corrosion).
4. **Economic Considerations (Cost):**
    - **Total Cost:** Includes not just raw material cost, but also manufacturing, finishing, maintenance, and potential failure costs.
    - The goal is to achieve the required performance at the **minimum total cost**.
5. **Environmental and Societal Factors:**
    - **Sustainability:** Recyclability, energy consumption during production, and environmental impact.
    - **Availability:** Abundance and supply chain security of the material.
    - **Safety:** Toxicity and flammability during production and use.

Other Important Questions:
Q1. What are engineering materials and how are they classified? (W24 Q1a, 03 marks)
Answer: Engineering materials are substances used to construct machines, structures, devices, and systems to perform desired functions. They are selected based on specific properties like strength, hardness, and corrosion resistance. Classification: **1. Metals &**

Alloys (Ferrous/Non-ferrous), **2. Polymers** (Thermoplastics/Thermosets/Elastomers), **3. Ceramics** (Traditional/Advanced), **4. Composites**, **5. Semiconductors**, **6. Advanced Materials** (Biomaterials, Smart materials).

Q2. Explain the role of material science and metallurgy in advancement of civilization. (S24 Q1b, 04 marks)
Answer:

- **Historical Eras Defined by Materials:** Civilizational progress is marked by material usage – **Stone Age, Bronze Age, Iron Age, Silicon Age**.
- **Metallurgy Enables Technology:** Extraction and processing of metals led to tools, weapons, machinery, and infrastructure, driving the **Industrial Revolution**.
- **Material Science Drives Innovation:** Understanding structure-property relationships enables the design of new materials (e.g., polymers, composites, semiconductors).
- **Foundation for Modern Life:** It underpins every modern industry – **aerospace** (lightweight alloys), **electronics** (semiconductors), **healthcare** (biomaterials), and **energy** (solar cells, batteries).

Q3. What is Metallurgy? List its functions. (S23 Q1a, 03 marks)
Answer: Metallurgy is the science and technology of extracting metals from their ores, refining them, and preparing them for use. Its main functions are:

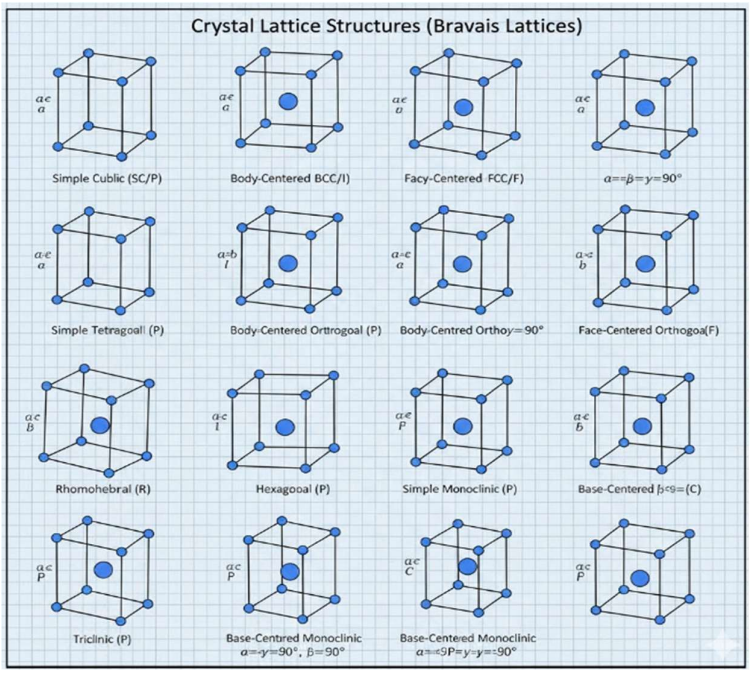
1. **Mineral Processing** (beneficiation of ore).
2. **Extractive Metallurgy** (extraction of metal from concentrated ore).
3. **Physical/Mechanical Metallurgy** (shaping, alloying, heat treatment to achieve desired properties).
4. **Characterization and Testing** of metals.

Q4. List mechanical properties and explain any two. (S23 Q1b, 04 marks)
Answer: Mechanical Properties: Strength, Hardness, Ductility, Brittleness, Toughness, Elasticity, Plasticity, Fatigue, Creep.

- **Toughness:** The ability of a material to **absorb energy and plastically deform** before fracturing. It is the total area under the stress-strain curve. A tough material (e.g., mild steel) is both strong and ductile.
- **Fatigue:** The **progressive and localized structural damage** that occurs when a material is subjected to **cyclic or fluctuating loads** at stresses below its ultimate tensile strength. It leads to sudden, catastrophic failure.

Unit 2: Crystal Geometry and Crystal Imperfection

Question 2.1: Explain Bravais lattice with neat diagrams.
(Appeared in: S23 (Q1c, 07 marks))
Answer:
A **Bravais lattice** is an infinite array of discrete points in space, arranged such that the environment around each point is identical. It is defined by a set of **lattice points** generated by translation vectors. In 3D, there are **14 possible Bravais lattices**, derived from **7 crystal systems** by adding **centering** (P: Primitive, I: Body-Centered, F: Face-Centered, C: Base-Centered).
Diagram:



Key Points:

- It represents the **translational symmetry** of the crystal.
- The **unit cell** is the smallest repeating unit of the Bravais lattice.
- Each lattice point is typically associated with a **basis** (atom or group of atoms) to form the complete crystal structure.

Question 2.2: Calculate atomic packing factor for SC, BCC, FCC structures.
(Appeared in: W24 (Q1b, 04 marks), S25 (Q1c, 07 marks), S24 (Q2b, 04 marks))
Answer:
Atomic Packing Factor (APF) is the fraction of volume in a unit cell occupied by atoms, assuming they are hard spheres. **APF = (Volume of atoms in unit cell) / (Volume of unit cell)**.
1. Simple Cubic (SC):

- **Atoms per cell:** 1 atom (8 corners × 1/8).
- **Atomic radius, r:** a = 2r.
- **Volume of atoms:** $1 \times (4/3)\pi r^3$.
- **Volume of cell:** $a^3 = (2r)^3 = 8r^3$.

- **APF (SC) =** [$(4/3)\pi r^3$] / [$8r^3$] = **$\pi/6 \approx 0.52$ (52%)**.

2. Body-Centered Cubic (BCC):

- **Atoms per cell:** 2 atoms (1 center + 8 corners × 1/8).
- **Atomic radius, r:** Body diagonal = $4r = \sqrt{3}\, a \rightarrow a = 4r/\sqrt{3}$.
- **Volume of atoms:** $2 \times (4/3)\pi r^3$.
- **Volume of cell:** $a^3 = (4r/\sqrt{3})^3 = 64r^3/(3\sqrt{3})$.
- **APF (BCC) =** [$2 \times (4/3)\pi r^3$] / [$64r^3/(3\sqrt{3})$] = **$(\sqrt{3}\,\pi)/8 \approx 0.68$ (68%)**.

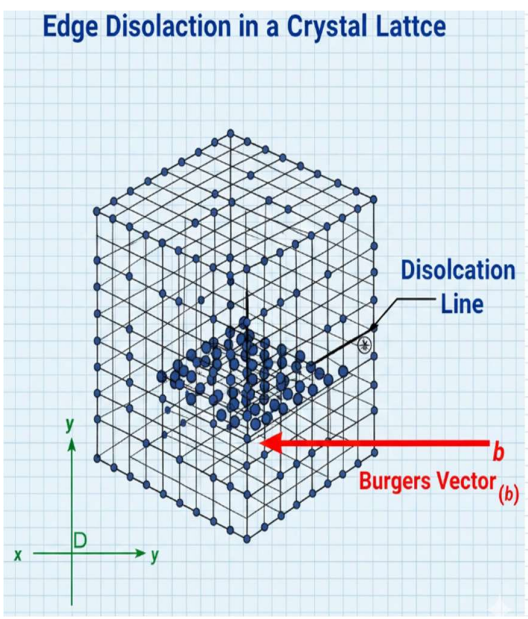
3. Face-Centered Cubic (FCC):

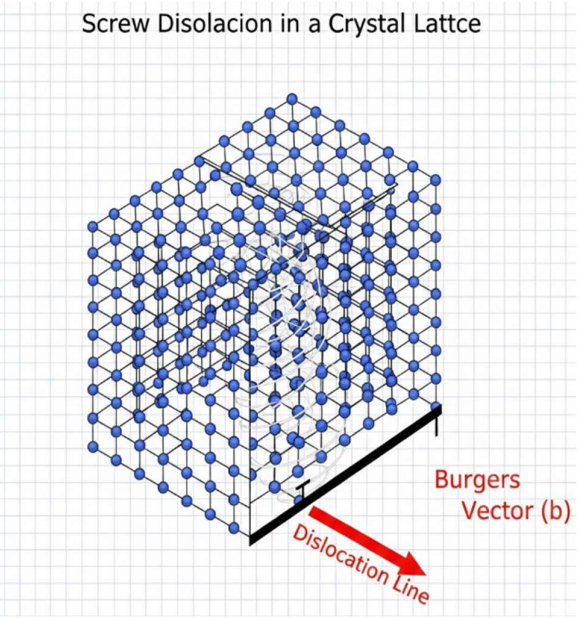
- **Atoms per cell:** 4 atoms (6 faces × 1/2 + 8 corners × 1/8).
- **Atomic radius, r:** Face diagonal = $4r = \sqrt{2}\, a \rightarrow a = 4r/\sqrt{2} = 2\sqrt{2}\, r$.
- **Volume of atoms:** $4 \times (4/3)\pi r^3$.
- **Volume of cell:** $a^3 = (2\sqrt{2}\, r)^3 = 16\sqrt{2}\, r^3$.
- **APF (FCC) =** [$4 \times (4/3)\pi r^3$] / [$16\sqrt{2}\, r^3$] = **$\pi/(3\sqrt{2}) \approx 0.74$ (74%)**.

Conclusion: FCC and HCP have the highest possible APF (0.74) for equal-sized spheres, making them **close-packed structures**.

Question 2.3: Differentiate between edge dislocation and screw dislocation with neat sketches.
(Appeared in: W22 (Q1c, 07 marks), W23 (Q1c, 07 marks), W24 (Q2c OR, 07 marks), S24 (Q3b, 04 marks))
Answer:

Feature	Edge Dislocation	Screw Dislocation
Definition	A **line defect** where an extra half-plane of atoms is inserted into the crystal lattice.	A **line defect** where lattice planes are sheared relative to each other, forming a helical ramp.
Burgers Vector (b)	**Perpendicular** to the dislocation line.	**Parallel** to the dislocation line.
Motion	Moves **perpendicular** to the dislocation line under shear stress (glide/climb).	Moves **parallel** to the dislocation line under shear stress (glide).
Significance	Primary mechanism for **plastic deformation by slip** in many materials.	Allows deformation in directions not possible by edge dislocations alone.
Diagram:		





Other Important Questions:

Q1. Explain grain boundary as a crystalline imperfection. (S23 Q2a, 03 marks)

Answer: A **grain boundary** is a **planar defect** that separates two crystals (grains) of the same composition but different crystallographic orientation. It is a region of **atomic mismatch** and disorder, typically 2-10 atoms wide. Grain boundaries:

- **Hinder dislocation motion**, increasing strength (Hall-Petch effect).
- Act as **preferential sites** for corrosion, precipitation, and diffusion.
- Affect electrical, magnetic, and thermal properties.

Q2. Determine Miller indices of a plane that makes intercepts of 2Å, 3Å, 4Å on orthorhombic crystal axes (a:b:c = 4:3:2). (S23 Q2b, 04 marks)

Answer:

Given: Intercepts: 2, 3, 4 (in Å). Axial ratios: a:b:c = 4:3:2.

Step 1: Express intercepts in terms of lattice parameters: Intercepts = (2/a, 3/b, 4/c). Use axial ratios: Let a=4k, b=3k, c=2k.

Step 2: Calculate intercepts in unit lengths: (2/(4k), 3/(3k), 4/(2k)) = (1/(2k), 1/k, 2/k).

Step 3: Take reciprocals: (2k, k, k/2).

Step 4: Clear fractions (multiply by 2): (4k, 2k, k).

Step 5: Reduce to smallest integers (divide by k): **(4, 2, 1)**.

Final Answer: The Miller indices are **(4 2 1)**.

Q3. Explain arrangement of atoms in BCC, FCC, HCP lattices. (S23 Q2c, 07 marks)

Answer:

- **BCC (Body-Centered Cubic):**
  - Atoms at **all 8 cube corners** and **one atom at the cube center**.
  - Coordination Number (CN) = **8**.
  - Examples: α-Iron (Ferrite), Chromium, Tungsten.
- **FCC (Face-Centered Cubic):**
  - Atoms at **all 8 cube corners** and **atoms at the center of all 6 cube faces**.
  - Coordination Number (CN) = **12**.
  - Close-packed structure. Examples: γ-Iron (Austenite), Aluminum, Copper, Nickel.

- **HCP (Hexagonal Close-Packed):**
  - **Two-layer** close-packing sequence (ABAB...).
  - Top and bottom layers (A) have atoms at corners and center of a hexagon. The middle layer (B) has atoms nestled in the depressions of the A layer.
  - Coordination Number (CN) = **12**.
  - Ideal c/a ratio = 1.633. Examples: Zinc, Magnesium, Titanium (α).

Q4. Explain Frenkel and Schottky defects. (S24 Q3b OR, 04 marks)
Answer:

- **Frenkel Defect:**
  - An **ion** (usually the smaller cation) is displaced from its lattice site into an **interstitial site**, creating a **vacancy-interstitial pair**.
  - **Overall density and stoichiometry remain unchanged**.
  - Common in ionic solids with large size difference (e.g., AgBr, ZnS).
- **Schottky Defect:**
  - A **pair of oppositely charged ions** (one cation + one anion) leave their lattice sites, creating two vacancies.
  - Maintains electrical neutrality but **decreases the density** of the crystal.
  - **Stoichiometry remains constant**.
  - Predominant in ionic solids with similar cation-anion sizes (e.g., NaCl, KCl).

Q5. Explain different methods for grain size measurement. (S23 Q2c OR, 07 marks)
Answer:

1. **Comparison Method (ASTM E112):**
   - The micrograph is compared visually with standard charts (ASTM grain size number, G). Higher G means smaller grains.
   - **Simple but subjective.**
2. **Intercept (Heyn) Method:**
   - Straight lines of known length are drawn on the micrograph.
   - The number of grain boundaries intersected is counted.
   - **Mean Linear Intercept, L = (Total line length) / (Number of grain boundaries intersected)**. More accurate and reproducible.
3. **Planimetric (Jeffries) Method:**
   - The number of grains within a known area (circle) on the micrograph is counted.
   - **Number of grains per unit area, N_A**, is calculated.
4. **Automatic Image Analysis:**
   - Uses computer software to analyze digital micrographs. It's the **fastest and most accurate** method for large sample sizes.

Unit 3: Solidification and Theory of Alloys

Question 3.1: Explain mechanism of crystallization: nucleation and growth.
(Appeared in: W24 (Q2c, 07 marks), S24 (Q2c, 07 marks))
Answer:
Solidification or crystallization is the phase transformation from liquid to solid state. It occurs via two sequential stages:

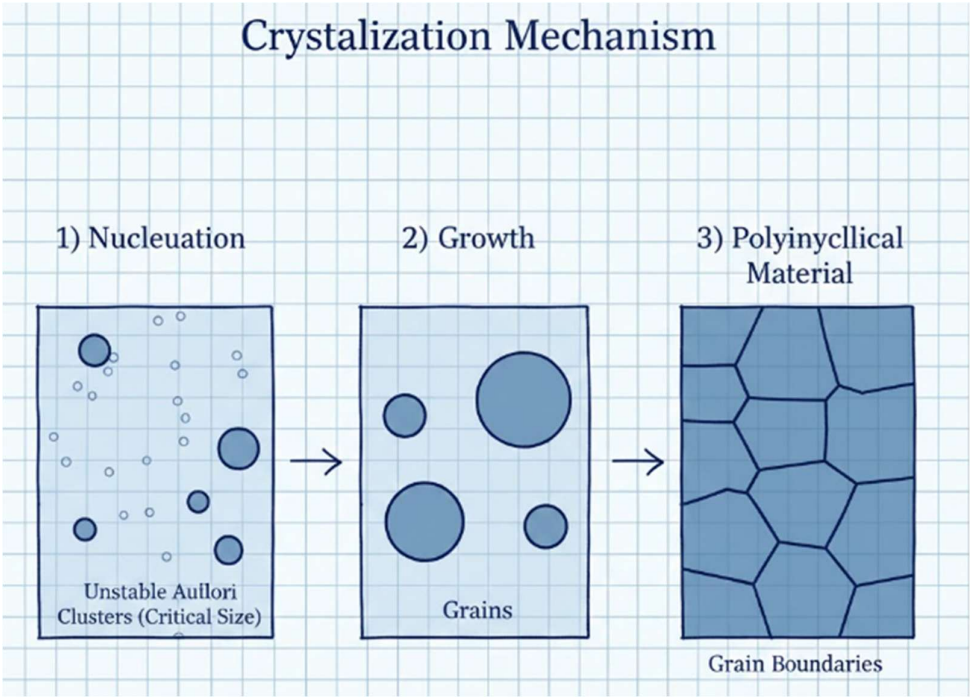
1. Nucleation:

- Formation of **stable, minute solid particles (nuclei)** within the supercooled liquid.
- It begins with the random formation of atomic clusters. For a cluster to become a stable nucleus, it must reach a **critical radius (r*)**.
- **Driving Force:** The **volume free energy decrease** (ΔGv) when liquid turns solid.
- **Retarding Force:** The **surface free energy increase** (γ) due to creation of new solid-liquid interface.
- **Net Free Energy Change:** $\Delta G = (4/3)\pi r^3 \Delta Gv + 4\pi r^2 \gamma$. The critical radius is found where $d(\Delta G)/dr = 0$.

2. Growth:

- **Atoms from the liquid attach to the surfaces of the stable nuclei**, causing the solid phase to expand.
- **Types of Growth:**
  - **Planar Growth:** For pure metals, the solid-liquid interface remains planar and advances into the liquid.
  - **Dendritic Growth:** For alloys (or under high supercooling), instability leads to branched, tree-like projections (dendrites). This occurs due to constitutional supercooling.
- Growth continues until **impingement** occurs—when growing grains meet each other, forming distinct **grain boundaries**.

Diagram:



Question 3.2: Explain homogeneous vs. heterogeneous nucleation.

(Appeared in: S23 (Q4b OR, 04 marks), W24 (Q3b OR, 04 marks))
Answer:

Feature	Homogeneous Nucleation	Heterogeneous Nucleation
Definition	Nucleation that occurs **uniformly throughout** the parent phase without any preferential site.	Nucleation that occurs on **pre-existing surfaces or impurities** like mold walls, container surfaces, or inoculant particles.
Energy Barrier	**Very high.** Requires significant supercooling ($\Delta T \sim 0.2\ Tm$).	**Significantly lower.** The foreign surface reduces the surface energy term (γ), lowering ΔG^*.
Critical Radius (r*)	Same for both types, derived from ΔG equation.	Same as homogeneous.
Critical Free Energy (ΔG*)	High. $\Delta G^*_{hom} = (16\pi\gamma^3) / (3\Delta G_v^2)$.	Lower. $\Delta G_{het} = \Delta G_{hom} \times f(\theta)$, where $f(\theta) < 1$. 'θ' is the contact/wetting angle.
Frequency	**Rare** in practical casting.	**Very common** and dominant in industrial processes.
Nucleation Sites	Random within the bulk liquid.	At interfaces (mold wall, impurities, grain refiners).
Resultant Grain Size	Leads to **many fine grains** if it occurs.	Leads to **fewer, often larger grains** unless many potent sites are added (grain refinement).

Question 3.3: Derive formula for critical radius for homogeneous nucleation.
(Appeared in: W23 (Q2c OR, 07 marks), S24 (Q2c, 07 marks))
Answer:
Given: A spherical solid nucleus of radius 'r' forming from a supercooled liquid.
Forces: 1) **Volume Free Energy Change (ΔGv):** Energy released per unit volume (negative). 2) **Surface Free Energy (γ):** Energy required to create new surface (positive).
Step 1: Express Total Free Energy Change (ΔG)

- ΔG = (Free energy change due to volume) + (Free energy change due to surface)
- ΔG = (Volume of nucleus) × (ΔG_v) + (Surface area of nucleus) × (γ)
- $\Delta G = (\frac{4}{3}\pi r^3)\ \Delta G_v + (4\pi r^2)\ \gamma$

Step 2: Find Critical Radius (r*)

- The nucleus becomes stable when growth leads to a decrease in ΔG. This happens after reaching a maximum point on the ΔG vs. r curve.
- Find this maximum by taking the first derivative of ΔG with respect to r and setting it to zero:
  - $d(\Delta G)/dr = d/dr\ [\ (\frac{4}{3}\pi r^3 \Delta G_v) + (4\pi r^2 \gamma)\ ]$
  - $d(\Delta G)/dr = 4\pi r^2 \Delta G_v + 8\pi r\gamma$
- Set $d(\Delta G)/dr = 0$:

- $4\pi r^2\Delta Gv + 8\pi r\gamma = 0$
- Divide by $4\pi r$: $r\Delta Gv + 2\gamma = 0$

Step 3: Derive the Formula

- $r\Delta Gv = -2\gamma$
- **Critical Radius, $r = -2\gamma / \Delta Gv$***

Interpretation: The negative sign indicates that nucleation is only possible when ΔGv is negative (i.e., during supercooling, when T < Tm). The **critical radius is the minimum size a nucleus must achieve to become stable and grow**. Smaller clusters will redissolve.

Other Important Questions:

Q1. Explain solidification process in metals. (S25 Q3a, 03 marks)

Answer: The solidification process in metals involves:

1. **Supercooling:** Liquid metal is cooled below its equilibrium freezing temperature (Tm).
2. **Nucleation:** Stable solid nuclei form, typically via **heterogeneous nucleation** on mold walls or impurities.
3. **Growth:** Atoms from the liquid attach to the nuclei. For pure metals, growth is often **dendritic** initially, followed by **columnar grains** growing opposite to the heat flow direction.
4. **Grain Formation:** Growth continues until grains impinge, forming a **polycrystalline** solid with **columnar** (near mold walls) and **equiaxed** (center) zones.

Q2. Explain types of growth of nucleus for metals and alloys. (S23 Q4a OR, 03 marks)

Answer:

- **Planar Growth:** Occurs in **pure metals** under slow cooling with a positive temperature gradient. The solid-liquid interface is smooth and planar, advancing uniformly.
- **Dendritic Growth:** Occurs in **alloys** or pure metals under a **negative temperature gradient/constitutional supercooling**. The interface becomes unstable, forming branched, tree-like projections called **dendrites**. This is the most common growth mode in casting.

Question 3.3: What are requirements for solidification to initiate and proceed?
(S23 Q4c, 07 marks)

Answer:

For solidification to successfully initiate and proceed from a liquid to a solid state, several thermodynamic, kinetic, and microstructural conditions must be satisfied. These requirements are sequential and interdependent.

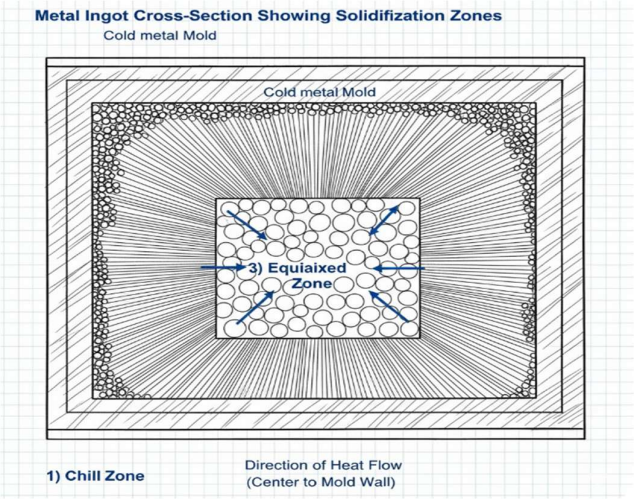
1. **Thermodynamic Requirement – Supercooling:**
   - **Essential Condition:** The liquid must be **supercooled**, i.e., cooled below its equilibrium melting/freezing temperature (**Tm**).
   - **Reason:** Supercooling ($\Delta T = Tm - T$) creates a **negative volume free energy change (ΔGv)**. This ΔGv is the fundamental **driving force** for the phase transformation, as the solid phase becomes thermodynamically more stable than the liquid below Tm. Without supercooling, there is no net driving force for solidification.
2. **Microstructural Requirement – Nucleation:**
   - **Initiation Step:** The process begins with **nucleation** – the formation of stable, minute solid particles (nuclei) within the supercooled liquid.

- **Overcoming Energy Barrier:** Nucleation requires overcoming an **activation energy barrier (ΔG*)**. This barrier exists because creating a new solid-liquid interface incurs a positive surface energy cost (γ).
- **Critical Nucleus:** A cluster of atoms must grow to a **critical radius (r*)**. Clusters smaller than r* will redissolve; those larger are stable and will grow. The critical radius is inversely proportional to the degree of supercooling ($r^* \propto 1/\Delta T$).
- **Role of Heterogeneous Sites:** While homogeneous nucleation (in the bulk liquid) requires very high ΔT, in practice, **heterogeneous nucleation** on pre-existing surfaces (mold walls, impurities, inoculants) is dominant. These sites lower ΔG*, making nucleation feasible with minimal supercooling.

3. **Kinetic Requirement – Growth:**
   - **Propagation Step:** Once a stable nucleus forms, **growth** proceeds by the **diffusion and attachment** of atoms from the liquid to the solid interface.
   - **Heat Removal:** For growth to continue, the **latent heat of fusion** released at the solid-liquid interface must be continuously removed (conducted away through the solid and mold). The **rate of heat extraction (cooling rate)** controls the growth velocity.
   - **Interface Stability:** The mode of growth (planar, cellular, dendritic) depends on the temperature gradient (G) and growth rate (R), often described by the **constitutional supercooling criterion** for alloys.
4. **Macro-scale Requirement – Continued Undercooling & Impingement:**
   - The process will only proceed to completion if the system remains undercooled at the solidification front.
   - Growth of individual grains continues until they **impinge** upon neighboring grains, forming a **polycrystalline solid** with defined **grain boundaries**.

In summary, solidification requires: **1) Supercooling** (Driving Force), **2) Formation of stable nuclei via nucleation** (Initiation), and **3) Sustained atomic attachment and heat removal for growth** (Propagation), culminating in grain impingement.

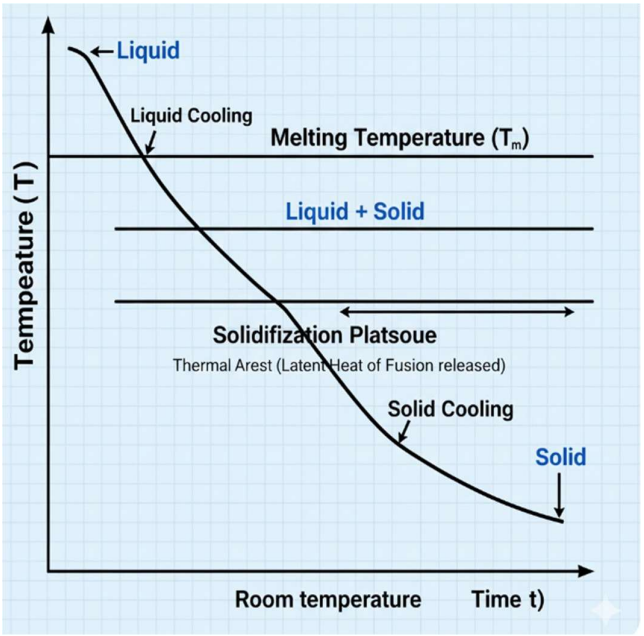
Question 3.4: Draw microstructure of solidified pure metal ingot.
(S24 Q4a, 03 marks)
Answer:
The microstructure of a typical solidified pure metal ingot (cast in a static mold) is not uniform and exhibits three distinct zones from the mold wall towards the center:
Diagram:



Explanation of Zones:

1. **Chill Zone:** Rapid heat extraction at the cold mold wall causes a high degree of supercooling, resulting in rapid nucleation and many fine, randomly oriented grains.
2. **Columnar Zone:** Grains with favorable growth orientation (perpendicular to the mold wall, along the thermal gradient) grow preferentially at the expense of others, forming long columnar structures.
3. **Equiaxed Zone:** In the center, where the thermal gradient is shallow, nucleation can occur in the remaining liquid from impurities or detached dendrite arms, leading to coarse, non-directional equiaxed grains.

Question 3.5: Draw cooling curve for pure metal.
(S24 Q4a OR, 03 marks)
Answer:
A cooling curve is a plot of temperature versus time for a material as it cools. For a **pure metal**, it distinctly shows the release of latent heat during solidification.
Diagram:



Key Features:

- The **plateau** is the signature of a pure metal's cooling curve.
- The **absence of a plateau** or a sloping plateau indicates an alloy or impure metal, where solidification occurs over a temperature range.
- The cooling rate before and after the plateau can vary depending on the heat extraction conditions.

Unit 4: Phase and Phase Equilibrium

Question 4.1: State and explain Hume-Rothery rules.
(Appeared in: W23 (Q2c, 07 marks), W24 (Q3a, 03 marks))
Answer:
The **Hume-Rothery rules** are a set of guidelines that predict the extent of solid solubility (primarily substitutional) in alloy systems. For significant solid solubility to occur, the following conditions should be met:

1. **Atomic Size Factor (Crystal Structure Factor):**
    - **Rule:** The atomic radii of the solute and solvent atoms should not differ by more than **±15%**.
    - **Explanation:** A larger size difference creates substantial lattice strain, making it energetically unfavorable to substitute atoms, thereby limiting solubility.
2. **Electrochemical Factor (Valency Effect):**
    - **Rule:** The solute and solvent should have **similar electronegativity**.
    - **Explanation:** A large difference in electronegativity favors the formation of stable **intermetallic compounds** (ionic/covalent bonding) rather than a random solid solution.
3. **Relative Valency Factor:**
    - **Rule:** A metal of **lower valency** is more likely to dissolve in a metal of **higher valency** than vice-versa.
    - **Explanation:** This is related to electron concentration. A higher valency solvent can accommodate the extra electrons from a lower valency solute more easily without destabilizing the structure.
4. **Crystal Structure Factor:**
    - **Rule:** The solute and solvent metals must have the **same crystal structure** for complete solid solubility (i.e., to form an isomorphous system).
    - **Explanation:** Similar crystal structures ensure a coherent interface and minimal distortion when atoms substitute for one another.

Example: Copper (FCC, r=0.128 nm, valency 1) and Nickel (FCC, r=0.125 nm, valency 2) obey these rules, leading to **complete solid solubility**. Conversely, lead (FCC, r=0.175 nm) has very low solubility in aluminum (FCC, r=0.143 nm) due to the >15% size difference.

Question 4.2: Explain Gibbs phase rule and apply to unary/binary systems.
(Appeared in: W22 (Q2c OR, 07 marks), W24 (Q3c, 07 marks), S25 (Q2c OR, 07 marks), S24 (Q3c, 07 marks))
Answer:
The **Gibbs Phase Rule** is a fundamental thermodynamic relationship that determines the number of independent variables (degrees of freedom, F) that can be changed in a system at equilibrium without altering the number of phases present.
Formula: F = C - P + 2

- **F:** Degrees of freedom (Number of intensive variables - e.g., temperature, pressure, composition - that can be independently varied).
- **C:** Number of components (minimum number of independent chemical constituents).
- **P:** Number of phases present (physically distinct, homogeneous parts).

Application:

1. **To a Unary System (C=1, e.g., pure water):**
    - **Single Phase Region (P=1):** F = 1 - 1 + 2 = **2**. Both **Temperature (T)** and **Pressure (P)** can be varied independently (e.g., liquid water over a range of T & P).

- **Two Phase Coexistence Line (P=2):** F = 1 - 2 + 2 = **1**. Only T *or* P can be varied independently. If T is fixed, P is fixed (e.g., on the water-ice equilibrium line).
- **Triple Point (P=3):** F = 1 - 3 + 2 = **0**. This is an invariant point. Neither T nor P can be changed; all three phases (solid, liquid, vapor) coexist at a unique T and P.

2. **To a Binary System (C=2, e.g., Cu-Ni alloy) at constant pressure (common in metallurgy):**
   - The phase rule simplifies to **F = C - P + 1** (since pressure is fixed).
   - **Single Phase Field (P=1):** F = 2 - 1 + 1 = **2**.
     Both **Temperature** and **Composition** can be varied independently within the field (e.g., within the liquid region).
   - **Two Phase Field (P=2):** F = 2 - 2 + 1 = **1**. If temperature is chosen, the compositions of both phases (e.g., liquid and solid on a phase diagram) are fixed by the tie-line. Or, if one phase's composition is fixed, T is determined.
   - **Three Phase Reaction (Eutectic/Eutectoid Point) (P=3):** F = 2 - 3 + 1 = **0**. This is an invariant reaction. Temperature and the compositions of all three phases are fixed (e.g., the eutectic point in a Pb-Sn diagram).

Question 4.3: Define solid solution and explain types.
(Appeared in: S25 (Q2a, 03 marks), S24 (Q4c OR, 07 marks))
Answer:
Solid Solution: A homogeneous crystalline phase that contains two or more chemical species (elements). It consists of a **solvent** (host lattice) and a **solute** (dissolved element), where the solute atoms are distributed atomically within the crystal structure of the solvent.
Types of Solid Solutions:

1. **Substitutional Solid Solution:**
   - **Mechanism:** Solute atoms **replace or substitute** solvent atoms on their lattice sites.
   - **Requirements:** Governed by Hume-Rothery rules (similar atomic size, electronegativity, valency, and crystal structure).
   - **Examples:** Brass (Zn in Cu), Cu-Ni alloys.
2. **Interstitial Solid Solution:**
   - **Mechanism:** Solute atoms occupy the **interstitial spaces (voids)** between the solvent atoms in the lattice.
   - **Requirements:** The solute atom (e.g., C, N, H, B) must be **significantly smaller** than the solvent atom (typically < 0.59 times the solvent radius).
   - **Example:** Carbon in γ-iron (Austenite, FCC) is a key example in steel.
3. **Based on Solubility Limit:**
   - **Primary (Terminal) Solid Solution:** Solubility extends from a pure component.
   - **Intermediate Solid Solution:** Exists over a composition range not including a pure component (e.g., β-phase in Cu-Zn).

Other Important Questions:
Q1. Explain Lever rule with binary phase diagram. (S25 Q3b OR, 04 marks)
Answer:
The **Lever Rule** is a method used to determine the **weight fractions or percentages of each phase** present in a two-phase region of a binary phase diagram at a specific temperature and overall composition.

Procedure:

1. At the given temperature and overall composition (C_0), draw a horizontal **tie-line** across the two-phase region. The tie-line ends intersect the phase boundary lines.
2. The intersections give the **compositions** of the two phases in equilibrium (e.g., C_L for liquid and C_α for solid α).
3. The tie-line acts as a lever. The fraction of one phase is proportional to the length of the lever *opposite* to that phase.
    - **Weight Fraction of α-phase:** $W_\alpha = (C_L - C_0) / (C_L - C_\alpha)$
    - **Weight Fraction of L-phase:** $W_L = (C_0 - C_\alpha) / (C_L - C_\alpha)$
    - **Check:** $W_\alpha + W_L = 1$.

Q2. Write invariant reactions: eutectic, peritectoid, monotectic, eutectoid. (S24 Q4b, 04 marks)

Answer:

- **Eutectic Reaction: Liquid (L) → Solid₁ (α) + Solid₂ (β)**
    - A liquid transforms into two different solid phases upon cooling. (e.g., Pb-Sn alloy)
- **Peritectoid Reaction: Solid₁ (α) + Solid₂ (β) → Solid₃ (γ)**
    - Two solid phases react to form a new solid phase upon cooling. (e.g., Fe-C system, formation of δ-ferrite)
- **Monotectic Reaction: Liquid₁ (L_1) → Solid (α) + Liquid₂ (L_2)**
    - One liquid phase transforms into a solid and a different liquid phase upon cooling. (e.g., Cu-Pb system)
- **Eutectoid Reaction: Solid₁ (γ) → Solid₂ (α) + Solid₃ (β)**
    - One solid phase transforms into two different solid phases upon cooling. (e.g., Austenite (γ) → Ferrite (α) + Cementite (Fe_3C) in steels).

Q3. Explain non-equilibrium cooling. (S25 Q3b, 04 marks)

Answer:

Non-equilibrium cooling occurs when an alloy is cooled rapidly (e.g., during quenching), preventing sufficient time for **atomic diffusion** to maintain the equilibrium phase compositions predicted by the phase diagram.

Consequences (Coring):

- **Segregation:** The first solid to form (core of a dendrite) is richer in the higher-melting-point element. The last solid to form (interdendritic regions) is richer in the lower-melting-point element.
- **Microstructural Result:** A **cored structure** with a composition gradient across grains, instead of uniform grains.
- **Suppressed Reactions:** Rapid cooling can suppress equilibrium phase transformations (like pearlite formation in steel), leading to non-equilibrium phases (like martensite).
- **Property Impact:** This leads to **non-uniform mechanical properties** and can increase susceptibility to corrosion.

Q4. Explain allotropy with reference to iron. (S25 Q3c, 07 marks)

Answer:

Allotropy (or Polymorphism) is the property of a material to exist in **more than one crystal structure** at different temperatures and pressures. The different structures are called **allotropes**.

Allotropy in Iron (Fe):

Iron exhibits allotropic transformation, which is fundamental to the heat treatment of steel.

1. **α-Iron (Ferrite):** Stable at room temperature up to 912°C. Has a **Body-Centered Cubic (BCC)** structure. It is **magnetic** below its Curie temperature (768°C).

2. **γ-Iron (Austenite):** Stable between 912°C and 1394°C. Has a **Face-Centered Cubic (FCC)** structure. It is **non-magnetic** and can dissolve a significant amount of carbon interstitially (~2.1 wt% C), which is crucial for hardening steel.
3. **δ-Iron (Delta Ferrite):** Stable from 1394°C up to the melting point (1538°C). Has a **Body-Centered Cubic (BCC)** structure (same as α-Fe but at higher temperature).

Significance in Steelmaking:

- The **γ-Fe (FCC)** phase's high carbon solubility allows for homogeneous distribution of carbon during austenitizing.
- The subsequent transformation of austenite (γ) upon cooling to the BCC phases (α or body-centered tetragonal martensite) is the basis for various microstructures (ferrite, pearlite, bainite, martensite) and properties in steel.

Unit 5: Non-ferrous Metal and Alloys (Unit of New Syllabus)

Question 5.1: Compare the properties and applications of aluminum alloys and copper alloys.
Answer:

- **Aluminum Alloys:**
  - **Properties:** Low density (lightweight), good corrosion resistance (forms protective oxide layer), high electrical & thermal conductivity, good formability, non-magnetic, moderate strength (can be enhanced by alloying & heat treatment).
  - **Applications:**
    - **Aerospace & Aviation:** Airframes, skins, fittings (series 2xxx, 7xxx).
    - **Transportation:** Automotive bodies, engine blocks, wheels (series 3xxx, 5xxx, 6xxx).
    - **Construction:** Window frames, cladding, roofing (series 6xxx).
    - **Electrical:** Overhead power lines, conductors (high-purity Al).
    - **Packaging:** Cans, foils (series 1xxx, 3xxx).
- **Copper Alloys:**
  - **Properties:** Excellent electrical & thermal conductivity, good corrosion resistance (especially to seawater), antimicrobial, easily joined (soldered, brazed), attractive color, good strength.
  - **Applications:**
    - **Electrical & Electronics:** Wiring, contacts, printed circuit boards, transformers (Electrolytic Tough Pitch Copper).
    - **Heat Exchangers & Condensers:** Tubes, plates (Admiralty brass, Cupronickel).
    - **Marine:** Propellers, fittings, ship hulls (Naval brass, Bronze).
    - **Architecture:** Roofing, statues, decorative elements.
    - **Industrial:** Valves, pumps, bearings, gears (Bronzes, Gunmetal).

Question 5.2: State composition, properties and applications of Hindalium and Invar.
(Appeared in: W22 Q3a OR, S25 Q3a OR, W23 Q4a OR)
Answer:

1. **Hindalium:**
   - **Composition:** It is an **aluminum alloy** primarily containing **Aluminum (Al)** as the base (96.8%), along with **Magnesium (Mg: 0.6%)**, **Manganese (Mn: 0.6%)**, **Silicon (Si: 1.5%)**, and **Iron (Fe: 0.3%)**.
   - **Properties:** Lightweight, good corrosion resistance, good strength-to-weight ratio, excellent anodizing characteristics, and good machinability.
   - **Applications:** Primarily used for **manufacturing anodized utensils** (cookware, pots, pans) due to its attractive finish and durability. Also used in architectural fittings and furniture.
2. **Invar (Fe-Ni36 or 64FeNi):**
   - **Composition:** An iron-nickel alloy containing approximately **64% Iron (Fe)** and **36% Nickel (Ni)**.
   - **Properties:** Its most notable property is an **exceptionally low coefficient of thermal expansion (CTE)** near room temperature. It is also ductile, machinable, and has good weldability.
   - **Applications:**
     - **Precision Instruments:** Pendulum rods, clock balance wheels, laser

components, optical mounts.
- **Thermal Engineering:** Bimetallic strips (as the low-expansion member), length standards, shadow masks in color TV tubes.
- **Cryogenics:** Storage tanks for liquefied gases.

Question 5.3: State composition and specific applications of: Muntz metal; German silver; Naval brass.
(Appeared in: W22 Q4a)
Answer:

1. **Muntz Metal:**
   - **Composition:** 60% Copper (Cu), 40% Zinc (Zn). A type of **alpha-beta brass**.
   - **Applications:** Primarily used for **marine applications** such as sheathing for ship hulls (due to good corrosion resistance in seawater), bolts, nuts, and architectural trim.
2. **German Silver (Nickel Silver):**
   - **Composition:** 60% Copper (Cu), 20% Zinc (Zn), 20% Nickel (Ni). *Contains no silver.*
   - **Applications:** Used for making **ornamental work, silverware (electroplated), musical instruments (flutes, saxophones), electrical resistance wires, and nameplates** due to its silvery appearance, corrosion resistance, and hardness.
3. **Naval Brass:**
   - **Composition:** 60% Copper (Cu), 39.25% Zinc (Zn), 0.75% Tin (Sn). The addition of tin improves corrosion resistance in seawater.
   - **Applications:** As the name suggests, it is extensively used in **marine environments** for propeller shafts, marine hardware, pump rods, valves, and condenser tubes.

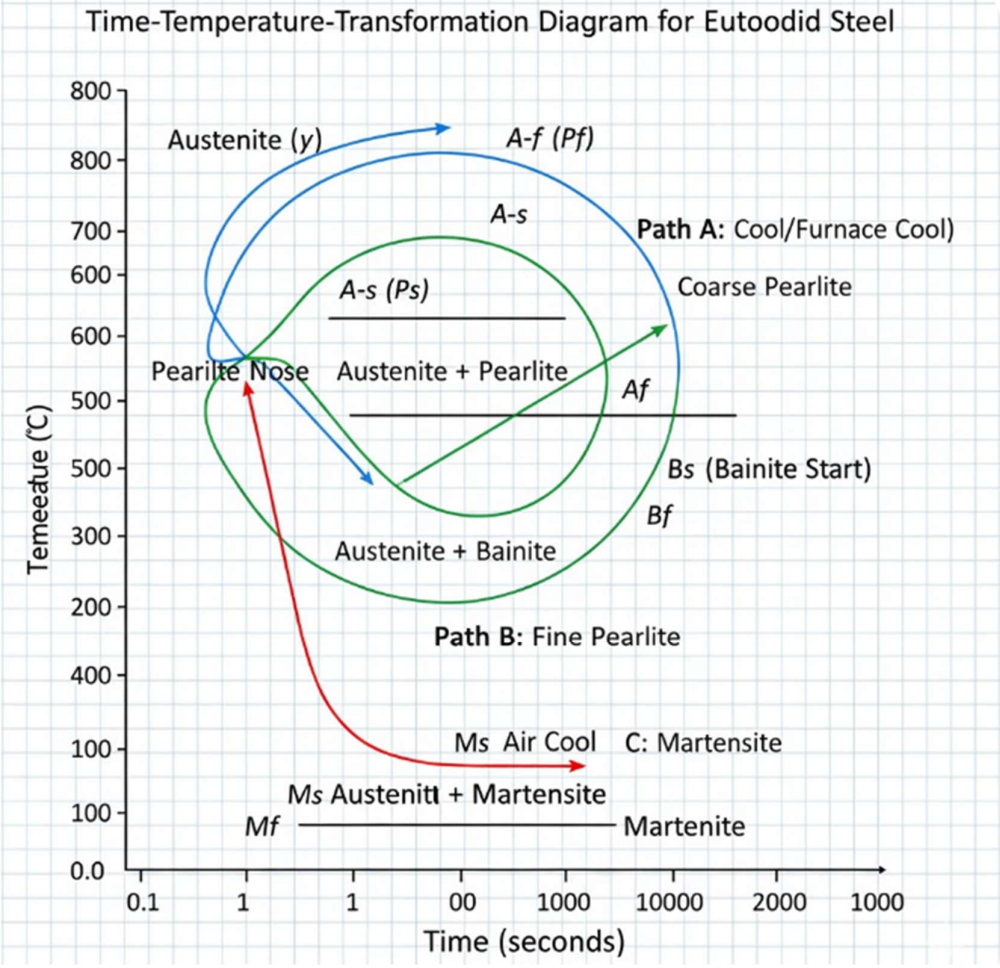
Question 5.4: Compare nodular cast iron and malleable cast iron.
(Appeared in: W22 Q4a OR, S25 Q5a OR)
Answer:

Feature	Nodular Cast Iron (Ductile Iron)	Malleable Cast Iron
Graphite Form	**Spheroidal (Nodular)** graphite particles.	**Temper Carbon** (irregular, clustered aggregates) in a ferrite or pearlite matrix.
Production Method	Achieved by adding **Magnesium (Mg)** or **Cerium (Ce)** as a nodulizer to molten iron **before casting**.	Produced by **heat treatment (annealing)** of **white cast iron** casting for extended periods (up to several days).
Mechanical Properties	Excellent **ductility and toughness**, high tensile strength, good wear resistance.	Good **ductility and machinability**, moderate strength and toughness. Less ductile than nodular iron.
Microstructure	Ferritic, Pearlitic, or Austenitic matrix with spherical graphite.	Ferritic or Pearlitic matrix with irregular graphite clusters.

Feature	Nodular Cast Iron (Ductile Iron)	Malleable Cast Iron
Advantages	Combines castability of iron with strength & ductility approaching steel. Can be welded.	Good shock and vibration absorption. Easier to machine than most cast irons.
Applications	Crankshafts, gears, pipe fittings, heavy-duty machine parts, automotive components.	Railroad equipment, pipe fittings, hardware, agricultural implements, hand tools.

Unit 6: TTT Diagrams and Heat Treatment of Steel

Question 6.1: Draw TTT diagram for eutectoid steel with necessary notations.
(Appeared in: W24 (Q4c, 07 marks))
Answer:
A Time-Temperature-Transformation (TTT) diagram for eutectoid steel (0.8% C) plots the transformation of austenite into various microstructures as a function of time and temperature.
Diagram:



Question 6.2: Justify need of heat treatment for metals and explain TTT diagram.
(Appeared in: W22 (Q4c, 07 marks), S25 (Q4c, 07 marks))
Answer:
Part 1: Justification for Heat Treatment
Heat treatment is a controlled process of heating and cooling metals in the solid state to alter their **microstructure** and thereby obtain desired **mechanical properties** (hardness, strength, toughness, ductility) and sometimes physical properties. The need arises because:

1. **To Relieve Internal Stresses:** Casting, welding, and machining induce residual stresses that can cause distortion or failure. Processes like **stress relieving** are used.
2. **To Improve Machinability: Annealing** softens metals, making them easier to cut and shape.
3. **To Increase Strength and Hardness:** Processes like **quenching and tempering**

(hardening) are used to produce strong, wear-resistant components (e.g., gears, tools).

4. **To Improve Toughness/Ductility:** Hardened steels are often brittle. **Tempering** after quenching reduces brittleness while retaining much of the strength.
5. **To Refine Grain Structure: Normalizing** produces a uniform, fine-grained structure, improving mechanical properties and preparing the steel for further hardening.
6. **To Alter Chemical Composition at Surface: Case hardening** (e.g., carburizing) creates a hard, wear-resistant surface over a tough core.

Part 2: Explanation of TTT Diagram

- **Purpose:** The **Time-Temperature-Transformation (TTT) diagram** is a tool that predicts the **kinetics** of austenite transformation for a specific steel composition (e.g., eutectoid). It shows what microstructure forms based on **cooling rate**.
- **Axes: Y-axis = Temperature**, **X-axis = Time (log scale)**.
- **Key Components:**
  - **'C' Curves:** Represent the start and finish times for **diffusion-controlled transformations** (Pearlite, Bainite). The "nose" is the point of shortest time, indicating the temperature where transformation is fastest.
  - **Ms and Mf Lines:** Represent the start and finish temperatures for the **diffusionless, shear transformation** to Martensite. This transformation is time-independent; it depends only on how far below Ms the steel is cooled.
- **Interpretation:** A cooling path (line from high temp to low) plotted on this diagram shows which microstructures will form:
  - Path crossing the upper 'C' curve → **Pearlite** (coarse or fine).
  - Path crossing the lower 'C' curve → **Bainite**.
  - Path avoiding both 'C' curves → **Martensite**.
- **Critical Cooling Rate:** The minimum cooling rate needed to miss the nose of the pearlite curve and form martensite.

Question 6.3: Differentiate annealing and normalizing.
(Appeared in: W22 (Q4b, 04 marks), S23 (Q4b, 04 marks), W23 (Q4b, 04 marks))
Answer:

Feature	Annealing	Normalizing
Purpose	To soften the metal, relieve internal stresses, improve ductility/machinability, and produce a homogeneous microstructure.	To refine grain structure (after forging/casting), improve mechanical properties, and produce a more uniform, tougher structure than annealing.
Heating Temperature	Heated to **above the upper critical temperature (A3 or Acm)** for hypoeutectoid steels, or **above A1** for hypereutectoid steels, and held.	Heated to **about 40-50°C above the upper critical temperature (A3 or Acm)**, i.e., higher than annealing.
Cooling Method	**Very slow cooling** inside the furnace itself (furnace cooling).	Cooled in **still air** (air cooling). This is faster than furnace cooling.

Feature	Annealing	Normalizing
Cooling Rate	**Slowest**.	**Faster** than annealing but slower than quenching.
Resultant Microstructure	**Coarse pearlite** (in steels) with relatively soft ferrite. Largest possible grain size for that steel.	**Fine pearlite** with finer ferrite grains than annealed steel. Grain structure is more uniform.
Hardness & Strength	**Lowest** hardness and strength for that steel composition.	**Higher** hardness and strength than annealed steel due to finer grains (Hall-Petch effect).
Primary Application	Stress relief, softening for machining, improving ductility.	Pre-treatment before hardening, refinement of cast/wrought structures, final treatment for low-carbon steels.

Other Important Questions:

Q1. Define heat treatment and classify processes. (W23 Q4a, 03 marks)

Answer:

Heat treatment is a set of controlled operations involving the heating and cooling of metals/alloys in the solid state to obtain desired properties by altering their microstructure.

Classification:

1. **Softening Processes:** Annealing, Process Annealing, Spheroidizing.
2. **Hardening Processes:** Quenching (to form martensite).
3. **Tempering Processes:** Tempering of hardened steel.
4. **Surface Hardening Processes:**
    - **Case Hardening:** Carburizing, Nitriding, Cyaniding.
    - **Selective Hardening:** Flame hardening, Induction hardening.
5. **Normalizing.**

Q2. Explain full annealing process. (S25 Q4a, 03 marks), (S24 Q5c, 07 marks)

Answer (for 07 marks):

Full annealing is a softening heat treatment used primarily for hypoeutectoid steels to produce coarse pearlite, maximum softness, and good machinability.

1. **Heating:** The steel is heated to about **30-50°C above the A3 line** (into the fully austenitic region). For hypereutectoid steel, it is heated above the A1 line.
2. **Holding (Soaking):** Held at this temperature long enough to achieve a **homogeneous austenitic structure** throughout the cross-section.
3. **Cooling:** It is then **cooled very slowly**, usually by turning off the furnace and allowing the steel to cool inside (**furnace cooling**). This very slow cooling rate allows austenite to transform into the **softest, most stable microstructure** (coarse pearlite and proeutectoid ferrite).
4. **Purpose/Result:** Relieves internal stresses, reduces hardness, increases ductility and toughness, refines grain structure (if previously distorted), and improves machinability.

Q3. Explain flame hardening. (W22 Q5b, 04 marks), (S25 Q4b, 04 marks)
Answer:
Flame hardening is a **surface hardening** process used for medium to large-sized components (e.g., gears, cams, crankshafts).

1. **Principle:** An oxy-fuel gas flame (e.g., oxy-acetylene) is used to **rapidly heat only the surface layer** of a steel part above its upper critical temperature (austenitizing range).
2. **Process:** Immediately after heating, the hot surface is **quenched** by a spray of water or other coolant. This rapid quenching transforms the austenitized surface into hard **martensite**.
3. **Key Feature:** Only the surface is hardened, leaving the **core soft and tough**. No change in surface chemical composition occurs.
4. **Advantages:** Suitable for large parts, localized hardening, fast process, low equipment cost.
5. **Disadvantages:** Risk of overheating, requires skilled operator, control of case depth is less precise than induction hardening.

Q4. Explain pack carburizing. (W22 Q4b OR, 04 marks)
Answer:
Pack carburizing is a **case hardening** process that increases the surface carbon content of low-carbon steel.

1. **Setup:** The component is packed in a sealed container with a carbon-rich solid compound (**carburizer**), typically charcoal mixed with an energizer like $BaCO_3$.
2. **Heating:** The container is heated to **900-950°C** (within the austenite region) and held for several hours.
3. **Mechanism:** The energizer produces CO gas, which decomposes at the steel surface, releasing atomic carbon that diffuses into the austenite.
4. **Result:** A high-carbon surface layer (typically 0.8-1.2% C) is formed. After carburizing, the part is **quenched** to transform this high-carbon surface into hard martensite, creating a wear-resistant case over a tough, low-carbon core.
5. **Advantage:** Simple, low-cost equipment.
6. **Disadvantage:** Slow, less control over case depth and carbon gradient, messy process.

Q5. List various heat treatment processes for steels. (S23 Q5a OR, 03 marks)
Answer:

1. Annealing (Full, Process, Spheroidize)
2. Normalizing
3. Hardening (Quenching)
4. Tempering
5. Austempering
6. Martempering
7. Case Hardening: Carburizing, Nitriding, Cyaniding, Carbonitriding
8. Selective Hardening: Flame Hardening, Induction Hardening

Unit 7: Powder Metallurgy

Question 7.1: Define powder metallurgy and state advantages, limitations, applications.
(Appeared in: W22 (Q5c, 07 marks), S25 (Q4c OR, 07 marks), W24 (Q5a, 03 marks))
Answer:
Powder Metallurgy (P/M) is a manufacturing process where **fine metal powders** are compressed (compacted) into a desired shape (**green compact**) and then heated (**sintered**) at a temperature below the melting point of the major constituent to bond the particles, forming a solid, coherent component with controlled porosity and properties.
Advantages:

1. **Material Efficiency & Low Waste:** Near-net-shape production minimizes or eliminates machining, leading to **very high material utilization** (up to 97%).
2. **Complex Shapes:** Capable of producing intricate and complex shapes that are difficult or impossible to make by casting or machining (e.g., gears with internal splines).
3. **Controlled Porosity:** Can produce parts with **controlled porosity**, such as self-lubricating bearings (oil-impregnated) and filters.
4. **Unique Material Combinations:** Allows fabrication of **composite materials** and parts from materials with very high melting points or that are immiscible in liquid state (e.g., tungsten filaments, metal-ceramic composites).
5. **Good Dimensional Accuracy:** Provides good dimensional control and surface finish.
6. **Mass Production:** Highly suitable for **high-volume production** of small, precise parts (e.g., automotive components) with consistent quality.

Limitations:

1. **High Initial Tooling Cost:** Dies and equipment require significant capital investment, making it **economical only for high-volume** production.
2. **Size and Shape Restrictions:** The size of parts is limited by press capacity, and very thin walls or sharp corners can be difficult to produce.
3. **Lower Strength:** Compared to wrought products of the same material, P/M parts can have **lower strength and ductility** due to residual porosity.
4. **Material Cost:** Metal powders are more expensive than bulk material.
5. **Design Limitations:** Undercuts and transverse holes cannot be molded directly and require secondary operations.

Applications:

1. **Automotive:** Engine bearings (porous oil-retaining), gears, sprockets, connecting rods, valve guides.
2. **Cutting Tools & Wear Parts:** Cemented carbide tips for tools, diamond-impregnated grinding wheels.
3. **Electrical & Magnetic:** Electrical contacts, brushes, soft magnetic cores for relays.
4. **Filters:** Porous metal filters for gases and liquids.
5. **Aerospace:** High-temperature alloy components, brake pads.
6. **Consumer Goods:** Lock parts, sewing machine components.

Question 7.2: Explain production methods of metal powders.
(Appeared in: W24 (Q5b OR, 04 marks), S24 (Q5a, 03 marks))
Answer:
The production of fine, consistent metal powders is the first critical step in P/M. Common methods include:

1. **Atomization:** The **most common** method for producing powders of iron, steel, aluminum, brass, etc. Molten metal is forced through a nozzle and disintegrated by a

high-pressure stream of gas (air, nitrogen, argon) or water. This produces **spherical or irregular** powder particles.
    - **Gas Atomization:** Produces smoother, more spherical powders (better for high-performance applications).
    - **Water Atomization:** Produces irregular, oxidized powders at lower cost (common for iron powders).
2. **Reduction:** Metal oxides are reduced to metallic powder using a reducing gas (H_2, CO) at temperatures below the melting point. **Example:** Production of **iron powder** from iron ore (magnetite) or mill scale. Produces **spongy, porous particles**.
3. **Electrolytic Deposition:** Similar to electroplating, but under conditions that produce a **brittle, friable deposit** on the cathode, which is then scraped off and milled into powder. Produces **high-purity, dendritic powders** (e.g., copper, iron).
4. **Mechanical Comminution:** Involves crushing, milling, or grinding of brittle metals or alloys (e.g., ferroalloys) in ball mills or hammer mills. Produces **angular, irregular particles**.
5. **Carbonyl Process:** Based on thermal decomposition of metal carbonyls. **Example: Nickel powder** is produced by decomposing nickel carbonyl [$Ni(CO)_4$] gas. Produces **very fine, spherical, high-purity** powders.

Question 7.3: Explain characteristics of metal powders.
(Appeared in: W23 (Q4c OR, 07 marks), W24 (Q4b OR, 04 marks))
Answer:
The properties of the final P/M product are heavily influenced by the characteristics of the starting metal powder. Key characteristics are:

1. **Particle Size and Size Distribution:**
    - **Size:** Affects compaction density, sintering rate, and final porosity. Finer powders compact better but flow poorly.
    - **Distribution:** A **mixture of sizes** improves packing density, as smaller particles fill voids between larger ones.
2. **Particle Shape:**
    - **Spherical:** Good flowability, lower compact strength (poor mechanical interlocking).
    - **Irangular/Irregular:** High green strength due to interlocking, but poor flow.
    - **Dendritic:** Very high surface area, excellent compressibility and green strength, but oxidizes easily.
    - **Flaky:** Poor flow and apparent density.
3. **Apparent Density:** The mass per unit volume of loose powder as poured. It affects the **fill depth** in the die.
4. **Flow Rate:** The time required for a standard weight of powder to flow through a standard funnel. **Crucial for automatic die filling**. Spherical powders flow best.
5. **Compressibility:** The ability of powder to reduce in volume under pressure. Measured by the **green density** achieved at a specific compacting pressure.
6. **Green Strength:** The mechanical strength of the unsintered compact. It must be sufficient to withstand ejection from the die and handling before sintering.

Other Important Questions:
Q1. Explain sintering process. (W22 Q5a OR, 03 marks)
Answer:
Sintering is the heat treatment process where the **green compact** is heated to a temperature below the melting point of the major constituent (typically 70-90% of Tm).

- **Purpose:** To develop **metallurgical bonds (necks)** between powder particles through **solid-state diffusion**, thereby increasing strength, density, and conductivity.
- **Stages:** 1) **Neck Formation:** Initial bonding at contact points. 2) **Pore Channel Closure:** Pores become rounded and isolated. 3) **Final Densification** (if pressure is applied, as in hot pressing).
- **Atmosphere:** Performed in a controlled (reducing or inert) atmosphere to prevent oxidation.

Q2. List applications of powder metallurgy. (S24 Q5a OR, 03 marks)
Answer: Key applications include: **1) Porous Oil-Retaining Bearings** (self-lubricating), **2) Cemented Carbide Cutting Tools** (WC-Co), **3) Automotive Components** (gears, sprockets, connecting rods), **4) Electrical Contacts** (Ag-W, Ag-CdO), **5) Friction Materials** (brake pads, clutch plates), **6) Metal Filters**, and **7) Magnetic Cores**.

Q3. Explain any one method for production of metal powders. (S25 Q4a OR, 03 marks)
Answer (Atomization):
Atomization is the most versatile and widely used production method. **Molten metal is forced through a nozzle** to form a fine stream, which is then **disintegrated by impinging jets of high-pressure gas (N_2, Ar) or water**.

- **Gas Atomization:** Produces **spherical, clean powders** (e.g., for aerospace alloys). The rapid cooling yields fine microstructures.
- **Water Atomization:** Produces **irregular, oxidized powders** at a lower cost (e.g., for iron and steel powders). The particles are less spherical due to faster quenching.

Unit 8: Non-Destructive Testing

Question 8.1: Explain dye penetrant testing with principle, procedure, advantages, limitations.
(Appeared in: W22 (Q5a, 03 marks), S25 (Q4b OR, 04 marks), S24 (Q5c OR, 07 marks), W24 (Q5c OR, 07 marks))
Answer:
Dye Penetrant Testing (DPT) or Liquid Penetrant Testing (LPT) is a surface NDT method for detecting cracks, porosity, and other discontinuities open to the surface.
Principle: It is based on **capillary action**. A low-viscosity, highly visible or fluorescent liquid (penetrant) is drawn into surface-breaking defects by capillary forces. After cleaning the excess, a developer draws the penetrant back out, creating a visible indication.
Procedure (for Visible Dye):

1. **Surface Preparation:** Clean the surface thoroughly to remove oil, grease, paint, and rust.
2. **Penetrant Application:** Apply the penetrant by spraying, brushing, or dipping. Allow **dwell time** (5-30 min) for it to seep into flaws.
3. **Excess Penetrant Removal:** Carefully wipe and clean the surface with a remover/cleaner to remove all penetrant from the surface, but **not from within the defect**.
4. **Developer Application:** Apply a thin, even coat of white developer (spray or powder). The developer acts as a blotter, drawing the trapped penetrant back to the surface.
5. **Inspection:** After a developing time (10-60 min), inspect under adequate white light. Defects appear as red lines or spots against the white developer background.
6. **Post-Cleaning:** Clean the part after inspection.

Advantages:

1. Simple, inexpensive, and portable.
2. Highly sensitive to fine, tight surface cracks.
3. Can inspect complex shapes and large areas quickly.
4. Results are directly visible on the surface.

Limitations:

1. **Surface defects only.** Cannot detect subsurface flaws.
2. Requires a **very clean, non-porous surface**.
3. Not suitable for rough or porous materials (e.g., castings with sand inclusions).
4. Chemical cleaners and penetrants can be hazardous.
5. Operator skill influences effectiveness.

Question 8.2: Explain radiography testing method with advantages and limitations.
(Appeared in: W22 (Q4c OR, 07 marks), S23 (Q5c, 07 marks), S25 (Q5c, 07 marks))
Answer:
Radiography Testing (RT) uses penetrating **X-rays or Gamma rays** to inspect the internal structure of components for defects.
Principle: High-energy radiation is passed through the object. Denser areas or thicker sections **absorb more radiation**, while flaws (like voids or cracks) allow more radiation to pass through. This varying transmission creates a **latent image** on a radiographic film or a digital detector placed behind the object, producing a 2D shadowgraph of the internal structure.
Procedure:

1. Set up the radiation source (X-ray tube or gamma ray source like Ir-192, Co-60) on

one side of the object.
2. Place the film or digital detector in a cassette on the opposite side.
3. Shield the area for safety.
4. Expose the object to radiation for a calculated time based on material thickness and density.
5. Process the film or analyze the digital image. Defects like porosity, slag, or cracks appear as **darker areas** on the film (more exposure) compared to sound metal.

Advantages:

1. Provides a **permanent visual record** (radiograph) of the internal condition.
2. Can detect **both surface and subsurface** defects (volumetric defects like porosity are especially clear).
3. Effective for a wide range of materials and thicknesses.
4. Useful for inspecting complex internal geometries of castings and welds.

Limitations:

1. **High capital and operational cost.**
2. **Serious health and safety hazards** due to ionizing radiation; requires strict licensing, shielding, and safety protocols.
3. **Orientation Sensitivity:** The radiation beam must be aligned with the defect's major dimension for detection (e.g., cracks parallel to the beam may not be seen).
4. **Access required to both sides** of the object (for source and film).
5. Not ideal for planar defects like laminations or tight cracks that are parallel to the beam.

Question 8.3: Compare destructive and non-destructive testing.
(Appeared in: S25 (Q5b, 04 marks))
Answer:

Feature	Destructive Testing (DT)	Non-Destructive Testing (NDT)
Definition	Testing that **destroys or permanently alters** the specimen, rendering it unusable for service.	Testing that **does not damage or affect** the serviceability of the component. The part can be used after inspection.
Objective	To determine **ultimate mechanical properties** (tensile strength, toughness) and failure modes.	To detect **flaws/discontinuities** (cracks, porosity), measure dimensions, or characterize properties **without causing damage**.
Specimen	Uses **separate test coupons** or samples taken from production. The actual component is not tested.	The **actual component in service or production** is inspected directly.
Cost Implication	Cost of destroyed specimen. Not suitable for 100% inspection of expensive parts.	No cost of part destruction. Allows for **100% inspection** of critical components.

Feature	Destructive Testing (DT)	Non-Destructive Testing (NDT)
Examples	Tensile test, Impact test (Charpy), Bend test, Hardness test (to some extent).	Ultrasonic Testing (UT), Radiography (RT), Dye Penetrant (PT), Magnetic Particle (MT), Visual Inspection (VT).
Result	Provides quantitative data on material properties.	Provides qualitative or semi-quantitative data on integrity and quality.
Primary Use	Material qualification, quality control of batches, research & development.	Quality assurance in manufacturing (welds, castings), in-service inspection for safety, preventive maintenance.

Other Important Questions:

Q1. State various NDT methods and advantages of RT over UT. (W24 Q5b, 04 marks)

Answer:

Common NDT Methods: Visual Testing (VT), Liquid Penetrant Testing (PT), Magnetic Particle Testing (MT), Radiographic Testing (RT), Ultrasonic Testing (UT), Eddy Current Testing (ET).

Advantages of RT over UT:

1. **Permanent Record:** RT provides a **radiograph (film/digital image)** that serves as a permanent, reviewable record of the internal condition. UT typically provides an A-scan, which is more transient and interpretive.
2. **Ease of Interpretation:** For volumetric defects (porosity, slag), the **image is often easier to interpret** and understand for a wider range of personnel compared to ultrasonic signal patterns.
3. **Less Couplant/Surface Sensitivity:** RT does not require couplant and is less sensitive to surface roughness or complex geometries that can complicate UT inspections.
4. **Better for Certain Materials:** RT is generally more effective than UT for inspecting **coarse-grained materials** (like some austenitic stainless steel welds or castings) where UT signals suffer from severe scattering and attenuation.

Q2. Explain ultrasonic testing method with advantages and limitations. (S25 Q5c OR, 07 marks)

Answer:

Principle: Ultrasonic Testing (UT) uses high-frequency sound waves (typically 0.5-25 MHz) generated by a piezoelectric transducer. These waves travel through the material and are **reflected** from internal flaws or external boundaries. The reflected echoes are detected and analyzed.

Procedure (Pulse-Echo):

1. A couplant (gel, oil, water) is applied to ensure sound transmission between the transducer and the part.
2. The transducer sends a short ultrasonic pulse into the material.
3. The time taken for the echo to return from the back wall or a defect is measured and displayed on a screen (A-scan).
4. The **position (depth)** of the flaw is calculated using the **time of flight** and the material's sound velocity. The **size** is estimated from the echo amplitude.

Advantages:

1. High sensitivity to **both surface and subsurface** flaws.
2. Excellent **depth penetration** for thick sections.
3. Can determine **exact depth and size** of defects.
4. **Portable, fast, and provides immediate results.**
5. Only one-side access is needed.

Limitations:

1. Requires a **skilled and experienced operator** for calibration and interpretation.
2. Requires **couplant** and a smooth surface for good coupling.
3. Difficult to use on rough, irregular, or very thin parts.
4. Can be challenging for **coarse-grained or anisotropic materials** due to signal scattering.
5. No permanent record unless coupled with data recording systems.

Q3. Explain LPT and MPT differences. (W23 Q5b, 04 marks)
Answer:

Feature	Liquid Penetrant Testing (LPT)	Magnetic Particle Testing (MPT)
Applicable Materials	**Any non-porous material** (metals, plastics, ceramics).	**Only ferromagnetic materials** (iron, steel, nickel, cobalt).
Defect Detection	**Surface-breaking defects only.**	Can detect **surface and slightly subsurface** defects (just below the surface).
Principle	**Capillary action** of a liquid dye.	**Magnetic flux leakage** caused by a discontinuity in a magnetized part.
Required Condition	Clean, dry, non-porous surface.	Surface can be lightly scaled or painted (magnetism penetrates).
Sensitivity	High for tight cracks. Sensitivity depends on penetrant type.	High for linear defects perpendicular to the magnetic field.
Post-Cleaning	**Essential** to remove chemicals.	Less critical, but residual particles may need cleaning.

Q4. Explain principle of radiography testing and use in metal testing. (W23 Q4c OR, 07 marks)
(Answer covered in detail in Q8.2 above)

Q5. Explain NDT methods for inspection of castings. (W23 Q5c, 07 marks)
Answer:
Castings are inspected for defects like porosity, shrinkage cavities, cracks, and inclusions. Common NDT methods include:

1. **Visual Testing (VT):** The first step to check for surface defects, finish, and gross

irregularities.

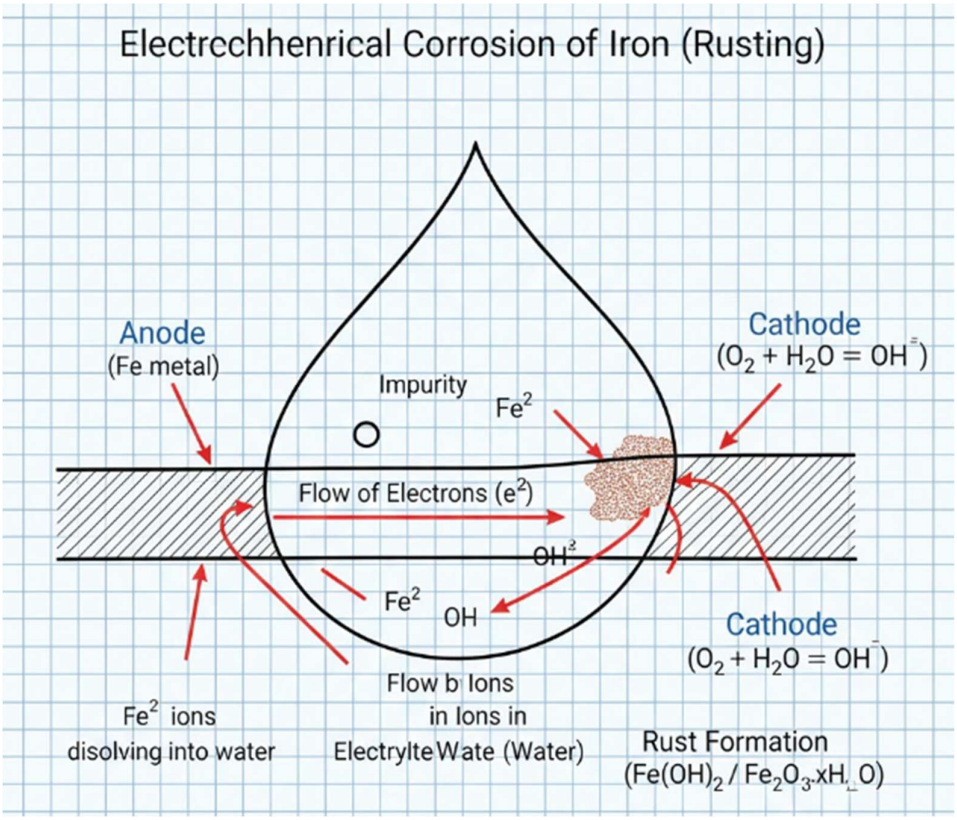
2. **Radiographic Testing (RT): Most common and effective** for castings. It reveals **internal defects** like gas porosity, shrinkage, slag inclusions, and core shifts. Provides a comprehensive picture of internal soundness.
3. **Ultrasonic Testing (UT):** Used for **thick-walled castings** to detect internal flaws and measure wall thickness. Effective for large castings where RT is impractical.
4. **Dye Penetrant Testing (PT):** Used to detect **surface cracks** (hot tears, cold shuts) and surface porosity.
5. **Magnetic Particle Testing (MT):** Used for **ferrous castings** (iron, steel) to detect surface and near-surface cracks.
6. **Pressure Testing:** For castings designed to hold pressure (pipes, valves). They are filled with liquid or gas under pressure and checked for leaks.

Unit 9: Corrosion of Metals and Alloys

Question 9.1: Explain mechanism of corrosion and prevention techniques.
(Appeared in: W22 (Q5c OR, 07 marks), W24 (Q5c, 07 marks))
Answer:
Part 1: Mechanism of Corrosion (Electrochemical Corrosion)
Most corrosion, especially in aqueous environments, is **electrochemical**. It requires:

1. **Anode:** The site where **metal oxidizes (loss of electrons)**, dissolving as ions into the solution. $M \rightarrow M^{n+} + ne^-$
2. **Cathode:** The site where a **reduction reaction** consumes the electrons released at the anode. Common cathode reactions are:
    - Hydrogen evolution (in acidic media): $2H^+ + 2e^- \rightarrow H_2(g)$
    - Oxygen reduction (in neutral/alkaline aerated water): $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
3. **Electrolyte:** A conductive liquid (e.g., water, soil, moisture) that allows ion movement.
4. **Electrical Connection:** Direct metal contact completing the circuit for electron flow from anode to cathode.

Process: A potential difference exists on the metal surface due to impurities, grain boundaries, or stress variations, creating local anodes and cathodes. Electrons flow internally from the anode to the cathode, ions flow through the electrolyte, and the anode metal corrodes.
Diagram:



Part 2: Corrosion Prevention Techniques

1. **Material Selection & Design:**
    - Use **corrosion-resistant alloys** (stainless steel, monel, brass).

- Avoid **galvanic couples** or insulate dissimilar metals.
- Design to avoid water traps and ensure good drainage.

2. **Protective Coatings:**
   - **Barrier Coatings:** Paint, enamel, plastic, or grease to isolate metal from environment.
   - **Galvanic Coatings (Sacrificial Anodes):** Coat steel with a more active metal (e.g., **zinc** in galvanizing). Zinc corrodes preferentially, protecting the steel.
   - **Noble Coatings:** Coat with a less active metal (e.g., **tin, chromium, nickel**). These provide a passive barrier, but if scratched, the underlying steel corrodes rapidly.
3. **Cathodic Protection:**
   - **Sacrificial Anode:** Connect the structure to a more active metal (Mg, Zn, Al alloy) that corrodes instead.
   - **Impressed Current:** Use an external DC power source to force the structure to be cathodic.
4. **Anodic Protection (for passive metals):** Apply a potential to maintain the metal in its passive region (used for stainless steel, titanium in acids).
5. **Environmental Control:**
   - **Deaeration/Dehumidification:** Remove oxygen or moisture from the environment.
   - **Inhibitors:** Add chemicals to the environment that form protective films on the metal surface or retard the cathodic/anodic reaction (e.g., chromates, phosphates in cooling water).

Question 9.2: Explain cathodic protection against corrosion.
(Appeared in: S25 (Q5a, 03 marks), S23 (Q5b, 04 marks))
Answer:
Cathodic protection (CP) is an electrochemical technique used to control the corrosion of a metal surface by making it the **cathode** of an electrochemical cell. This prevents the anodic reaction (metal dissolution).
Two Main Methods:

1. **Sacrificial Anode (Galvanic) Cathodic Protection:**
   - The metal structure to be protected (e.g., steel pipeline) is electrically connected to a **more active (less noble) metal** such as **magnesium, zinc, or aluminum alloy**.
   - This active metal acts as the **sacrificial anode** and corrodes preferentially, supplying electrons to the structure.
   - The protected structure becomes the cathode and does not corrode.
   - **Applications:** Small pipelines, ship hulls, water heaters, offshore platforms.
2. **Impressed Current Cathodic Protection (ICCP):**
   - Uses an **external DC power source** (rectifier) to force current to flow from an **inert anode** (graphite, platinum-coated titanium, mixed metal oxide) through the electrolyte to the structure.
   - The power source supplies electrons, making the structure cathodic.
   - **Advantages:** Can protect large structures, longer anode life, adjustable current.
   - **Applications:** Large pipelines, storage tank bottoms, steel in concrete (rebars), piers.

Principle: Both methods shift the potential of the protected metal in the negative (active) direction, pushing it into the **immunity region** of its Pourbaix diagram, where metal

dissolution is thermodynamically unfavorable.

Question 9.3: Classify types of corrosion.
(Appeared in: S25 (Q5b OR, 04 marks), S24 (Q5b OR, 04 marks))
Answer:
Corrosion can be classified based on appearance, mechanism, and environment:

1. **Uniform (General) Corrosion:** Most common type. Corrosion proceeds uniformly over the entire exposed surface (e.g., rusting of iron).
2. **Galvanic (Bimetallic) Corrosion:** Occurs when **two dissimilar metals** are electrically connected in a corrosive electrolyte. The less noble metal (anode) corrodes faster.
3. **Crevice Corrosion:** Localized attack in **shielded areas** (under gaskets, bolts, deposits) where stagnant electrolyte exists and oxygen concentration is low.
4. **Pitting Corrosion:** Highly localized, forming **small pits or holes**. It is insidious and can lead to sudden failure. Common in stainless steels in chloride environments.
5. **Intergranular Corrosion:** Preferential attack along **grain boundaries**. Often caused by sensitization (e.g., chromium carbide precipitation in stainless steels).
6. **Stress Corrosion Cracking (SCC):** Combined action of **tensile stress** and a **specific corrosive environment** leads to crack propagation and brittle failure.
7. **Corrosion Fatigue:** Cracking under the combined action of **cyclic stress** and corrosion. Reduces fatigue life.
8. **Erosion-Corrosion:** Accelerated material loss due to **relative movement** between a corrosive fluid and the metal surface (e.g., in pipes, propellers).
9. **Selective Leaching (Dealloying):** Selective removal of one element from an alloy (e.g., dezincification of brass, graphitization of cast iron).
10. **Microbiologically Influenced Corrosion (MIC):** Corrosion accelerated by the metabolic activity of microorganisms (bacteria, fungi).

Other Important Questions:
Q1. Define corrosion and classify. (W24 Q5a OR, 03 marks)
Answer:
Corrosion is the **deterioration or destruction of a metal due to an electrochemical or chemical reaction with its environment**. It is a natural process that tries to return the metal to its thermodynamically stable, oxidized state (ore).
Classification (Broad):

- **Based on Mechanism:**
    1. **Electrochemical Corrosion** (most common, requires anode, cathode, electrolyte).
    2. **Direct Chemical Corrosion** (e.g., dry oxidation at high temperature, reaction with dry gases).
- **Based on Appearance/Form:** Uniform, Galvanic, Pitting, Crevice, Intergranular, Stress Corrosion Cracking, etc. (as listed in Q9.3).

Q2. Differentiate dry and wet corrosion. (W23 Q5b, 04 marks)
Answer:

Feature	Dry Corrosion (Chemical)	Wet Corrosion (Electrochemical)
Environment	Occurs in **dry gases** or non-conductive liquids at **high**	Occurs in the presence of an **aqueous electrolyte** (water, moisture) at or near

Feature	Dry Corrosion (Chemical)	Wet Corrosion (Electrochemical)
	temperatures.	room temperature.
Mechanism	Direct **chemical reaction** between metal and gas (e.g., oxidation, sulfidation). $2M + O_2 \rightarrow 2MO$	**Electrochemical reaction** involving anodic dissolution and cathodic reduction. Requires an electrolyte and potential difference.
Product	Forms a **solid, continuous layer** (oxide, sulfide scale) on the surface.	Forms **corrosion products** (e.g., rust, hydroxides) which may be porous or non-adherent.
Rate Control	Controlled by **diffusion of ions/atoms** through the surface scale.	Controlled by **electrode kinetics** and conductivity of the electrolyte.
Examples	Tarnishing of silver, oxidation of steel in furnace, scaling.	Rusting of iron in moist air, corrosion of ship hulls in seawater, pitting of stainless steel.

Q3. Explain various corrosion prevention methods. (W24 Q5c, 07 marks)
Answer:
(This answer consolidates and expands on techniques from Q9.1)

1. **Proper Material Selection:** Choose metals/alloys suitable for the environment (e.g., stainless steel for oxidizing conditions, nickel alloys for acids).
2. **Design Modification:** Avoid crevices, ensure drainage, prevent galvanic couples, allow easy access for maintenance.
3. **Protective Coatings:**
    - **Metallic Coatings:** Galvanizing (Zn), Tin plating, Chrome plating.
    - **Organic Coatings:** Paints, varnishes, enamels, plastics (epoxy, polyethylene).
    - **Inorganic Coatings:** Anodizing (Al), Phosphate coating, Chromate conversion coating.
4. **Cathodic & Anodic Protection:**
    - **Cathodic:** Sacrificial anodes (Mg, Zn) or Impressed current for buried/immersed structures.
    - **Anodic:** For metals that exhibit passivity (Stainless steel, Ti).
5. **Environmental Control:**
    - **Deaeration:** Removing oxygen from water (in boilers).
    - **Dehumidification:** Reducing atmospheric moisture.
    - **Inhibitors:** Adding chemicals (organic/inorganic) to cooling water, acids, or fuels to slow corrosion.
6. **Surface Treatment:** Using techniques like **nitriding, carburizing, or shot peening** to induce compressive surface stresses or create a corrosion-resistant surface layer.
7. **Corrosion Allowance:** In design, adding extra material thickness to account for expected corrosion loss over the service life.

Unit 10: Metallography (Unit of New Syllabus)

Question 10.1: Explain the detail procedure of polishing the specimen for micro examination.
(Appeared in: W22 Q2c, 07 marks)
Answer:
Polishing is a critical step in metallographic sample preparation to obtain a flat, scratch-free, mirror-like surface suitable for microscopic examination. The procedure is sequential and meticulous.
Detailed Procedure:

1. **Mounting (if required):** Small or irregularly shaped samples are **mounted** in a plastic (thermoset like Bakelite or thermosetting resin) or castable resin to facilitate handling during grinding and polishing.
2. **Coarse Grinding (Planar Grinding):**
    - **Purpose:** To remove surface damage from cutting and achieve a flat surface.
    - **Process:** Use a series of progressively finer abrasive papers (silicon carbide) on a rotating wheel or automated polisher. Start with a coarse grit (e.g., 80-120 grit) and progress through finer grits (180, 240, 320, 400, 600).
    - **Technique:** After each step, **rotate the specimen 90°** before moving to the next finer grit to ensure removal of scratches from the previous stage. Rinse the sample thoroughly between steps to avoid contaminating finer papers with coarse grit.
3. **Fine Grinding (Final Grinding):**
    - Use even finer grit papers (800, 1000, 1200, 2000 grit) to remove scratches from coarse grinding.
    - This step is crucial for minimizing the time required in the subsequent polishing steps.
4. **Polishing (Rough and Final Polish):**
    - **Rough Polishing:** Use a rotating cloth-covered wheel impregnated with a **diamond abrasive paste or suspension** (typically 6µm or 3µm diamond). This step removes the fine grinding scratches.
    - **Final Polishing:** Use a different, softer cloth (e.g., microcloth, chemomet) with a **fine abrasive** (e.g., 1µm diamond, 0.05µm alumina slurry, or colloidal silica). The goal is to achieve a **scratch-free, mirror finish** where only the microstructure features are visible, not preparation artifacts.
    - **Key Practice:** Use **copious amounts of lubricant/coolant** (water or specialized fluid) to prevent overheating, washing away debris, and minimizing pulling out of inclusions.
5. **Cleaning and Drying:**
    - After final polishing, **immediately and thoroughly rinse** the specimen with water and then alcohol (ethanol or methanol) to remove all polishing abrasive and slurry residues.
    - **Dry** the specimen carefully using a warm air blower or lint-free cloth. Air drying can cause water spots.
6. **Etching (if required for microstructure revelation):**
    - Apply a suitable chemical etchant (e.g., Nital for steels, Keller's reagent for aluminum) by swabbing or immersion for a few seconds to decades.
    - **Immediately rinse and dry** to stop the etching reaction.

The final polished (and etched) specimen is now ready for microscopic examination.

Question 10.2: Explain Macro examination and Micro examination.
(Appeared in: W22 Q3b, 04 marks; W23 Q3b, 04 marks; S25 Q2b, 04 marks; W24 Q2a, 03 marks)
Answer:
These are two fundamental levels of metallographic inspection.
1. Macro Examination (Macrostructure):

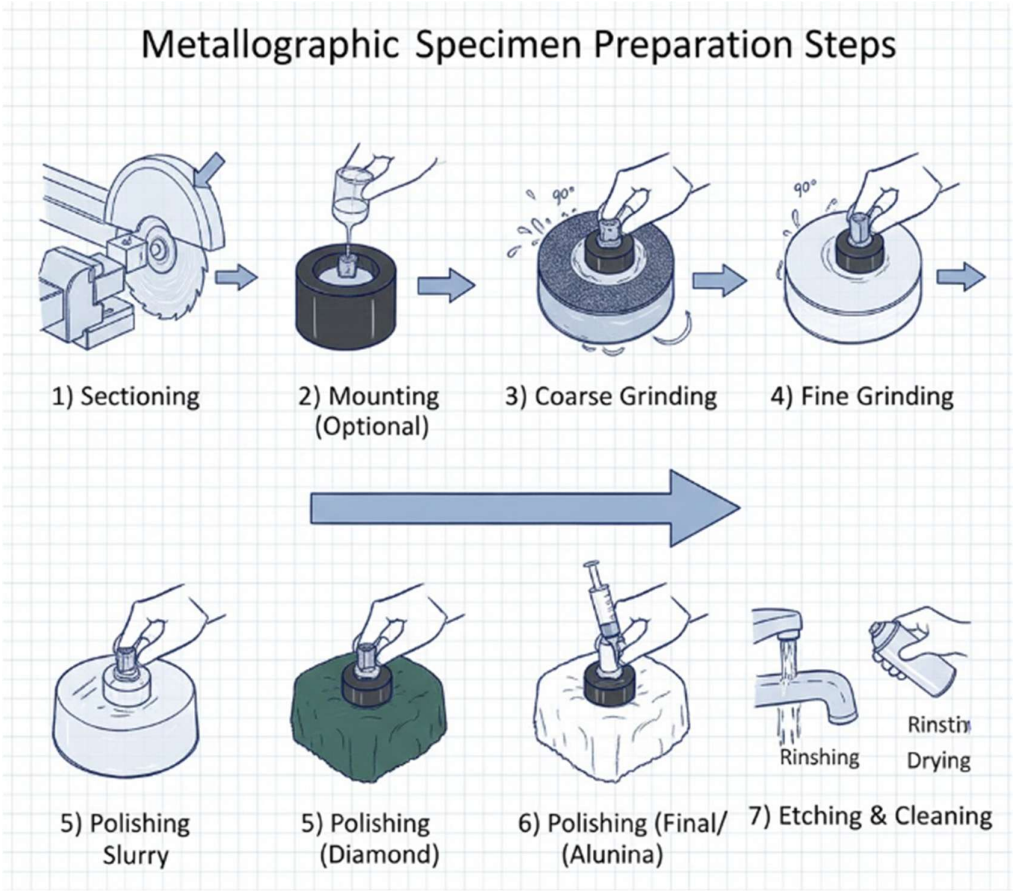
- **Scale:** Examination with the **naked eye or under low magnification** (typically up to 10x-50x).
- **Purpose:** To assess the **overall quality and soundness** of the material.
- **Reveals:** Features like **grain flow** (in forgings), **casting defects** (shrinkage cavities, porosity, cold shuts), **weld penetration and defects**, **segregation patterns**, **case depth** in hardened samples, and the **three zones of an ingot** (chill, columnar, equiaxed).
- **Sample Preparation:** Requires a flat, smooth surface obtained by machining or coarse grinding. Often enhanced by **macro-etching** with strong acids to reveal the structure.
- **Tools:** Magnifying glass, stereomicroscope, or low-power metallurgical microscope.

2. Micro Examination (Microstructure):

- **Scale:** Examination under **high magnification** (typically 50x to 1000x or more) using a **metallurgical microscope**.
- **Purpose:** To study the **detailed internal structure** of the material, which directly determines its properties.
- **Reveals: Grain size and shape**, **phase distribution** (e.g., ferrite, pearlite, cementite in steel), **precipitates**, **inclusions**, **micro-cracks**, and the effects of **heat treatment**.
- **Sample Preparation:** Requires an extremely **flat, scratch-free, mirror-polished surface**, often followed by **chemical etching** to reveal grain boundaries and phases.
- **Tool:** Primarily a **metallurgical microscope** with reflected light.

Key Difference: Macro-examination gives the "big picture" of material integrity, while **micro-examination provides the "fine details"** of the internal constitution.

Question 10.3: Explain with neat sketch the steps involved in preparing specimen for microscopic examination.
(Appeared in: S25 Q2c, 07 marks; S23 Q3c, 07 marks)
Answer:
Preparation of a metallographic specimen for microscopic examination is a multi-step process to reveal the true microstructure without artifacts.
Diagram:



Detailed Steps (as per the flow):

1. **Sectioning (Cutting):** A representative sample is cut from the bulk material using a **hacksaw, abrasive cutter, or precision saw** (like a Struers Accutom). Care is taken to **minimize heat and deformation** to avoid altering the microstructure at the cut surface.
2. **Mounting:** For small, irregular, or fragile samples, mounting is done in a **thermosetting (Bakelite) or castable (epoxy, acrylic) resin** using a mounting press or cold-setting method. This provides a standard size for handling and protects edges.
3. **Grinding (Coarse to Fine):** The sample surface is ground flat using progressively finer silicon carbide (SiC) abrasive papers on a rotating wheel or automated system. Start with **80-120 grit** and proceed sequentially through **240, 320, 400, 600, 800, 1000, 1200, 2000+ grit**. **Rotate the sample 90°** between each step to ensure scratches from the previous grit are removed. Rinse thoroughly between steps.
4. **Polishing (Rough):** The finely ground sample is polished on a cloth-covered wheel using a **diamond abrasive suspension** (e.g., 6µm or 3µm). This removes the fine grinding scratches. A lubricant is used.
5. **Polishing (Final):** A final polish is performed on a **soft, nap-free cloth** (microcloth, chemomet) using a very fine abrasive such as **1µm diamond, 0.05µm alumina (Al_2O_3) slurry, or colloidal silica**. The goal is a **scratch-free, mirror finish**.
6. **Cleaning:** After each polishing step and especially after the final polish, the sample is **rinsed thoroughly** with water and then alcohol (ethanol/methanol) to remove all abrasive particles. It is then dried carefully with compressed air or a warm blower.
7. **Etching (Optional but usually necessary):** To reveal the microstructure, the polished surface is treated with a **chemical etchant** (e.g., Nital for steels, Picral for

cast iron, Keller's reagent for aluminum) for a few seconds. The etchant attacks grain boundaries and phases at different rates, creating contrast. **Immediate rinsing and drying** follows to stop the reaction.

The specimen is now ready for observation under the **metallurgical microscope**.

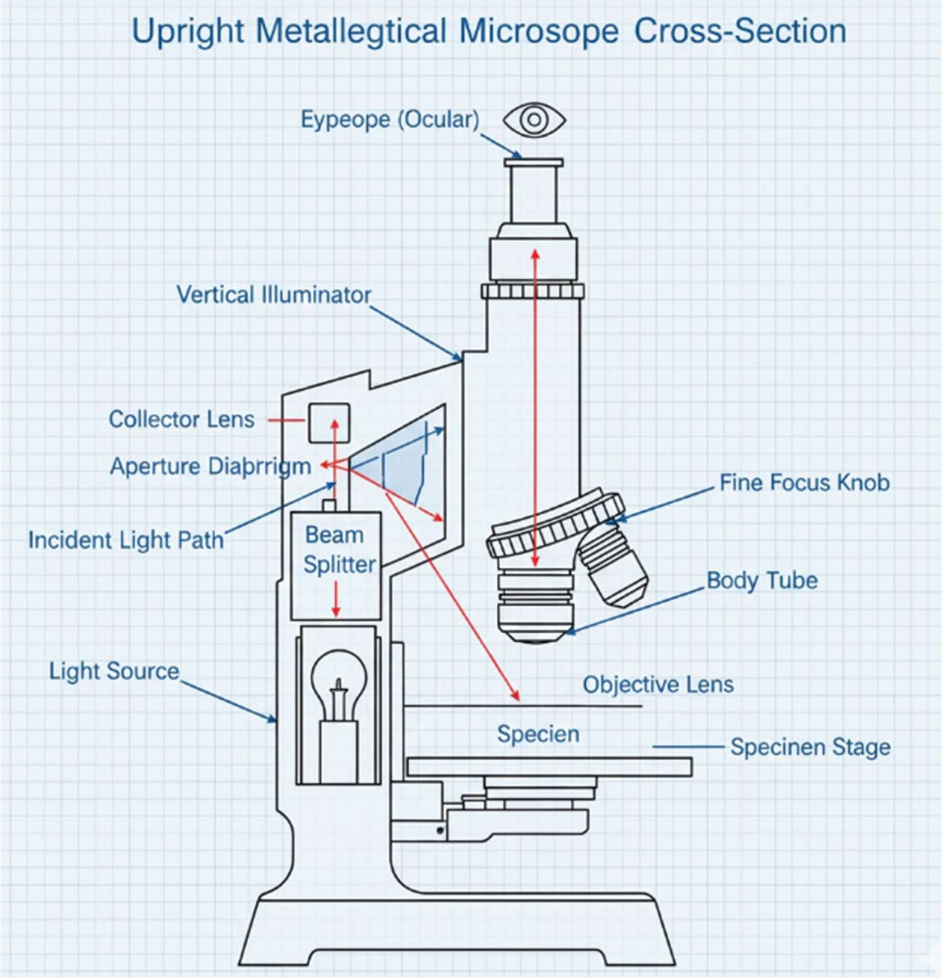
Question 10.4: Explain the construction and working of a metallurgical microscope with neat diagram.

(Appeared in: S23 Q3c OR, 07 marks)

Answer:

A metallurgical microscope (incident-light or reflected-light microscope) is used to examine opaque specimens like metals. Unlike biological microscopes, it illuminates the specimen from above.

Diagram:



Construction & Working Principle:

1. **Light Source:** A high-intensity lamp (halogen, LED) provides illumination.
2. **Vertical Illuminator:** Houses the **beam splitter**. This is the key difference from a biological microscope. The beam splitter is a semi-transparent mirror set at 45°.
3. **Objective Lens:** Serves a **dual purpose**. **First,** it focuses the incident light onto the specimen surface. **Second,** it collects the light reflected from the specimen and forms the primary image. Metallurgical objectives are specially designed for this and are often labeled "EPI" or "BD" (Brightfield/Darkfield).
4. **Working:**

- Light from the source passes through the collector lens and aperture diaphragm, enters the vertical illuminator, and strikes the **beam splitter**.
- The beam splitter **reflects the light vertically downward** through the **objective lens**, which focuses it onto the polished surface of the specimen.
- The light **reflects off the specimen surface** and travels back up through the **same objective lens**.
- This reflected light now passes **through** the semi-transparent beam splitter and continues up the body tube.
- It then passes through the eyepiece, which magnifies the primary image formed by the objective, allowing the observer to see the microstructure.

5. **Modes of Illumination:** The microscope can often operate in:
   - **Brightfield:** Standard mode, flat surfaces appear bright, recessed features (pits, grooves) appear dark.
   - **Darkfield:** Light hits the specimen obliquely; only light scattered by surface features enters the objective, making them appear bright on a dark background—good for revealing relief.
   - **Polarized Light:** Used for anisotropic materials to reveal grain structure.

The use of the objective lens for both illumination and imaging is the defining characteristic of a metallurgical microscope.