GUJARAT TECHNOLOGICAL UNIVERSITY

BE-3 SEMESTER – PAPER SOLUTION – SUMMER 2025

Subject Name & Code:
Material Science and Metallurgy- 3131904

Q.1 (a) Define following properties of materials: (a) Strength, (b) Elasticity and (c) Hardness **03**

Answer:

1. **Strength:**
   Strength is the ability of a material to withstand an applied load without failure or plastic deformation. It is usually measured in terms of stress.
   Types include tensile strength, compressive strength, and shear strength.
2. **Elasticity:**
   Elasticity is the property of a material by which it returns to its original shape and size after the removal of the applied load within the elastic limit.
   Example: Steel is more elastic than rubber.
3. **Hardness:**
   Hardness is the resistance offered by a material to localized plastic deformation such as scratching, indentation, or abrasion.
   Measured by tests like Brinell, Rockwell, or Vickers hardness tests.

(b) Give classification of engineering materials **04**

Answer:

Engineering materials are broadly classified as:

1. **Metals and Alloys:**
   - *Ferrous metals*: Contain iron (e.g., steel, cast iron)
   - *Non-ferrous metals*: No iron (e.g., aluminum, copper, zinc)
2. **Polymers:**
   - Plastics and rubbers (e.g., polyethylene, PVC, natural rubber)
3. **Ceramics:**
   - Non-metallic and inorganic (e.g., glass, porcelain, brick)
4. **Composites:**
   - Combination of two or more materials to achieve better properties (e.g., fiber-reinforced plastics, concrete)
5. **Smart Materials:**
   - Materials that respond to external stimuli like temperature or pressure (e.g., piezoelectric materials)

(c) Define atomic packing factor (APF). Calculate APF for FCC and BCC structures. **07**

Answer:

Definition:
The Atomic Packing Factor (APF) is the fraction of volume in a crystal structure that is occupied by atoms. It is given by:

$$\text{APF} = \frac{\text{Volume of atoms in a unit cell}}{\text{Total volume of the unit cell}}$$

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1. FCC Structure (Face Centered Cubic):

- Number of atoms per unit cell = 4
- Radius (r) relation: $a = 2\sqrt{2}r$
- Volume of atoms = $4 \times \frac{4}{3}\pi r^3$
- Volume of unit cell = $a^3 = (2\sqrt{2}r)^3 = 16\sqrt{2}r^3$

$$\text{APF}_{FCC} = \frac{4 \times \frac{4}{3}\pi r^3}{16\sqrt{2}r^3} = \frac{16.76r^3}{16\sqrt{2}r^3} \approx 0.74 \text{ or } 74\%$$

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2. BCC Structure (Body Centered Cubic):

- Number of atoms per unit cell = 2
- Radius (r) relation: $a = \frac{4r}{\sqrt{3}}$
- Volume of atoms = $2 \times \frac{4}{3}\pi r^3$
- Volume of unit cell = $a^3 = \left(\frac{4r}{\sqrt{3}}\right)^3 = \frac{64r^3}{3\sqrt{3}}$

$$\text{APF}_{BCC} = \frac{2 \times \frac{4}{3}\pi r^3}{\frac{64r^3}{3\sqrt{3}}} = \frac{8.38r^3}{\frac{64r^3}{3\sqrt{3}}} \approx 0.68 \text{ or } 68\%$$

✅ **Conclusion:**

- APF for **FCC** = **0.74**
- APF for **BCC** = **0.68**

Q.2 (a) What is a solid solution? Explain with a neat sketch various types of solid solutions. **03**

Answer:

Solid Solution:
A solid solution is a homogeneous crystalline phase that contains two or more elements mixed at the atomic level, where the solute atoms occupy positions within the solvent crystal structure.

Types of Solid Solutions:

1. **Substitutional Solid Solution:**
   - The solute atoms replace the solvent atoms in the crystal lattice.
   - Example: Brass (Copper-Zinc alloy).
   - *Conditions:* Similar atomic size, same crystal structure, and close electronegativity.
2. **Interstitial Solid Solution:**

- Smaller solute atoms occupy the interstitial spaces between solvent atoms.
- Example: Steel (Carbon atoms in iron matrix).
- *Conditions:* Solute atoms must be significantly smaller.

Sketch (for exam)

(b) Differentiate Macrostructure and Microstructure examination. **04**

Answer:

Criteria	Macrostructure	Microstructure
Definition	Structure visible with naked eye or low mag.	Structure seen under microscope (100x–1000x)
Tools Used	Magnifying glass, naked eye	Optical or Electron Microscope
Reveals	Grain flow, segregation, cracks	Grain size, phases, dislocations
Sample Preparation	Simple etching	Polishing, fine etching
Application	Foundry defects, welds, castings	Material science, alloy development

(c) Explain with neat sketch the steps involved in preparing specimen for microscopic examination. **07**

Answer:

Steps in Specimen Preparation:

1. **Sectioning:**
   - Cut a small piece from the bulk material using hacksaw/cutting wheel.
2. **Mounting:**
   - Embed the sample in resin/plastic to facilitate handling during polishing.
3. **Grinding:**
   - Flatten and remove surface irregularities using abrasive paper (emery paper grades 80 to 1200 grit).
4. **Polishing:**
   - Achieve mirror-like finish using fine abrasives and rotating cloth wheel.
5. **Etching:**
   - Apply chemical reagent to reveal microstructure by differential corrosion.
   - Example: Nital (2% nitric acid + ethanol) for steel.
6. **Microscopic Examination:**
   - Use an optical microscope to observe grain structure, phase boundaries, etc.

Sketch:

OR

(c) What is Gibb's phase rule? Define system, phase and degree of freedom. Show that the degree of freedom at eutectic point in a binary phase diagram is zero. **07**

Answer:

Gibbs Phase Rule:

The Gibbs Phase Rule is an equation used to determine the number of degrees of freedom (F) in a thermodynamic system at equilibrium:

$$\boxed{F = C - P + 2}$$

Where,
- F = Degrees of freedom (number of independent variables like temperature, pressure, or composition that can be changed without changing the number of phases).
- C = Number of components.
- P = Number of phases present.
- The '+2' accounts for temperature and pressure.

Definitions:
1. **System:**
   A specific portion of the universe under consideration for analysis.
   Example: Iron-carbon alloy or water-ice-steam system.
2. **Phase:**
   A homogeneous and physically distinct part of a system separated by boundaries.
   Example: Solid, liquid, and gas.
3. **Degree of Freedom (F):**
   The number of variables (such as temperature or composition) that can be changed independently without altering the number of phases in equilibrium.

At Constant Pressure (like in phase diagrams), Gibbs Rule simplifies to:

$$\boxed{F = C - P + 1}$$

Eutectic Point in Binary Phase Diagram:
- At the eutectic point:
  - Number of components, C=2
  - Number of phases in equilibrium, P=3
    (Liquid + α-solid + β-solid coexist)
  - Using simplified Gibbs Rule:

$$F = C - P + 1 = 2 - 3 + 1 = 0$$

- **Therefore, F=0** No degree of freedom. Temperature and composition are fixed — it is an invariant point.

Conclusion:
At the eutectic point in a binary system, there is **no freedom** to vary temperature or composition without disturbing the equilibrium. This proves the phase rule.
(Optional Sketch for better marks):

Q.3 (a) Explain the process of solidification in metals. **03**

Answer:

Solidification of Metals:
Solidification is the process by which a liquid metal transforms into a solid when its temperature is lowered below its freezing point.
Steps:
1. **Nucleation:**
   - Formation of tiny stable solid particles (nuclei) when the metal cools

slightly below its melting point.

2. **Crystal Growth:**
    - Nuclei grow into crystals (grains) as atoms from the liquid attach themselves to the existing solid surface.
3. **Grain Formation:**
    - As growth continues in different directions, grains form.
    - Eventually, the whole liquid transforms into a solid composed of many grains — called a **polycrystalline structure**.

Optional Sketch:

(b) What is non-equilibrium cooling? Explain. **04**

Answer:

Non-equilibrium Cooling:
Non-equilibrium cooling occurs when a metal is cooled **rapidly**, and does not allow sufficient time for atoms to arrange into equilibrium phases.
Characteristics:

- Occurs in industrial processes (like quenching).
- Leads to formation of metastable phases.
- Diffusion is suppressed due to fast cooling.

Example:
In the iron-carbon system, instead of forming pearlite, rapid cooling forms **martensite**, a hard and brittle structure.
Diagram Suggestion:
Show equilibrium vs non-equilibrium cooling curves on TTT diagram (optional for 4M).

(c) Define allotropy. Explain it with reference to iron. **07**

Answer:

Definition – Allotropy:
Allotropy is the ability of a material (usually an element) to exist in **two or more different crystalline forms** depending on temperature and pressure.

Allotropy of Iron (Fe):
Iron exhibits **three allotropic forms** depending on temperature:

Phase	Temperature Range (°C)	Crystal Structure	Name
α-Fe	Up to 912°C	BCC	Ferrite
γ-Fe	912°C – 1394°C	FCC	Austenite
δ-Fe	1394°C – 1539°C	BCC	Delta Iron

- **α-iron (Ferrite):**
  Soft and magnetic (up to 770°C – Curie point).
- **γ-iron (Austenite):**
  High solubility for carbon. Non-magnetic.
- **δ-iron:**
  Exists just below melting point.

Significance in Metallurgy:
- The allotropic transformation affects phase diagrams, heat treatments, and mechanical properties.
- Allotropes enable critical processes like **austenitizing** during heat treatment.

Sketch (for extra marks):

OR

Q.3 (a) State the composition, properties and applications of Hindalium and Invar. **03**

Answer:

1. Hindalium:
- **Composition:**
  ~92–95% Aluminum, 2–5% Magnesium, 0.5–1% Manganese, balance with Silicon, Copper.
- **Properties:**
  - Light weight
  - Good corrosion resistance
  - High strength and ductility
  - Good surface finish
- **Applications:**
  - Kitchen utensils
  - Pressure cookers
  - Food containers

2. Invar:
- **Composition:**
  ~64% Iron, ~36% Nickel
- **Properties:**
  - Extremely low coefficient of thermal expansion
  - High dimensional stability
  - Magnetic
  - High tensile strength
- **Applications:**
  - Precision instruments
  - Clocks, measuring tapes
  - Thermostats
  - Satellite structures

(b) Explain the 'Lever Rule' with the help of a binary phase diagram. **04**

Answer:

Lever Rule:
The Lever Rule is a graphical method used to determine the **relative amount of phases** in a two-phase region of a **binary phase diagram**.

Formula:
In a binary system at equilibrium:
Let:
- C0 = Overall alloy composition

- CL = Composition of the liquid phase
- CS = Composition of the solid phase

Then:

- **Fraction of solid (S):**

$$\frac{C_L - C_0}{C_L - C_S}$$

- **Fraction of liquid (L):**

$$\frac{C_0 - C_S}{C_L - C_S}$$

Working:

- Draw a horizontal tie-line at the given temperature in two-phase region.
- Identify phase compositions where tie-line intersects the solidus and liquidus.
- Apply formula to calculate proportions.

Sketch:

(c) Draw Iron-Iron carbide equilibrium diagram. Name all important phases, temperatures and reactions. **07**

Answer:

Iron–Iron Carbide ($Fe–Fe_3C$) Diagram:

- This is a **binary phase diagram** between iron (Fe) and iron carbide (Fe_3C) up to 6.67% carbon.
- Important up to **2.1% C** (for steels); beyond that lies **cast iron**.

Important Temperatures:

Temperature	Significance
1539°C	Melting point of pure iron
1493°C	δ to γ transformation (BCC → FCC)
912°C	γ to α transformation (FCC → BCC)
723°C	Eutectoid temperature

Key Reactions:

1. **Eutectoid Reaction (at 0.8% C, 723°C):**

$$\gamma\ (\text{Austenite}) \rightarrow \alpha\ (\text{Ferrite}) + Fe_3C\ (\text{Cementite})$$

2. **Eutectic Reaction (at 4.3% C, 1147°C):**

$$L \rightarrow \gamma + Fe_3C\ (\text{Ledeburite})$$

3. **Peritectic Reaction (at 0.16% C, 1493°C):**

$$L + \delta \rightarrow \gamma$$

Phases:

Phase	Structure	Composition
Ferrite (α)	BCC	Up to 0.02% C

Austenite (γ)	FCC	Up to 2.1% C
Cementite	Fe_3C	6.67% Carbon
Pearlite	α + Fe_3C	At eutectoid
Ledeburite	γ + Fe_3C	At eutectic

Neat Diagram:

Q.4 (a) Explain full annealing process **03**

Answer:

Full Annealing:
Full annealing is a **heat treatment process** applied mainly to **hypoeutectoid steels** (carbon content < 0.8%) to soften the material, improve ductility, and relieve internal stresses.

Procedure:

1. **Heating:**
   - Heat the steel to **30–50°C above upper critical temperature (A_3)**
   - For example: For low-carbon steel, heat to ~850–900°C
2. **Soaking:**
   - Maintain the temperature to allow uniform heating throughout the section.
3. **Slow Cooling:**
   - Furnace cooling at a very slow rate (e.g., 20–50°C/hour) to room temperature.

Result:

- Produces coarse **pearlite** and **ferrite**.
- Increases ductility, machinability; reduces hardness and strength.

(b) Explain flame hardening process. **04**

Answer:

Flame Hardening:
Flame hardening is a **surface heat treatment** where only the outer layer of a steel component is hardened, keeping the core tough and ductile.

Procedure:

1. A high-temperature oxy-acetylene flame is directed at the surface of the metal.
2. The surface is rapidly heated **above the austenitizing temperature**.
3. Immediately followed by **rapid quenching** (usually with water spray).
4. **Martensite** forms at the surface, increasing hardness.

Applications:

- Gears, shafts, cams, rails, and crankshafts.

Advantages:

- Increases wear resistance.
- Minimum distortion.

- Economical for localized hardening.

(c) Justify the requirement of Heat treatment processes for metals. Explain with neat sketch TTT diagram for heat treatment of steel. **07**

Answer:

Need for Heat Treatment:

1. Improve mechanical properties (strength, hardness, ductility).
2. Refine grain size.
3. Enhance wear and corrosion resistance.
4. Relieve internal stresses after manufacturing.
5. Improve machinability/formability.

TTT Diagram (Time-Temperature-Transformation Diagram):
A TTT diagram shows how **austenite transforms** into other phases like pearlite, bainite, and martensite at **constant temperature** (isothermal transformation).

Key Features of TTT Diagram:

- **X-axis:** Time (log scale)
- **Y-axis:** Temperature
- **Start and finish curves:** Represent beginning and end of transformations.

Transformation Products:

Temperature	Product Formed	Characteristics
~550–700°C	Coarse Pearlite	Soft, ductile
~450–550°C	Fine Pearlite	Stronger, harder
~250–550°C	Bainite	Tough, fine structure
Below 250°C	Martensite (via quenching)	Very hard and brittle

Sketch:

OR

Q.4 (a) Explain any one method for production of metal powders. **03**

Answer:

Atomization Method (Most Common):
Principle:
Molten metal is disintegrated into fine droplets by a high-velocity jet of gas or liquid, which solidify into powder particles.

Steps:

1. Metal is melted in a furnace.
2. The molten stream is forced through a nozzle.
3. A high-pressure gas (air, nitrogen) or water jet strikes the stream.
4. The stream breaks into fine droplets.
5. Droplets solidify into powders.

Advantages:
- High production rate
- Produces fine and uniform powders
- Applicable to many metals (e.g., iron, copper, aluminum)

Sketch Suggestion:

(b) Explain the steps involved in Dye penetrant testing with neat sketch. **04**

Answer:

Dye Penetrant Testing (DPT):
A **non-destructive testing** method used to detect **surface cracks and defects** in non-porous materials.

Steps:
1. **Surface Cleaning:**
   Remove oil, grease, dirt from the surface.
2. **Application of Penetrant:**
   Apply visible or fluorescent dye on the surface.
   Allow it to seep into surface flaws (dwell time: ~10–20 minutes).
3. **Excess Penetrant Removal:**
   Wipe off dye from the surface using a cleaner or cloth.
4. **Developer Application:**
   Spray white developer to draw out penetrant from defects.
5. **Inspection:**
   Visual inspection under white light or UV light (for fluorescent dye).

Sketch Suggestion:

(c) Define Powder Metallurgy. State advantages, limitations and applications of Powder Metallurgy **07**

Answer:

Definition:
Powder Metallurgy (PM) is a metal-forming process in which **metal powders are compacted and then sintered** (heated without melting) to form a solid component.

Steps:
1. **Powder production**
2. **Blending and mixing**
3. **Compaction (pressing into shape)**
4. **Sintering (heating below melting point)**
5. **Finishing operations (if required)**

Advantages:
- Minimal material wastage
- High dimensional accuracy
- Can produce complex shapes
- Controlled porosity possible
- No need for machining in many cases

Limitations:

- High cost of metal powders
- Limited to brittle and non-reactive metals
- Mechanical strength is generally lower than wrought parts
- Size limitation due to press capacity

Applications:

- Porous bearings, filters
- Gears, cams, bushings
- Tungsten filaments
- Self-lubricating components
- Automotive and aerospace parts

Q.5 (a) Explain cathodic protection against corrosion. **03**

Answer:

Cathodic Protection:
It is a corrosion prevention technique where the metal to be protected is made to act as a **cathode** in an electrochemical cell.

Types of Cathodic Protection:

1. **Sacrificial Anode Method:**
   - A more reactive metal (e.g., Mg, Zn, Al) is connected to the structure.
   - This anode corrodes instead of the protected metal.
2. **Impressed Current Method:**
   - An external DC power source supplies current to prevent corrosion.
   - An inert anode (e.g., graphite) is used.

Applications:

- Underground pipelines
- Marine structures
- Storage tanks
- Ship hulls

Sketch Suggestion:

(b) Compare destructive testing with non-destructive testing. **04**

Answer:

Criteria	Destructive Testing (DT)	Non-Destructive Testing (NDT)
Nature	Damages or destroys the specimen	Does not harm the specimen
Examples	Tensile, impact, fatigue tests	Ultrasonic, dye penetrant, radiography
Purpose	Measures mechanical properties	Detects flaws, cracks, and voids
Cost	Generally cheaper tests	Equipment can be expensive

Reuse of Sample	Not possible	Possible

(c) Explain in detail Radiography testing method along with its advantages and limitations. **07**

Answer:

Radiographic Testing (RT):
It is a **non-destructive testing (NDT)** technique that uses **X-rays or Gamma rays** to inspect the internal structure of components.

Working:
1. The test object is placed between a radiation source and a photographic film (or digital detector).
2. Radiation passes through the object.
3. Defects like cracks, voids, or inclusions **absorb less radiation** and appear as dark spots on the film.

Types:
- **X-ray Radiography:** Uses X-rays; requires electricity.
- **Gamma Radiography:** Uses isotopes (like Cobalt-60); portable.

Advantages:
- Can detect **internal** defects
- Permanent test record (radiograph)
- Can inspect complex shapes
- High sensitivity

Limitations:
- Expensive equipment and radiation shielding
- **Health hazard** due to radiation
- Not suitable for very thick or very small components
- Requires skilled operators

Sketch Suggestion:

OR

Q.5 **(a)** Compare nodular cast iron and malleable cast iron. **03**

Answer:

Property	Nodular Cast Iron	Malleable Cast Iron
Carbon Form	Graphite in **spheroidal (nodular)** form	Graphite in **irregular** form (temper carbon)
Production	Adding magnesium/cerium to molten iron	Heat treatment of white cast iron
Ductility	Higher ductility	Moderate ductility
Strength	Higher tensile strength	Lower strength than nodular cast iron
Applications	Crankshafts, gears, valves	Pipe fittings, brackets, farm tools

(b) Classify different types of corrosion. **04**

Answer:

1. Uniform Corrosion:
- Even material loss across the surface.
- Example: Rusting of iron in air and moisture.

2. Galvanic Corrosion:
- Occurs when two dissimilar metals are in contact in a conductive environment.
- The more active metal corrodes.

3. Pitting Corrosion:
- Localized corrosion forming small holes or pits.
- Dangerous as it is hard to detect.

4. Crevice Corrosion:
- Happens in confined spaces (under gaskets, bolts) due to stagnant electrolyte.

5. Intergranular Corrosion:
- Attacks grain boundaries in metals, especially in stainless steel.

6. Stress Corrosion Cracking (SCC):
- Cracks develop due to combined tensile stress and corrosive environment.

(c) Describe Ultrasonic Testing Method with its advantages and limitations. **07**

Answer:

Ultrasonic Testing (UT):
It is a **non-destructive testing** method that uses **high-frequency sound waves** (typically 1–10 MHz) to detect **internal flaws** in a material.

Working Principle:
1. A probe emits ultrasonic waves into the material.
2. The waves travel through the object and reflect back from discontinuities (cracks, voids).
3. Reflected waves are received and displayed on a screen (A-scan).

Modes of Testing:
- Pulse-Echo
- Through Transmission

Advantages:
- Can detect **deep internal** and **very small defects**
- High accuracy in depth measurement
- Portable and safe (no radiation)
- Suitable for **thickness** measurements

Limitations:
- Requires **smooth and clean surface**
- Needs skilled operator
- Not suitable for **porous or rough** materials
- Coupling medium (gel or oil) is required

Sketch Suggestion:

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