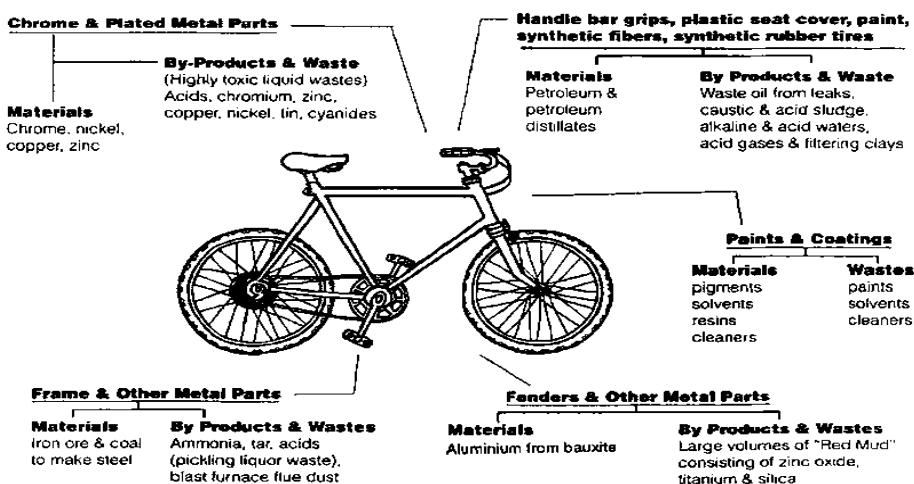


Module-I Material Science and Engineering

- Science is the intellectual and practical activity encompassing the systematic study of the structure and behaviour of the physical and natural world through observation and experiment.
- Engineering is the action of working artfully to bring something about.

Diversity of Materials



Classification: Metals are excellent conductors and ductile, such as steel and aluminum.

- Ceramics: High strength, brittle materials, such as glass and silicon carbide.
- Polymers: Lightweight and flexible materials, such as plastics and rubber.
- Composites: A combination of materials engineered for qualities, such as fiberglass.
- Semiconductors: Materials with intermediate conductivity, such as silicon and germanium.

Levels of Structure

- Atomic structure includes many types of atoms as well as bonding.
- The arrangement of atoms in space is the crystal structure.
- Grains and phases - seen under a microscope are referred to as microstructure.
- The overall material composition and imperfections that are visible to the human eye are referred to as the macrostructure.

Space lattice and Unit Cell

- Space Lattice is a three-dimensional collection of dots that represent the positions of atoms.
Unit Cell -The smallest repeated unit in lattice, distinguished by the following elements:
(Edge lengths) a , b , and c are the parameters of the lattice.
Angles: α , β , and γ (between three edges).

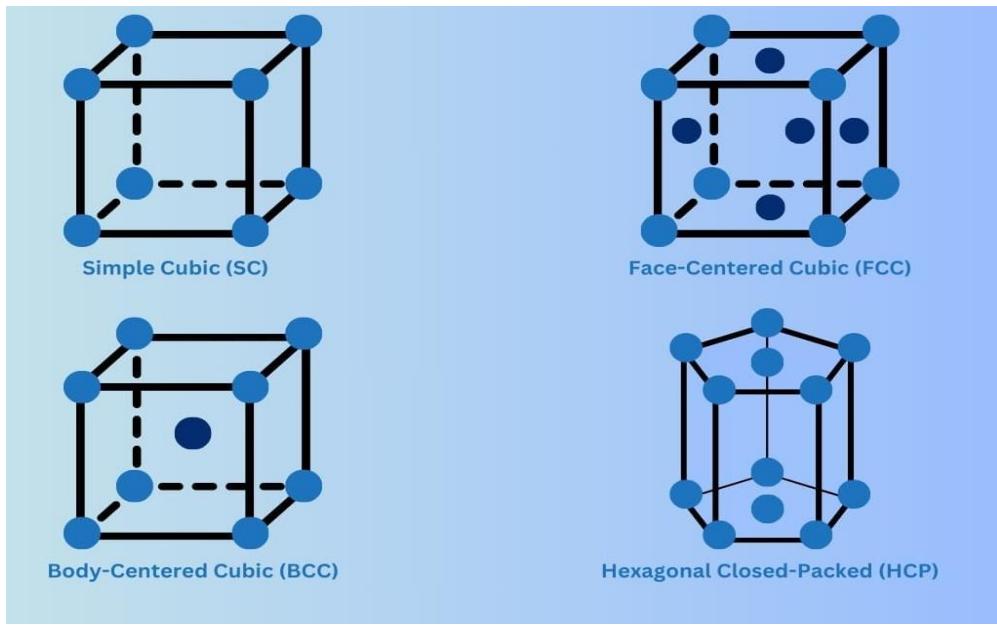
Metallic Crystal Structures

- At the corners of the simple cube (SC) are atoms.
- The number of coordination is six, and the efficiency of packing is fifty-two percent.
- Atoms are positioned at the corners and the center of the (body-centered cubic)- (BCC) structure.
- Packaging efficiency was 68%, and the coordination number was 8.
- Atoms will be positioned in the corners and face centers of the (face-centered cubic)- (FCC) type.
- 12 is the number of coordination, and 74% is the efficiency of packing.
- Atoms stacked in hexagonal layers are referred to as hexagonal close-packed (HCP) atoms.
- 12 is the number of coordination, and 74% is the efficiency of packing.
- While FCC metals have a high degree of ductility because they have several slip systems, HCP metals have a lower degree of ductility because they have fewer slip systems.
- Because of the more compact packing of atoms, FCC metals have a higher density than BCC and SC metals.
- At high temperatures, the crystal structure of certain metals, such as iron, undergoes a shift, resulting in the formation of FCC, while at ambient temperature, the structure of BCC is formed.
- Slip systems vary from structure to structure; for example, BCC has a moderate ductility, FCC has a high ductility because it has a large number of slip planes, and HCP has a limited ductility because it has restricted slip systems.

- BCC metals are normally tougher and stronger, but they are less ductile than FCC metals. On the other hand, FCC metals are softer and more ductile than HCP metals, whereas HCP metals are brittle yet strong in some applications.
- In comparison to BCC and HCP structures, FCC structures often have a higher thermal and electrical conductivity. This is because FCC structures have closer atomic packing together with superior electron mobility.

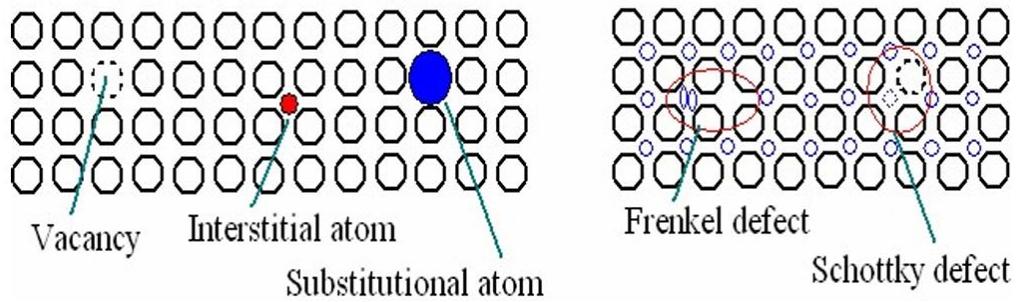
Metallic Crystal Structures

Crystal Structure	FCC	BCC
Unit Cell Type	Cubic	Cubic
Relationship Between Cube Edge Length a and the Atomic Radius R	$a = 2R\sqrt{2}$	$a = 4R/\sqrt{3}$
Close-Packed Structure	Yes	No
Atomic Packing Factor (APF)	74%	68%
Coordination Number	12	8
Number of Atoms per Unit Cell	4	2
Number of Octahedral Interstitial Sites	4	6
Tetrahedral Interstitial Sites	8	12



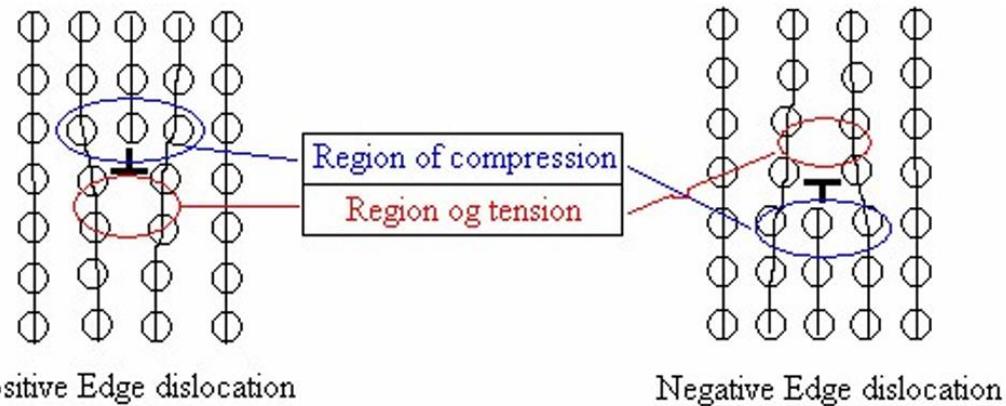
Crystal Imperfections

- ❖ Crystal defects are imperfections in the regular arrangement of elements within a crystal lattice that have a substantial impact on the properties of a material.
- ❖ Vacancies (absent atoms), interstitials (extra atoms in spaces), and substitutional defects (different atoms replacing host atoms) are all examples of point defects.

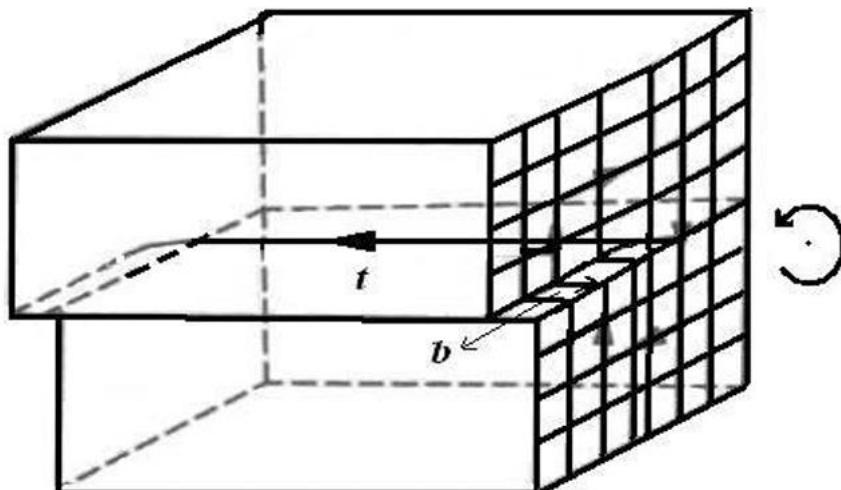


Schematic depiction of various point defects

- ❖ Dislocations, or line defects, are irregularities that occur along a line within the lattice. They are frequently classified as screw dislocations and edge dislocations.

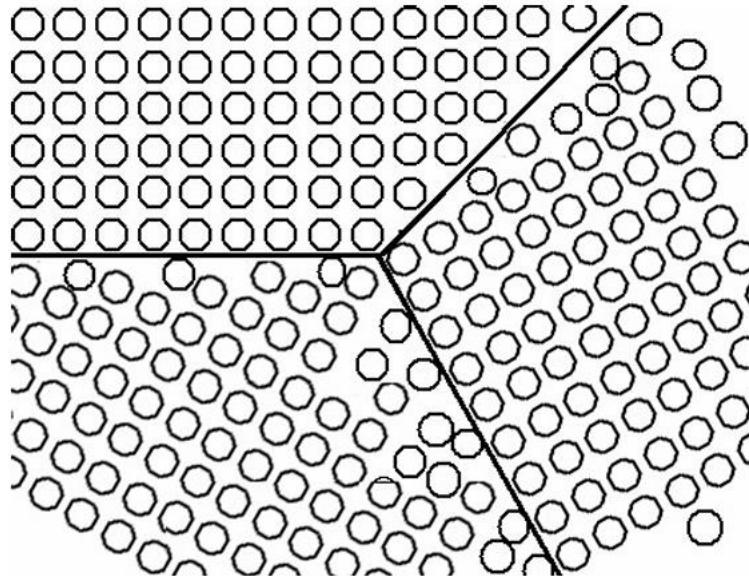


- ❖ Interstitial defects are the result of foreign atoms occupying the spaces between the regular atomic positions in the lattice.
- ❖ Volume defects, including voids, fractures, and inclusions, are three-dimensional imperfections that frequently compromise the material.



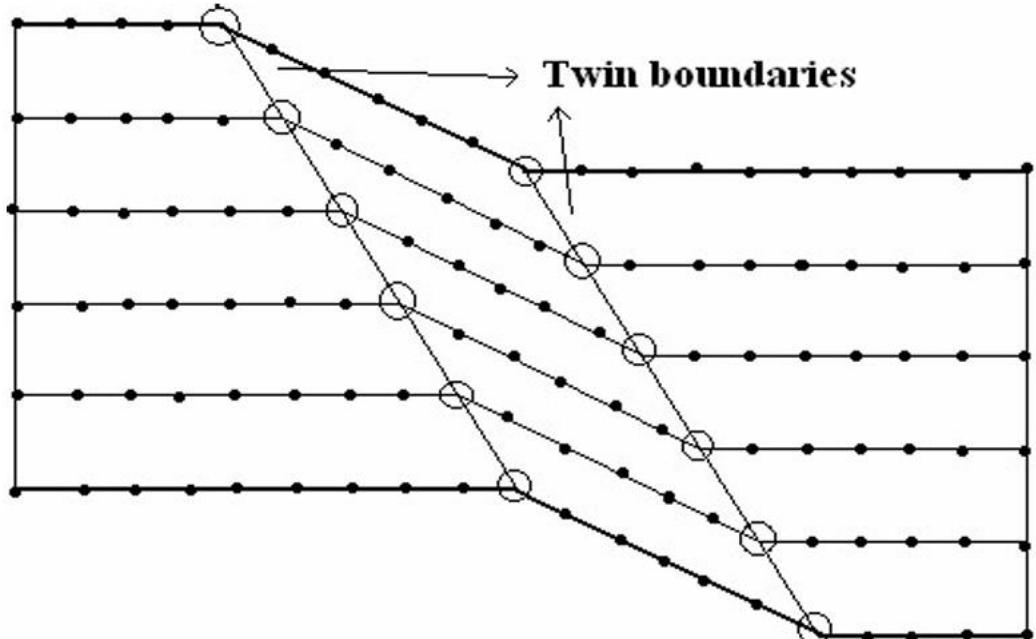
Negative screw dislocation.

- ❖ The presence of defects can improve ductility by facilitating dislocation movement; however, if they are present in excess, they may diminish strength.



Schematic presentation of grain boundaries

- ❖ The strength -of any material- is enhanced by the refining grain -boundaries, which serve as barriers to dislocation motion at the intersection of various crystal orientations.
- ❖ By allowing atoms to rearrange into a more stable structure, annealing processes can mitigate defects such as dislocations.
- ❖ Material properties, including conductivity, hardness, and corrosion resistance, are determined by the density and type of defects.



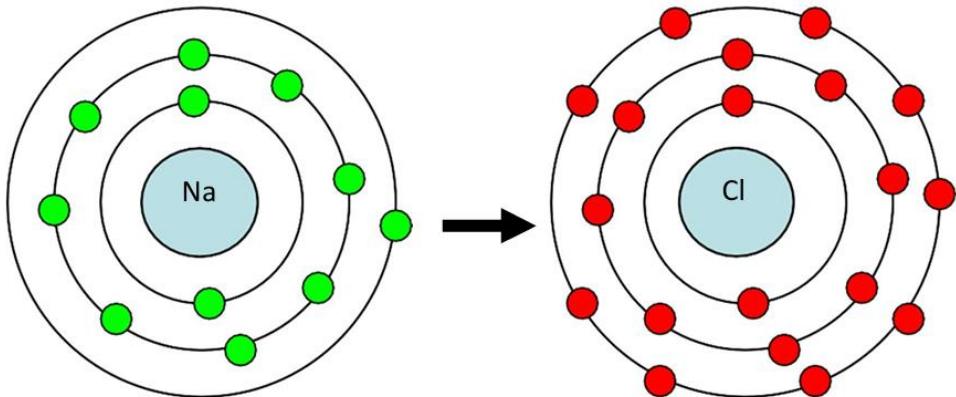
A pair of twin boundaries.

- ❖ The introduction of defects under controlled conditions, such as through alloying or work hardening, is employed to customize materials for specific applications.

Bonding

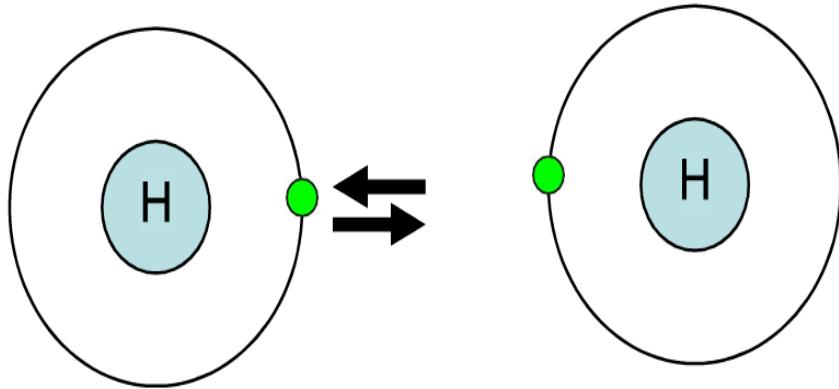
- ❖ The interaction between atoms or molecules is governed by bonding in materials, which determines their mechanical, thermal, electrical, and optical properties.

- ❖ Primary bonds are distinguished by the sharing or transfer of

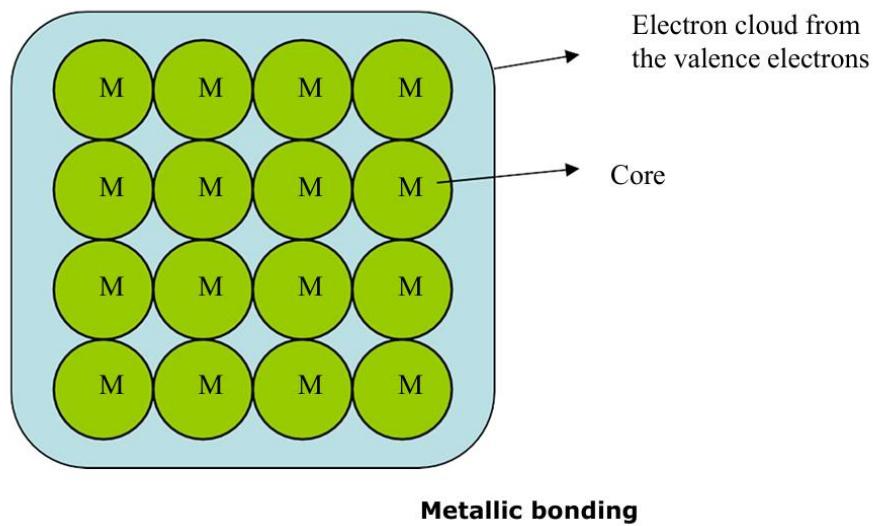


electrons and strong interatomic forces, and they include ionic, covalent, and metallic ones.

- ❖ Strong, brittle materials such as ceramics (e.g., NaCl) are the consequence of the formation of ionic bonds between atoms with significant differences in electronegativity.
- ❖ Covalent bonds, as seen in diamond or silicon, are formed by the sharing of electrons between elements with similar electronegativity, resulting in high strength and directional properties.
- ❖ Covalent bonds, as seen in diamond or silicon, are formed by the sharing of electrons between elements with similar electronegativity, resulting in high strength and directional properties.



- ❖ Metallic bonds are characterized by a "sea of delocalized electrons" that envelop positive metal ions, thereby enhancing their electrical conductivity, malleability, and ductility.



- ❖ Secondary bonds- including hydrogen- bonding and (van der Waals forces), are less robust than primary bonds; however, they are crucial to the properties of molecular materials and polymers.
- ❖ Van der Waals forces are generated by temporary dipoles in molecules, which result in mild attractions that affect properties such as melting and boiling points.

- ❖ Hydrogen bonds are a more potent form of secondary bonding that arise when an electronegative atom that is covalently bonded to a hydrogen atom interacts with another electronegative atom, as is the case in water.
- ❖ The hardness of a material is influenced by the type of bonding; ionic and covalent materials are generally harder, whereas metallic materials are more ductile but gentler.
- ❖ Thermal conductivity is also influenced by bonding. Metallic bonds exhibit high conductivity because of unrestricted electron movement, whereas covalent and ionic bonds restrict thermal flow.

Constitution of Alloys: Necessity of Alloying

- ❖ Alloying improves mechanical properties such as strength, hardness, and toughness, making metals suitable for demanding applications.
- ❖ It enhances corrosion resistance, as seen in stainless steel, where chromium prevents rust formation.
- ❖ Alloying alters thermal and electrical conductivity, tailoring materials for specific industrial uses like electrical wires or heat-resistant components.
- ❖ It allows for modification of physical properties like density, color, or magnetic behavior to meet specialized needs.
- ❖ The introduction of alloying elements refines grain structure, improving wear resistance and fatigue strength.

Constitution of Alloys: Necessity of Alloying

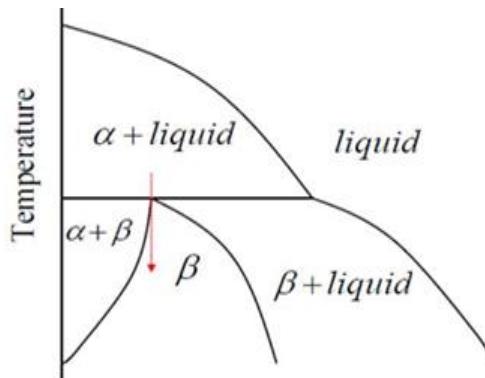
1. Gibbs's Phase Rule is denoted as $F=C-P+2$ and $F=C-P+2$, where F represents degrees of freedom, C represents the number of components, and P represents the number of phases.
2. It assists in determining the number of variables (such as temperature, pressure, or composition) that can be independently modified without affecting the number of phases.
3. The rule is essential for comprehending the equilibrium between phases in alloy systems and phase diagrams.
4. It clarifies the reason for the simpler phase diagrams of binary systems in comparison to ternary systems, which are attributed to the reduced number of components.
5. Alloy thermal treatment and the prediction of material behavior in multi-phase regions are practical applications.

Constitution of Alloys: Hume - Rothery's Rules for Solid Solubility

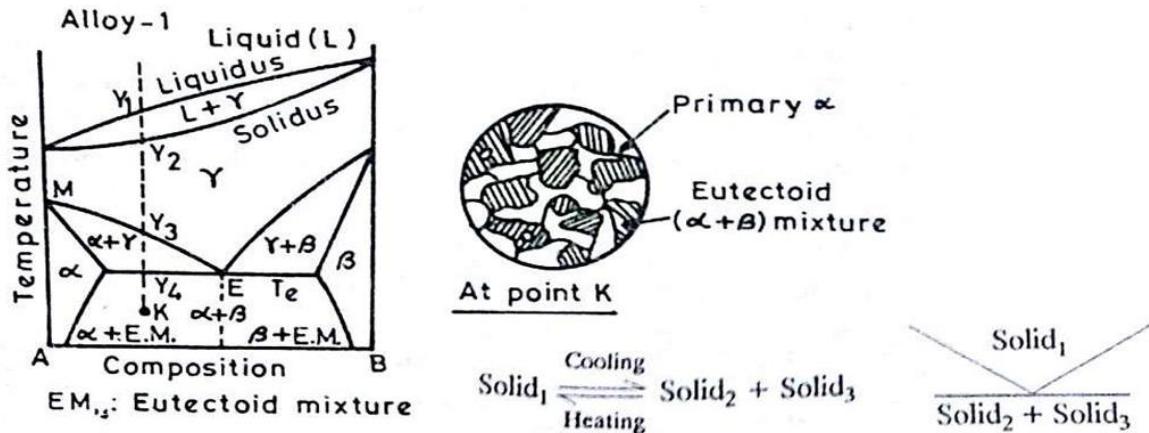
1. Hume Rothery rules govern the formation of solid solutions in alloy systems, emphasizing conditions for solubility.
2. Atomic size difference between elements should not exceed 15% to ensure minimal lattice distortion.
3. Components must have similar electronegativity to avoid compound formation instead of a solid solution.
4. Both elements should possess the same crystal structure for complete solubility (e.g., FCC-FCC or BCC-BCC).
5. Valency difference should be small, as higher valence solutes typically dissolve more readily in lower valence solvent metals.

Constitution of Alloys: The Lever principle

1. The approach is an instrument employed in phase diagrams to ascertain the proportion of coexisting phases at a specific temperature and composition.
2. It functions by establishing a horizontal tie-line that connects the phase boundaries at the specified temperature.
3. The fraction of one phase is directly proportional to the length of the tie-line opposite that phase, which is then divided by the total length of the tie-line.



3. The formula for the fraction of phase α is as follows:
5. f_{α} = The length of the tie-line that is perpendicular to α
6. The total length of the tie-line
6. f_{α} = The total length of the tie-line
7. The tie-line's length in the opposite direction of α

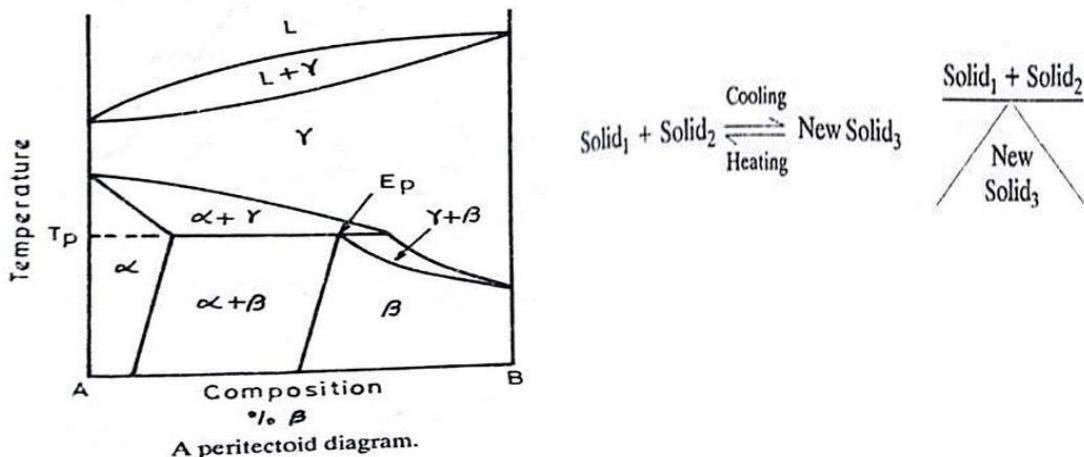


An eutectoid diagram.

3. The lever rule is frequently employed to forecast microstructure proportions in binary alloy systems, including the Aluminum-Copper and Iron-Carbon systems.
4. An alloy system undergoes a eutectic reaction at a specific temperature and composition, during which a liquid phase undergoes a direct transformation into two solid phases simultaneously.



5. This reaction takes place at the eutectic point in a phase diagram, which is defined as the lowest temperature at which the alloy is entirely liquid.

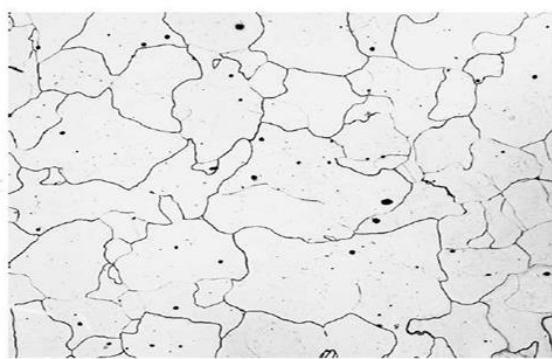


5. Eutectic alloys, including lead-tin (Pb-Sn) solder, are distinguished by their exceptional castability and acute melting point.

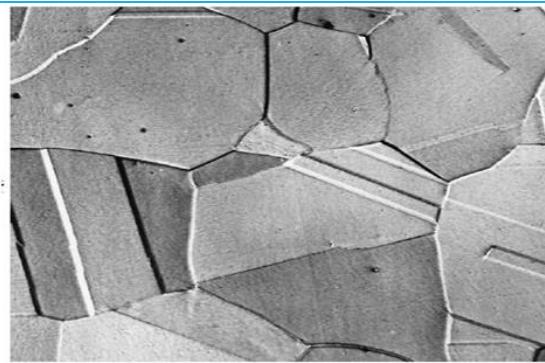
6. A eutectoid reaction is characterized by the simultaneous transformation of a solid phase into two other solid phases: $\gamma \rightarrow \alpha + \beta$
 $\gamma \rightarrow \alpha + \beta$
7. In the Iron-Carbon system, the eutectoid reaction takes place at 727°C and 0.8% carbon. Here, austenite (γ) undergoes a transformation into ferrite (α) and cementite (Fe_3C), resulting in the formation of pearlite.

Iron-Iron Carbide (Fe- Fe_3C) diagram

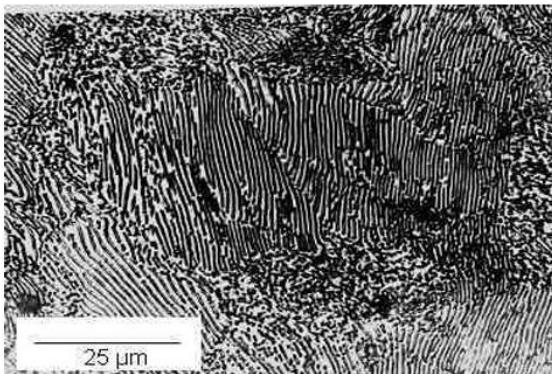
- The Iron-Iron Carbide (Fe- Fe_3C) diagram illustrates the equilibrium between iron and carbon up to 6.67% carbon, corresponding to the composition of cementite (Fe_3C).
- The diagram includes essential phases: ferrite (α), austenite (γ), cementite (Fe_3C), and liquid iron (L), as well as the mixes pearlite, bainite, and martensite (resulting from rapid cooling).
- Ferrite (α) is a body-centered cubic (BCC) phase characterized by minimal carbon solubility (<0.02%), which imparts ductility but results in low strength.
- Austenite (γ) is a face-centered cubic (FCC) phase characterized by enhanced carbon solubility (up to 2.1%), which improves strength and ductility at increasing temperatures.



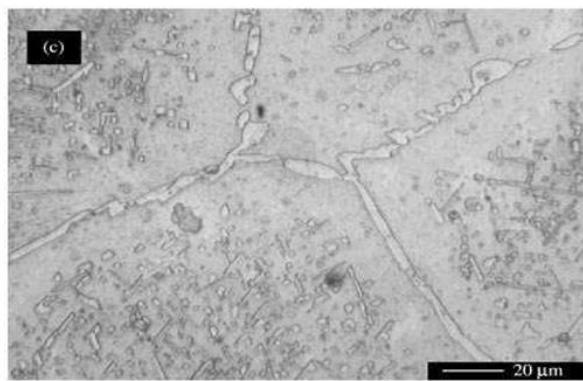
α -ferrite



Austenite

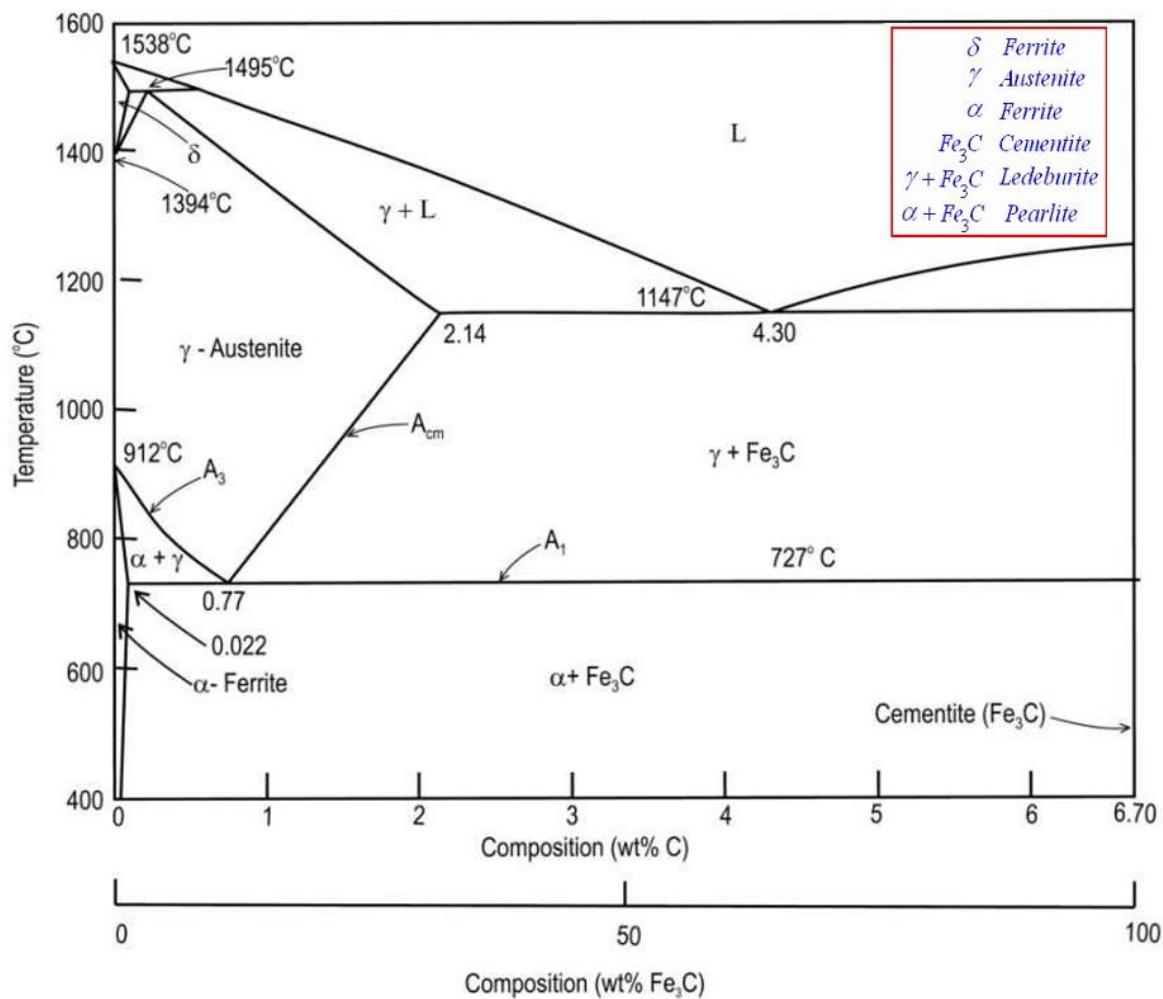


Pearlite

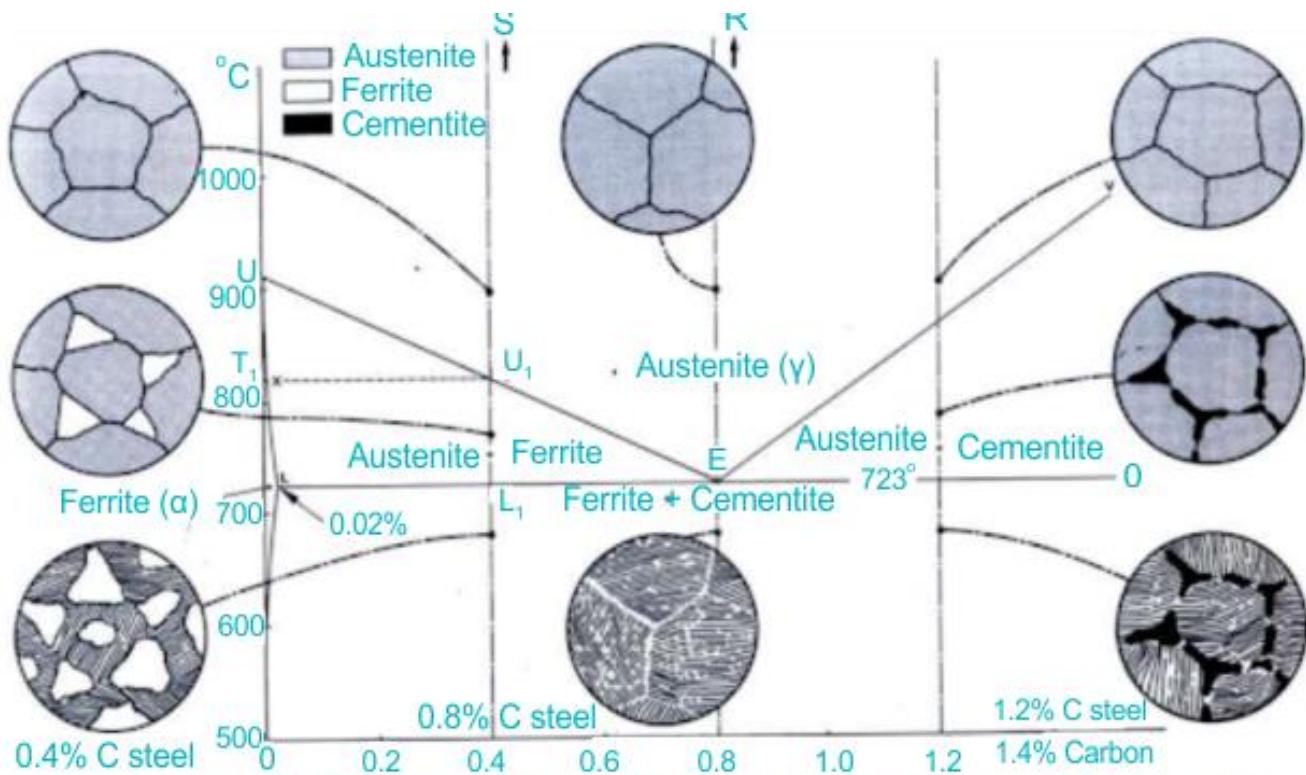


Cementite

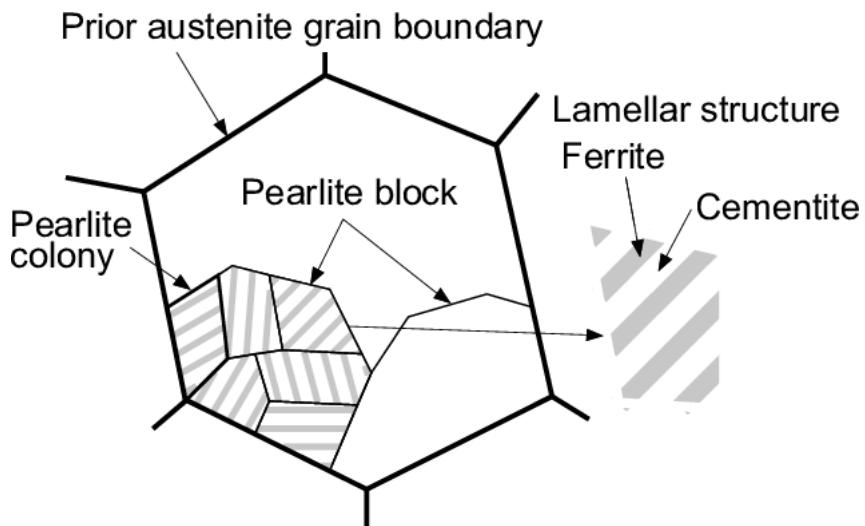
- Cementite (Fe_3C) is a rigid and brittle intermetallic compound that enhances hardness while diminishing ductility in steel.
- The eutectoid point is located at 0.8% carbon and 727°C, where austenite (γ) converts into pearlite, a lamellar configuration of ferrite (α) and cementite (Fe_3C).



- The eutectic point at 4.3% carbon and 1147°C signifies the simultaneous transformation of liquid into austenite and cementite, resulting in the production of ledeburite.
- Hypoeutectoid steels (carbon < 0.8%) comprise a combination of proeutectoid ferrite and pearlite, optimizing ductility and strength.
- Hypereutectoid steels (carbon > 0.8%) comprise proeutectoid cementite and pearlite, providing elevated hardness and wear resistance, albeit with reduced ductility.
- The Fe-Fe₃C diagram informs heat treatment procedures such as annealing, normalizing, and quenching to alter microstructures for certain mechanical properties in steels.



The Austenite \rightarrow Ferrite/Cementite transformation in relation to the iron-carbon diagram



Module-II Heat treatment of steels

- Heat treatment -controlled heating and cooling- of metals to modify their physical and mechanical properties without altering their shape. Welding and shaping heat or cool metal, requiring heat treatment. Heat treatment can improve machining, formability, and ductility following cold working in addition to enhancing material strength. This makes it a particularly enabling manufacturing process that can support other manufacturing processes and improve product performance by improving strength or other desirable features. Heat treatment works effectively on steels, which are used commercially more than any other material.
- Steels are heat treated for one of the following reasons:
 1. Softening
 2. Hardening
 3. Material modification
- **Softening:** Softening is performed to diminish strength or hardness, eliminate residual stresses, enhance toughness, restore ductility, refine grain size, or alter the electromagnetic characteristics of steel.
- Restoring ductility or eliminating residual stresses is essential when extensive cold working is to be conducted, as in cold-rolling or wire drawing processes. Annealing — The complete processes include spheroidizing, normalizing, tempering, aus tempering, and martempering.
- **Hardening:** Steels are hardened for strength and wear. A necessary condition for hardening is adequate carbon and alloy content. Steel can be immediately toughened if it has enough carbon content. Otherwise, the part's surface has to enhance carbon through diffusion treatment hardening.

- **Material Modification:** Heat treatment (HT) alters material properties beyond hardening and softening. These processes modify the behavior of the steels in a beneficial manner to maximize service life, e.g., stress relieving, or strength properties, e.g., cryogenic treatment, or some other desirable properties.
- **Full annealing** involves gradually increasing the temperature approximately 50 °C (90 °F) above the A3 or ACM lines for hypoeutectoid steels (containing < 0.77% carbon) and 50 °C (90 °F) into the Austenite-Cementite region for hypereutectoid steels (containing > 0.77% carbon).
- The material is kept at this temperature for long enough to completely change into Austenite or Austenite-Cementite, depending on the case. The material is cooled in a kiln at a rate of about 20°C/hr (36°F/hr) per hour until it reaches 50°C (90°F). This is where the Ferrite-Cementite region starts. At this point, natural airflow may cool it down in the air around it. Depending on whether it is hypo- or hyper-eutectoid, the grain structure is made up of coarse pearlite mixed with ferrite or cementite. The steel becomes flexible and easy to shape.
- **Normalizing**-The process of increasing the temperature to a level that exceeds 60 ° C (108 °F), completely entering the Austenite range, above line A3 or line ACM. It is maintained at this temperature to complete the conversion of the structure to Austenite. Subsequently, it is withdrawn from the furnace and cooled to room temperature through natural convection. This leads to a particle structure of fine Pearlite that contains an excess of Ferrite or Cementite. The material that results is soft; the extent of its tenderness is contingent upon the precise ambient cooling conditions. This process is significantly less expensive than complete annealing due to the absence of the additional expense associated with controlled furnace cooling.
- **Procedure Annealing** -employed to process work-hardened components fabricated from low-carbon steels (less than 0.25% carbon). This enables the components to remain sufficiently malleable for additional cold processing without shattering. Process annealing is conducted by

elevating the temperature to just below the Ferrite-Austenite boundary, denoted as line A1 on the diagram. The temperature is approximately 727 °C (1341 °F), hence heating it to around 700 °C (1292 °F) should be adequate. This is maintained for a sufficient duration to facilitate the recrystallization of the ferrite phase, followed by cooling in stagnant air. The material remains in a consistent phase throughout the operation, with the sole alterations being in the size, shape, and distribution of the grain structure. This technique is more economical than full annealing or normalizing, as the material is neither subjected to elevated temperatures nor cooled in a furnace.

- **Stress Alleviation Annealing** -employed to alleviate residual tensions in substantial castings, welded components, and cold-formed elements. Such components often experience strains resulting from temperature cycling or job hardening. Components are subjected to temperatures ranging from 600 to 650 °C (1112 to 1202 °F), maintained for a considerable duration (about 1 hour or longer), and thereafter cooled gradually in stagnant air.
- **Spheroidization** is an annealing technique employed for high carbon steels (Carbon > 0.6%) that will undergo machining or cold forming thereafter. This can be accomplished using one of the following methods: Elevate the component's temperature to slightly below the Ferrite-Austenite line, designated as line A1, or beneath the Austenite-Cementite line, namely below 727 °C (1340 °F). Maintain the temperature for an extended duration and subsequently implement gradual cooling.

(or)

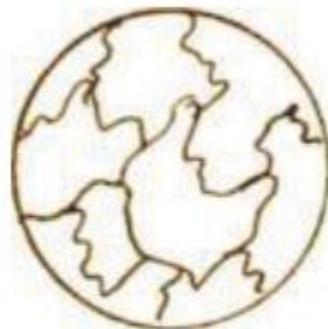
- Continuously oscillate between temperatures slightly exceeding and falling short of 727 °C (1340 °F), namely between 700 and 750 °C (1292 - 1382 °F), succeeded by a slow cooling phase.

(or)

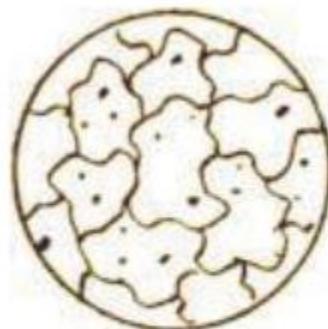
- To prepare tool and alloy steels, heat to 750-800 °C (1382-1472 °F) for many hours and then slowly cool. All procedures produce a structure with

cementite in minute globules (spheroids) scattered throughout the ferrite matrix. This design enhances machining in continuous cutting activities like lathes and screw machines. Spheroidization enhances abrasion resistance.

- **Tempering** follows quench hardening. Quench-hardened parts can be overly brittle. Martensite predominates, causing brittleness. Tempering eliminates this brittleness. Tempering produces a desired mix of hardness, ductility, toughness, strength, and structural stability. Tempering is distinct from tempers on rolled stock, which indicate the level of cold work done.
- Steel and tempering temperature determine tempering mechanism. Martensite, the dominant structure, is somewhat unstable. Heating Martensite causes carbon atoms to disperse, forming a carbide precipitate and stable Ferrite and Cementite. On the Rockwell C scale, tool steels lose 2 to 4 points of hardness. Although some strength is lost, impact strength indicates significant growth in toughness. To increase toughness, springs and other parts are tempered to a lower hardness. Tempering immediately follows quench hardening. Once the steel cools to approximately 40°C (104 °F) after quenching, it can be tempered. The component is warmed at 150-400 °C (302-752 °F). Troostite forms here, softer and harder. As an alternative, heating the steel to 400-700°C (752-1292 °F) creates a softer Sorbite structure. This is ductile and tougher than Troostite but weaker. For optimal tempering, immerse parts in oil up to 350 °C (662 °F) and heat the oil with the parts to the desired temperature. Bath heating guarantees that the entire section is heated and tempered the same way. For temperatures beyond 350 °C (662 °F), a nitrate salt bath is recommended. The salt baths can reach 625°C (1157 °F). No matter the bath, steady heating prevents steel breaking. After 2 hours at the desired temperature, the components are taken from the water and chilled in still air.



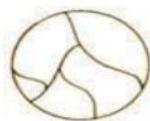
CEMENTITE



FERRITE

Hardening

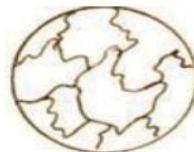
- Steel hardness depends on carbon content. To harden steel, its structure must transition from the body-centered cubic structure at room temperature to the face-centered cubic structure in the Austenitic zone. The steel is heated to the austenitic area. Martensite forms when quenched quickly. This structure is robust but fragile. Austenite and Pearlite, a partially hard and partly soft structure, form when gently quenched. During gradual cooling, Pearlite, a soft material, is predominant.
- Hardening and cooling occur mostly at the surface when hot steel is quenched. This penetrates the substance. By choosing the appropriate alloy, one can attain desirable qualities for a specific application and aid in hardening.



AUSTENITE



MARTENSITE



CEMENTITE



PEARLITE COARSE



PEARLITE FINE

Quench Media

- Water: Plunging hot steel in water quenches it. When water near heated steel vaporizes, it does not directly contact the steel. This slows cooling until bubbles split, allowing water to contact hot steel. Boiling water removes much heat from steel. Proper agitation prevents bubbles from clinging to steel, preventing soft areas.

Good agitation makes water a fast quencher. Water can corrode steel, and quick cooling might cause distortion or breaking.

Salt Water: Salt water cools parts faster than plain water because bubbles break readily. But salt water is considerably more caustic than plain water, so rinse it off promptly.

Oil: For slower cooling, apply oil. The high boiling point of oil slows the transition from Martensite formation to finish, reducing the risk of cracking. Fumes, spills, and fires result from oil quenching.

Precipitation hardening:

1. Involves a single-phase solution formed by dissolving all solute atoms through heat treatment.
2. Fast cooling across the solvus line to exceed solubility. A supersaturated solid solution remains stable (metastable) at low temperatures, preventing diffusion.
3. Precipitation heat treatment, where the supersaturated solution is heated to an intermediate temperature to precipitate and aged. Hardness decreases with long-term use. This is over aging.

For precipitation hardening, the solubility curve must decrease rapidly with temperature and have a significant maximum solubility.

- alloy composition below maximum solubility
- Polymers: Lightweight and flexible materials, such as plastics and rubber.
- Composites: A combination of materials engineered for qualities, such as fiberglass.
- Semiconductors: Materials with intermediate conductivity, such as silicon and germanium.

Precipitation Hardening:

Dislocation-blocking ultrafine precipitates increase hardening. Overcoming the solubility limit causes precipitates. Because it hardens over time, precipitation hardening is also called age hardening.

Case Hardening:

Case hardening creates a durable surface over a strong core. The main case hardening methods are carburizing, cyaniding, and nitriding. Only ferrous metals case-harden. Case hardening is particularly useful for parts that need a durable surface and can endure strong loads. Case hardening works best with low-carbon and low-alloy steels. High-carbon steels become brittle when case hardened due to core penetration. During case hardening, the metal surface is chemically altered by adding high carbide or nitride content. The core is chemically unchanged. Heat treatment hardens the high-carbon surface and toughens the core.

Carburizing:

Carburizing - a case-hardening- procedure that adds carbon to the surface of low-carbon steel. This produces carburized steel with a high-carbon surface and low-carbon inside. Heat-treating carburized steel hardens the casing but leaves the core soft and tough. Steel is carburized two ways. Steel can be heated in a carbon monoxide furnace. In another approach, steel is placed in a charcoal (carbon-rich container) and further heated in a furnace. You can air-cool the parts / leave the container- in the furnace to cool. Both components anneal with slow cooling. Carbon penetration varies on soaking time. Modern carburizing uses gas atmospheres virtually exclusively.

Cyaniding:

This case hardening is rapid and effective. Steel soaks in a heated cyanide bath. It is quenched and rinsed to eliminate cyanide after removal. This method generates a thin, rigid shell that is harder than carburizing and takes 20–30 minutes instead of hours. The biggest downside is that cyanide salts are fatal.

Nitriding:

This approach yields the toughest surface of all hardening processes. The pieces are heat-treated and tempered before nitriding, unlike previous procedures. The pieces are heated in an ammonia-gas furnace. No quenching is needed, reducing the risk of warping or deformation. The case hardening method is utilized for wear-resistant and high-heat engine parts including gears, cylinder sleeves, camshafts, and others.

Flame Hardening:

Metal surfaces can also be hardened by flame hardening. Using an (oxyacetylene type) flame quickly heats a tiny layer on the part to its critical temperature, which is subsequently quenched with a water spray and cool base metal. The internal parts keep their qualities as the thin, rigid surface is created. Here in, Torch burns/ heats metal quickly, and temperatures are usually measured visually, thus a close astute watch is needed whether the operation is manual or mechanized. Manual or automated flame hardening. Automation is better since it generates consistent outcomes. Further, automatic M/C's typically have variable travel speeds and can accommodate pieces of different sizes and forms. Parts determine torch size and form. The torch has- mixing head, extension tube, 90° extension head, adjustable -yoke, and water-cooled tip-as important components.

Various tips are available for hardening components-flats, rounds, gears, cams, cylinders, and other shapes. Use a hand-held welding torch to harden isolated regions. To avoid sputtering -in corners and grooves- usage of a slightly oxidizing flame instead of neutral for regular heating is preferred. Be careful not to overheat comers and grooves. Dark streaks on metal indicate overheating, so move the flame away. Accordingly, position the torch with the inner cone tip -approximately an eighth of an inch from the surface and direct the flame at right angles to the metal- for optimal heating effects. To get better results, you may need to modify this angle, but rarely more than 30 degrees. Adjust torch travel speed based on metal type, part mass and shape, and desired hardness. You must also choose steel with appropriate qualities. For surface hardness, use carbon steel, and for core physical qualities, alloy steel. Flame hardening requires more than 0.35% carbon in plain carbon steels. The effective carbon range for water quenching is 0.40%–0.70%. If heating and quenching rates are not regulated, parts having more above 0.70% carbon will surface crack. Flame-hardened sections have the same surface hardness as furnace-hardened sections. A relentless drop in hardness occurs - between the casing and core. Since flame hardening

does not impact the core, spalling and flaking are unlikely during use. Thus, flame hardening creates a wear-resistant casing and a core that preserves its qualities. Flame hardening has the following main methods:

1. stationary, 2. circular band progressive
3. straight-line progressive
4. spiral band progressive
- and 5. circular.

Module – III FERROUS MATERIALS AND ALLOYS

Various types of carbon steel

Carbon steel has 0.12–2.0% carbon as the predominant interstitial alloying element. Carbon steel is defined by the American Iron and Steel Institute (AISI) as: Carbon steel is defined as steel with no minimum or required content of chromium, cobalt, molybdenum, nickel, niobium, titanium, tungsten, vanadium, or zirconium, or any other element for alloying, copper minimum of 0.40 percent, Manganese 1.65, silicon 0.60, copper 0.60 or maximum content of any of the elements noted

Types:

Carbon content divides carbon steel into four classes

Mild and Low Carbon Steel:

- Mild steel (plain-carbon steel) is the most often used type of steel due to its low cost and versatile qualities, surpassing iron. Low-carbon steel is malleable and ductile due to its carbon content of 0.05-0.320%. Although mild steel has low tensile strength, it is affordable and pliable. Carburizing can increase its surface hardness. Large quantities of structural steel are often made from it. Mild steel has a density of 7.85 g/cm³ (7850 kg/m³ or 0.284 lb/in³) and a Young's modulus of 210 GPa (30,000,000 psi).

- Yield-point run out affects low-carbon steels with two yield points.
- Second yield point is lower than first, and yield reduces rapidly after top yield point. The surface of low-carbon steel may produce louder bands if stressed between the higher and lower yield points. Low-carbon steels are easier to cold-form and handle.

Higher Carbon Steels:

- Carbon steels with heat-treatment potential have a carbon content of 0.30-1.70 % by weight. Trace impurities of other elements might affect steel quality. At working temperatures, trace levels of sulfur render steel red-short, brittle, and crumbly. A36 grade low-alloy carbon steel melts at 1,426–1,53°C (2,599–2,800°F) and contains 0.05% sulfur. Manganese helps low-carbon steels harden. Some definitions call this low-alloy steel, although AISI's carbon steel allows up to 1.65% manganese by weight.

Low Carbon Steels:

- Under 0.3% c.

Medium Carbon Steel:

- About 0.30–0.59% carbon. Suitable for large parts, forging, and automotive components because to its ductility, strength, and wear resistance.

High Carbon Steel:

- Carbon content: 0.6–0.99%. Strong, used for springs and cables.

Ultra-High Carbon Steel:

- Between 1.0 and 2.0% carbon. Hard-tempered steels. For non-industrial knives, axles, and punches. Most steels with above 1.2% carbon content are produced by powder metallurgy. Cast iron steel has carbon above 2.14%.

Alloy Steel:

- To enhance mechanical qualities, alloy steel is alloyed with various elements in amounts between 1.0% and 50% by weight. There are two types of alloy steels: low-alloy and high-alloy. Smith and has hemi define the difference at 4.0%, while Degarmo, et al. put it at 8.0%. Most people mean low-alloy steels by "alloy steel".

Types:

- According to the World Steel Association, there are approximately 3,500 classes of steel with distinct physical, chemical, and environmental qualities. Steel is made up of iron and carbon, but the qualities of each grade depend on the amount of carbon, impurities, and alloying elements present. Steel can have 0.1-1.5% carbon, however the most common types contain 0.1-0.25%. Manganese is useful, whereas phosphorus and sulphur are harmful to steel's strength and durability.
 - To differentiate steels depending on their qualities, different grading schemes are utilized. The American Iron and Steel Institute (AISI) divides steels into four chemical composition groups:
 1. Carbon Steels
 2. Alloy Steels
 3. Stainless Steels
 4. Tool Steels

Carbon Steels:

- 90% of steel output is carbon steel with trace alloying components. Carbon steels are divided into three carbon content groups:
 - Carbon content in low/mild steels can reach 0.3%.
 - Medium Carbon Steels: 0.3-0.6% carbon
 - High Carbon Steels: >0.6% carbon

Alloy Steels:

- Alloy steels use different quantities of alloying elements (e.g. manganese, silicon, nickel, titanium, copper, chromium, and aluminum) to control qualities including hardenability, corrosion resistance, strength, formability, weldability, and ductility. Pipelines, vehicle parts, transformers, power generators, and electric motors use alloy steel.

Stainless Steel:

- Corrosion-resistant stainless steels-include 10-20% chromium. Steels over 11% chromium concentration enable (200 times more corrosion-resistant)than mild steel. Crystal structure divides steels into III categories:
- Austenitic:- Non-magnetic, non-heat-treatable, and typically include 18% chromium, 8% nickel, and less than 0.8% carbon. Austenitic steels dominate the global stainless-steel industry, commonly used in food processing, kitchen utensils, and pipelines.
- Ferritic: Ferritic steels contain trace nickel, 12-17% chromium, less than 0.1% carbon, molybdenum, aluminum, and titanium. Heat treatment cannot harden these magnetic steels, but cold works can strengthen them.
- Martensitic:- Martensitic steel composition includes 11-17% chromium, <0.4% nickel, and up to 1.2% carbon. These magnetic, heat-treatable steels are utilized in blades, cutting tools, and dental/surgical equipment.
- Tool Steel: Tool steels, with variable amounts of tungsten, molybdenum, cobalt, and vanadium, enhance heat resistance and durability, making them excellent for cutting and drilling equipment.

- Steel goods are also categorized by shape and use:
- Long/Tubular Products: bars, rods, rails, wires, angles, pipelines, forms, and sections. These goods are popular in automotive and construction.
- Flat products are plates, sheets, coils, and strips. Automotive parts, appliances, packaging, shipbuilding, and construction employ these materials.
- Valve, fitting, and flange products are mostly utilized for pipelines.

Cast Iron:

- Cast iron is heated until it liquefies and then set into a mold to solidify. The material is mainly pig iron. Carbide impurities in white cast iron allow fractures to slip through, changing its color when broken. Graphite flakes in grey cast iron deflect a crack and cause many more when it breaks. The principal alloying elements are carbon (C) and silicon (Si), with 2.1–4% and 1–3%, respectively. Iron alloys with low carbon are steel. The binary iron–carbon phase diagram explains cast iron solidification, even though these base alloys are ternary Fe–C–Si alloys. Because most cast irons have compositions near the eutectic point of the iron–carbon system, melting temperatures typically range from -1,150 – 1,200°C (2,100 /2,190 °F), which is approximately 300 °C (/572 °F) lower than pure iron. Alloyants alter cast iron's characteristics. Silicon drives carbon out of solution, making it the most important alloying after carbon. Instead, carbon creates graphite, softening iron, reducing shrinkage, strength, and density. Sulfur generates iron sulfide, which inhibits graphite and hardens. Sulfur causes molten cast iron to slow down, leading to short-term flaws. Manganese is added to counteract sulfur's effects because they generate manganese sulfide instead of iron.
- As manganese sulfide is lighter than the melt, it tends to float away and into the slag. The manganese needed to neutralize sulfur is 1.7 times sulfur content + 0.3%.

- Manganese carbide formed when more manganese is added, increasing hardness and cooling, except in grey iron, where up to 1% manganese enhances strength and density.
- Nickel is a popular alloying element that refines pearlite and graphite structure, enhances toughness, and balances hardness across section thicknesses. Chrome is supplied in modest amounts to the ladle to reduce free graphite, induce cool, and stabilize carbides; nickel is often added too.
- A modest amount of tin can replaces 0.5% chromium. Copper is added to the ladle or furnace at 0.5–2.5% to reduce chill, refine graphite, and increase fluidity. Add 0.3–1% molybdenum to improve chill and refine graphite and pearlite structure. Combine it with nickel, copper, and chromium to make high-strength irons. Titanium enhances fluidity and degasses and deoxidizes. Cast iron receives 0.15–0.5% vanadium to stabilize cementite, increase hardness, and resist wear and heat. 0.1–0.3% zirconium deoxidizes, forms graphite, and increases fluidity.
- Bismuth (0.002–0.01%) is added to malleable iron melts to improve silicon addition. Boron is added to white iron to produce malleable iron and lessen the coarsening effect of bismuth.

GCI:

- Grey cast iron/GCI is characterized by its graphitic microstructure, resulting in grey fractures. This is the most widely used cast iron material based on weight. Cast irons typically contain 2.5–4.0% carbon, 1–3% silicon, and the rest iron. Grey cast iron has lower tensile and shock resistance than steel, but comparable compressive strength to low and medium carbon steel.

WCI/White- Cast Iron:

- Due to cementite, cast iron has a white cracked surface. Because white cast iron contains less silicon (graphitizing agent) and cools faster, the carbon precipitates out as metastable phase cementite, Fe₃C, rather than graphite. Cementite precipitates from the melt as big particles in a eutectic mixture with austenite (which may cool to martensite). In some steels, cementite precipitates may limit plastic deformation by inhibiting dislocation movement through the ferrite matrix, but these eutectic carbides are too big to precipitation harden. They increase the bulk hardness of cast iron by virtue of their own high hardness and large volume percentage, which can be approximated by a rule of mixes. They sacrifice toughness for hardness. White cast iron could be considered a cermet because carbide is a major component. White iron is too brittle for many structural components, but its hardness, abrasion resistance, and low cost make it useful in applications like slurry pump impellers and volutes, ball mill shell liners and lifter bars, and coal balls and rings.
- It's hard to cool thick castings fast enough to solidify the melt as white cast iron. Rapid cooling can solidify a white cast iron shell, while the rest cools slowly to produce a grey core.
- Chilled castings offer a hard surface and a slightly tougher interior. High-chromium white iron alloys may be sand cast, allowing a 10-tonne impeller to be made without a high cooling rate, and they are abrasion-resistant. These high-chromium alloys are hard because of chromium carbides. These carbides are primarily eutectic or primary M₇C₃ carbides, with "M" representing iron or chromium and varying based on alloy composition. Eutectic carbides arise as hollow hexagonal rod bundles perpendicular to the hexagonal basal plane. These carbides have 1500-1800HV hardness.

Malleable Cast Iron:

- MCI begins as white iron casting, which undergoes heat treatment at around 900 °C (1,650 °F). The slower separation of graphite allows surface tension to create spheroidal particles instead of flakes.
- Owing to their decreased aspect ratio, spheroids are petite and far distant and have a lower propagating fracture or phonon cross section. They feature broad borders, unlike flakes, which reduces stress concentration in grey cast iron. Overall, malleable cast iron behaves like mild steel. Due to its white cast iron composition, malleable iron parts are limited in size.

Ductile Cast Iron:

- Recent developments include nodular or ductile cast iron. Adding small amounts of magnesium or cerium to these alloys slows graphite precipitate formation by attaching to graphite plane edges. Controlling other elements and time enables carbon to segregate into spheroidal particles during solidification. The qualities are like malleable iron, although larger pieces can be cast.

Typical Uses:

- Historic Markers and Plaques
- Hardware (Hinge, Latches)
- Columns, Balusters
- Stairs
- Structural Connectors

- Decorative Features
- Fences
- Tools and Utensils Ordnance
- Stoves and fire backs
- Piping

The cast iron material in all these applications may look the same or comparable, but component size, composition, use, condition, relationship to adjacent materials, exposure, and other characteristics may require distinct treatments to fix identical issues. Any substance should be considered as part of a broader system, and treatment methods should address all relevant elements.

Module-IV Non-Ferrous Metals and Alloys

- Non-ferrous metals- Example: - aluminum, copper, lead, nickel, tin, titanium and zinc, as well as copper alloys like brass and bronze.

Properties



- | | |
|---|--|
| <input type="checkbox"/> No-Fe | <input type="checkbox"/> High Thermal Conductivity |
| <input type="checkbox"/> Corrosion Resistance | <input type="checkbox"/> Formability and Castability |
| <input type="checkbox"/> High Electrical Conductivity | <input type="checkbox"/> Electric and Magnetic |

Copper - its Alloys

Copper is found as native metal and in minerals cuprite, malachite, azurite, chalcopyrite and bornite.

The largest end use for Copper is in the building industry. Within the building industry the use of copper-based materials is broad. Construction industry related applications for Copper include roofing, piping, electrical wiring etc.



Copper Applications

- In-Power transmission lines**
- ~ Architectural applications**
- ~ Cooking utensils**
- ~ Spark plugs**
- ~ Electrical wiring, cables and busbars**
- ~ High conductivity wires**
- ~ Electrodes**
- ~ Heat exchangers**
- ~ Refrigeration tubing**
- ~ Plumbing**
- ~ Water-cooled Copper crucibles**

Structure and Properties

- Copper has a face centered cubic (FCC) crystal structure.
- Copper and its alloys have a range of yellow/gold/red colors and when polished develop a bright metallic luster.
- Around 40% of the annual consumption of Cu alloys is derived from recycled Copper materials.

- tough, ductile malleable
- ~ Excellent heat conductivity
- ~ Excellent electrical conductivity
- ~ Good corrosion resistance
- ~ Good biofouling resistance
- ~ Good machinability
- ~ Retention of mechanical and electrical properties at
- ~ Non-magnetic

Structure and Properties-Brass

Brass is a binary alloy of copper and zinc

Copper – zinc alloys i.e., brasses have two different types of crystal structure.

Alpha brasses are solid solutions of zinc in copper with FCC crystal structure..

The maximum solubility of zinc in the α -phase is about 38%

It has good corrosion resistance, high strength and ductility.

Its electric conductive decreases with increase in zinc content and with higher zinc content, beta phase with BCC structure starts to form.

Brasses with zinc contents near 40% can have a structure of alpha and beta, but at around 50% zinc the structure is entirely beta

Catridge Brass



Cartridge Brass contains 70% copper and 30% zinc. It is very ductile and has excellent cold working properties.



It can be easily drawn into wires, rods and tubes and can be formed into intricate shapes by pressing.



It is used for cartridge cases, locomotive and condenser tubes.

Admiralty Brass

Admiralty brass is an alloy of copper, zinc and tin.

It contains 70% copper , 29% zinc and 1% tin.

It has good resistance to corrosion and is used for condenser tubes and marine parts.

Leaded Brass

Due to high ductility, machining of brass is difficult.

Lead (3% max) is usually added to brass to improve machinability.

Such a brass is called leaded brass or free cutting brass

The usual composition is Cu – 62.5%, Zn – 36% and Pb – 1.5%

Lead is insoluble in solid as well as in liquid phases and appears as globules in the microstructure.

These globules easily break into small chips and increase machinability.

It has low ductility and impact values. It is used for gears, screws and screw machine parts

Naval Brass



- Naval brass is an alloy of Cu – 60%, Zn – 39% and Sn – 1%.
- It has good corrosion resistance against salt water.
- Eg. condenser plates, propeller shafts & marine parts

Name	Composition %			Properties	Uses
	Cu	Zn	Other elements		
Cartridge Brass	70	30		Most ductile and has good tensile strength. Easily cold worked by drawing, pressing and spinning	Cartridge cases, locomotive and condenser tubes. Lamp fixtures and spring
Admiralty brass	70	29	1(Sn)	Resistance to corrosion	Condenser tubes, and marine parts
Muntz metal (Yellow Brass)	60	40		Strong, hard and more ductile	Valves, marine fitting electric equipment, fuses and grill work
Leaded Brass	62.5	36	1.5(Pb)	Good machinability resistance to corrosion, low ductility and impact values	Used for tubes, plates
Naval Brass	60	39	1(Sn)	Suitable for hot-rolled forging and casting. Good corrosion resistance.	Marine parts such as valves and fittings

Bronze

Bronze -an alloy of copper and tin is also referred as phosphorus bronze because it contains noticeable amount of phosphorus (upto 0.3%).

It has low coefficient of friction, and it can be rolled into sheets or cast into intricate castings

Bronzes are stronger than brasses, and have better corrosion resistance. The cost of (bronzes) is more than brasses.

The term bronze does not always imply copper-tin alloys. Alloy of copper with other elements (except zinc) are also called bronzes such as aluminum bronze, silicon bronze etc

The properties and applications of important types of bronzes are described below

Phosphorous and other Bronzes

Name	Composition %			Properties	Uses
	Cu	Sn	Other elements		
Phosphor Bronze	93.7	6	0.3(P)	Possess good castability, high fatigue strength	Springs, gears and bearing
Aluminium Bronze	90 – 95	-	5-10 (Al)	Possess high strength, and resistance to corrosion	Marine engineering, guides, seats, flanges, molding dies for plastics and condenser tubes
Gunmetal	88	10	2 (Zn)	Easily castable, possess high strength, toughness and resistance to sea water corrosion	Casting guns, boiler fittings, bolts, nuts and for many parts in naval constructions
Bell metal	80	20		Hard and resistance to surface wear	Bells gongs and utensils
Silicon Bronze	97.5	-	2.5(Si)	Strength, corrosion resistance	Marine application, High strength fasteners

Nickel Silver

1. Alloy containing 55% of copper, 27% zinc and 18% nickel is called Nickel Silver
2. This alloy do not contain any silver
3. The name is justified because the addition of nickel to brass causes the change of color from yellow to white, resembling that of silver
4. The corrosion resistance of nickel silver is better than the brass. Susceptibility to stress corrosion and dezincification decreases with increasing the nickel content.



5. Its strength can be increased by cold working
6. It is ductile and used for decorative purposes and cutlery.
7. It can also be used for rivets, screws, radio dials and similar applications.

Constantan

1. Constantan is a copper – nickel alloy consisting of 55% copper and 45% nickel.



2. It has the highest electrical resistivity and lowest temperature coefficient of resistance.
3. It is used for electrical resistors and thermo-couples.

Nickel and its Alloys

1. Pure nickel exhibits exceptional corrosion resistance and is both ductile and robust.
2. It is capable of being brazed, welded, and forged. It is employed in the combustion chambers of gas turbines and chemical apparatus.

It functions as a basal coating for the electroplating of chromium. Nickel is a primary component of numerous industrial alloys.

3. Nickel base alloys are composed of over 50% nickel. In the temperature range of 650 to 750 C, a large variety of nickel-based alloys are accessible, and these alloys maintain a significant degree of strength. The following is a description of the properties and applications of significant nickel alloys.
4. Nickel and copper form isomorphous system, and such alloys can be strengthened by cold working.
5. A wide range of properties can be obtained by varying proportions of nickel and copper, and addition of small quantities of other elements.

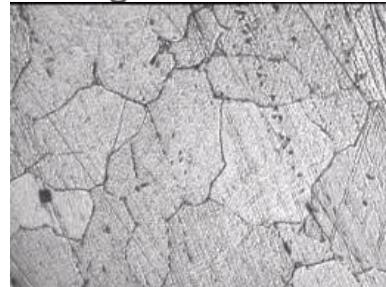
Monel Metal

1. Monel or Monel metal is a nickel –copper alloy with high strength and corrosion resistance.
2. It is harder and stronger than brass and bronze, but weaker than that of alloy steel.
3. It contains about 67% nickel and 30% copper with small quantities of iron, manganese, silicon and carbon
4. Monel is widely used in chemical and textile industries
5. Applications of monel include house hold equipment, heat exchanger tubes, containers, valves, pumps and parts used in food textile and chemical industries

Al and alloys

1. Both groups include non-heat treatable as well as heat treatable alloys.
2. Heat treatable alloys achieve their properties by solid solution strengthening while non-heat treatable alloys are strengthened by cold working.

3. The composition properties and applications of important aluminum alloys are given in the table given below
4. Aluminum alloys are cast in considerable quantity.
5. The main alloying elements in cast alloys are silicon, copper and magnesium.
6. Cast alloys contains enough silicon (11-13%) to form eutectic alloy giving materials low melting point and good fluidity
7. They can be sand cast and die cast into intricate shapes. They are used for engine cylinder blocks, gear box cases, crank cases etc.
8. Wrought alloys are those that are shaped by plastic deformation.
9. They possess good formability characteristics, such as low yield strength, high ductility and good fracture resistance.
10. They can be obtained in the form of sheets, bars and tubes and they can be forged
11. The total alloy content in wrought alloy is about 7% and include copper, manganese and magnesium



Al and its alloys

Type of alloy	Composition %					Properties and applications	
	Balance = Al						
	Cu	Mg	Mn	Si	Other elements		
Wrought alloy – work hardened	-	5	-	-	-	High resistance to corrosion (sea water) marine applications	
Wrought alloy – Heat treatable (Duralumin)	4	0.5	0.5	0.5	0.5 (Fe)	Non-magnetic, resistance to corrosion; good strength Air craft and automobile industry in the form of forgings, bars, sheets,	
Wrought alloy – Heat treatable (magnalium)	1.75	6	-	-	-	Light weight; good mechanical properties Aircraft and automobile components	
Wrought alloy – Work hardened (Hindalium)	-	3.5	-	-	0.25 Cr	Strong and corrosion resistance; utensils	
Cast alloy – work hardened	3.0	-	0.4	5.0	-	Good casting characteristics with moderate strength manifolds and valve bodies	
Heat treatable (Y-alloy]	4	1.5	-	-	2 (Ni)	Retains strength at high temperature, resistance to corrosion	
Cast alloy – Heat treatable	1.8	-	-	9.0		High strength; air craft industry	

Titanium and its alloys

1. Compared to pure titanium, titanium alloys have a high strength, ductility and corrosion resistance, and retain these properties at elevated temperatures.
2. These merits titanium alloys are used in air craft engineering, marine application, chemical processing and other industries.
3. They may be processed by casting, forming and also by advanced methods such as powder metallurgy and hot –isostatic pressing
4. Depending on stable phases at room temperature, titanium alloys are classified as :
 - α – phase titanium alloy
 - β – phase titanium alloy
 - $(\alpha+\beta)$ – phase titanium alloy
5. α – phase is stabilized and hardened by adding about 5 percent aluminum and 2.5% percent tin.
6. Addition of tin improves strength without affecting ductility. α – phase alloys are used for gas turbine engine casings and chemical processing equipment.
7. β – phase alloys are produced by adding larger amounts of molybdenum, chromium and vanadium.
8. The usual composition of β – phase alloys is 13% vanadium, 11% chromium and 3% aluminium.
9. They possess good ductility and formability when they are not heat treated
10. Age hardening produce very high strength but ductility and toughness are reduced, β – phase alloys are used for high strength airframe components

11. An alloy composition of 6% aluminum and 4 % vanadium produces $(\alpha+\beta)$ – phase titanium alloys.
12. This is most popular titanium alloy accounting for nearly 50 – 70% of all titanium alloys used in the entire industries

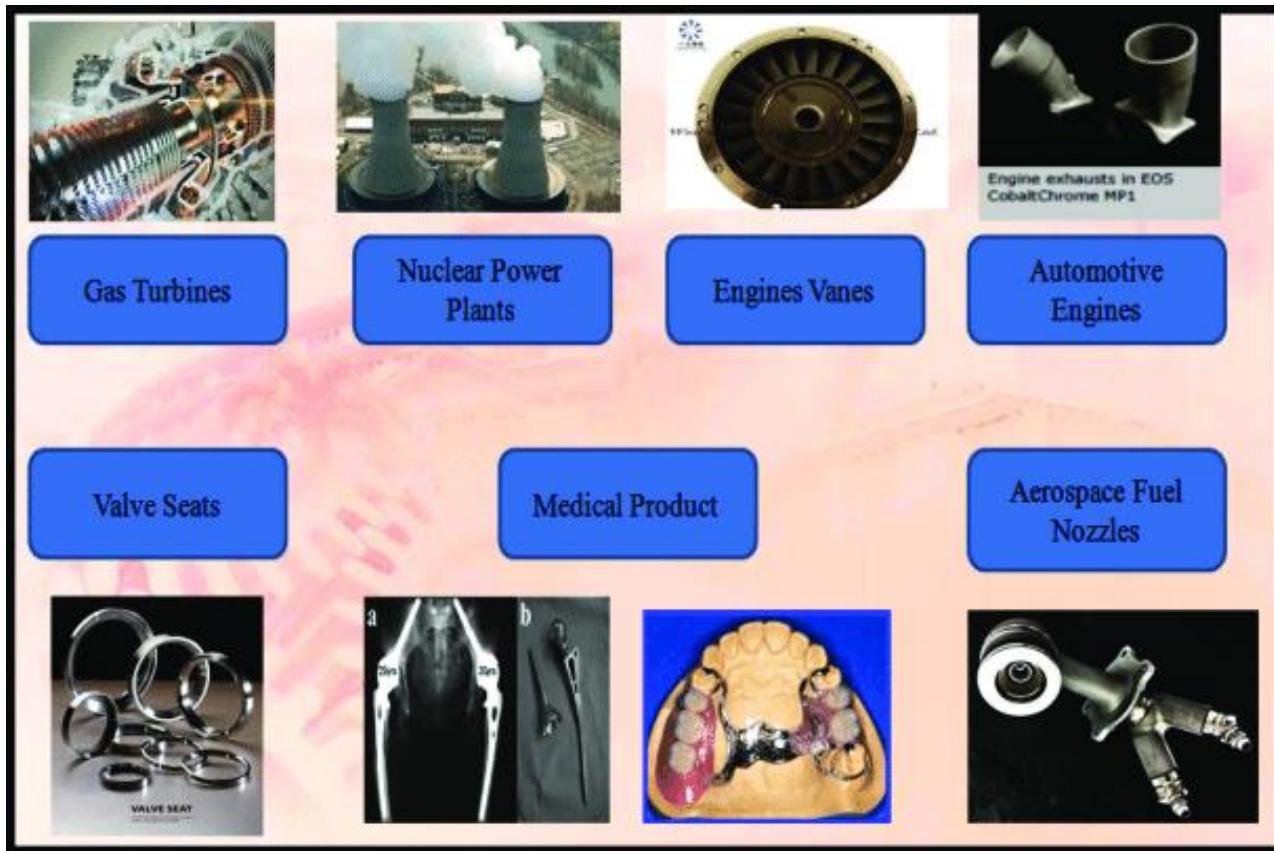
Alloy	Composition %					Properties and applications
	Al	V	Sn	Mo	Cr	
α – Alloy	5	-	2.5			<ul style="list-style-type: none"> ➤ High Strength and ductility, creep resistance up to 500 C, good formability ➤ Gas turbine engine casings, chemical processing equipment
β – Alloy	3	13			11	<ul style="list-style-type: none"> ▪ High ductility and good formability; low strength to weight ratio ▪ High strength air frame components
	3	8	-	4	6	
$(\alpha+\beta)$ Alloy	6	4	-	-	-	<ul style="list-style-type: none"> ✓ Good strength and formability ✓ Chemical processing equipment and <u>aircraft</u> components

13. Ti – 6Al – 4V alloys have strength and good creep, fatigue and corrosion resistance.
14. They are used for aircraft components such as airframes, turbine compressor blades and rings

Cobalt and its alloys

Around the time of World War II, cobalt alloys were developed for use in adverse conditions, including high temperature exposure, mechanical stress, and contact with chemically aggressive gaseous or molten media. Some of these alloys were derived from cobalt chromium alloys that were already in existence for other purposes.

1. Used as hot components in the first jet engines, including turbine blades
2. Cobalt alloys are classified into two different classes: casting alloys and wrought by (hot) forging alloys.
3. In particular, four cobalt-chromium alloys are commonly used for biomedical applications:
 4. ASTM F75: Co-28Cr-6Mo, casting alloy.
 5. –ASTM F799: Co-28Cr-6Mo, thermodynamically processed alloy.
 6. –ASTM F90: Co-20Cr-15W-10Ni, wrought alloy.
 7. –ASTM F562: Co-35Ni-20Cr-10Mo, wrought alloy.



Mg and its alloys

1. Contains 3 to 10 % Al, 1 to 3.5% Zn and 0.4% manganese.
2. Dow metal : 91 Mg 9 Al / Cu
3. The tensile strength is not high
4. Risk hazards due to burning
5. Weight is 2/3 of AL and Quarter of that of steel.
6. Dow metal cant be forged/ welded/drawn in wires.
7. Mg alloys are called light alloys.

Refractory and precious materials

The term "refractory metals" is generally applied to metals that have melting points greater than 2000⁰ C.

Element	Symbol	Melting point, °C	Remarks
Tungsten	W	3410	
Tantalum	Ta	2996	Also used in the chemical industry
Molybdenum	Mo	2610	
Niobium	Nb	2497	Also used in the chemical industry
Zirconium	Zr	1825	Mainly used in the chemical industry
Osmium	Os	3045	Also a member of the platinum group
Iridium	Ir	2410	Also a member of the platinum group
Rhenium	Re	3180	Brittle, difficult to fabricate

Silver, gold, and the six platinum group metals—platinum, palladium, ruthenium, rhodium, osmium, and iridium—are all included in the definition of "precious metals."

The term "fineness" is employed to denote purity in parts per thousand by weight.

For example, 995 fine gold is 99.5% gold, and 925 fine silver (sterling silver) is 92.5% silver.

Throughout history, gold has been exceptionally valuable due to its numerous qualities.

It is highly malleable, durable to the point of virtual indestructibility, and typically found in nature in a comparatively pure form.

Additionally, it is attractive in colour and luminosity.



MODULE -V

CERAMICS, POLYMERS AND COMPOSITES MATERIALS

Introduction:

Heat-resistant, non-metallic, inorganic ceramics are composites of metallic and non-metallic materials. Commonly, ceramics are hard, corrosion-resistant, and brittle. Most ceramics insulate well and resist high temperatures. They are used in almost every facet of modern life due to their qualities. The main ceramic categories are conventional and advanced. Traditional ceramics are comprised of clay and cements that have been hardened through high temperatures. Traditional ceramics are used for plates, kitchenware, flowerpots, roof and wall tiles. Advanced ceramics include carbides like SiC, oxides like Al₂O₃, nitrides like Si₃N₄, and many others, including mixed oxide ceramics that can behave as

superconductors. Medical and engineering improvements have resulted from contemporary ceramic processing processes. Glass is occasionally ceramic. Ceramics are crystalline, while glasses include impurities that hinder crystallization. Amorphous glasses are like liquids. Ceramics have high, well-defined melting points, while glasses soften throughout a range of temperatures before becoming liquids. Ceramics are opaque to visible light, while glasses are translucent. Glass ceramics are made of several small crystalline areas in a non-crystalline substrate. This structure provides them ceramic and glass characteristics. When heated, glass ceramics expand less than most glasses, making them ideal for windows, wood stoves, and radiant glass-ceramic cooktops.

Composition:

Some ceramics have two components. Alumina and zirconia are aluminum oxide, Al_2O_3 and ZrO_2 , respectively. Ceramics are good insulators and can resist high temperatures. Artwork with ceramics is popular. SiO_2 . Numerous minerals and other ceramics have complicated and varied compositions. KAlSi_3O_8 is the formula for granite's ceramic material feldspar. The chemical bonding in ceramics can be covalent, ionic, or polar covalent, depending on their composition. The bonding is mostly ionic when the ceramic components are a metal and a nonmetal, such as MgO and BaTiO_3 . BN and SiC are covalent ceramics made of a metalloid and a nonmetal. Unit cells, three-dimensional units, are repeated throughout most ceramics' extremely crystalline structure. In rock salt, magnesium oxide crystallizes. Along each perpendicular axis, Mg^{2+} and O^{2-} ions alternate in this arrangement.

Manufacture of Traditional Ceramics:

Traditional ceramics are manufactured from clay that has been baked by high temperatures, which drives away water and forms strong chemical bonds between the flakes. The word “ceramic” derives from the Greek word “keramos,” meaning “burnt earth.” Clay, typically blended with other materials, is molded by artists to create ceramic sculptures. Kiln ovens heat and solidify shaped objects “fire” them. Clay is made of several microscopic flat plates layered and separated by thin water layers. Water helps the plates stick together and slide by lubricating them. Clay is easily formed. High temperatures remove water and build connections between plates, keeping them in place and forming a hard solid. Bone ash is added to clay to strengthen bonding and make ceramics break-resistant. Due to iron oxides, flowerpot and roof tile clay is red-orange. Kaolin, a rare and expensive white clay, is used to make white pottery. Figurines from former Czechoslovakia are the oldest known human-made pottery, dating to 27,000 B.C.E. To create figurines, clay was mixed with bone, animal fat, soil, and bone ash, molded into desired shapes, and cooked in a domed pit. Ancient Greece and Egypt made pots, dishes, and storage vessels from 9000 to 6000 B.C.E. White porcelain was a major advance. Porcelain is stronger and less fragile than previous ceramics. Strong enough to make elegant containers with translucent walls. Kaolin and china stone are heated to 1,300°C (2,372°F) to make it. Chinese blue and white porcelain was refined during the Ming dynasty after the T'ang dynasty produced it approximately 600 C.E. The porcelain method originated in the Arab area in the ninth century and moved to Spain and Europe.

Manufacture of Advanced Ceramics:

Advanced ceramic materials are made from finely separated powder blended with an organic binder to consolidate and form. The unfired ceramic body is "green." The binder is decomposed or oxidized by heating the green body at a low temperature. It is "sintered," or hardened, at high temperatures into a dense,

robust ceramic. Chemical bonding form between powder particles at this point. Sintering can shrink ceramic by 10–40%. Because shrinkage is uneven, ceramic may need further machining to get a perfect shape.

Sol-gel Technology:

Due to molecular mixing of ions in solution, sol-gel technology produces more homogenous ceramics. A sol-gel technique hydrolyzes an organometallic compound solution to create a "sol," a colloidal suspension of a solid in a liquid. A metal alkoxide like tetramethoxysilane in alcohol is typical. Sols occur when formula units polymerize into chains and networks. The sol can be prepared as a thin film, microspheres, or a gel in a mold to create a ceramic object with the appropriate shape. Many cross connections between formula units make this ceramic less fragile. The sol-gel process is expensive, but it allows the ceramist to control porosity and form films, spheres, and other structures that are hard to mold, as well as specialized ceramic compositions and high product purity. Sol-gel creates porous ceramics. These ceramics are sponge-like with many pore-like lacunae, or openings, making up 25–70% of the volume. Pore size ranges from huge to as small as 50 nanometers (2×10^{-6} inches). Porous ceramics, with their numerous pores, offer high surface areas (up to 500 square meters or 5,382 square feet per gram), making them ideal catalysts. Zirconium oxide, a ceramic oxygen sensor, measures car exhaust air-to-fuel ratios.

Aerogels are solid foams created by eliminating liquid during a sol-gel process at high temperatures and low pressures. Aerogels are ideal for spacecraft due to their excellent insulation, low density, and non-melting properties.

Properties and Uses:

Ceramics were utilized by persons unfamiliar with their construction for ages. Understanding ceramic structure and qualities allows designers and engineers to create novel ceramics.

Most ceramics are hard, chemically inert, refractory, and poor heat and electrical conductors. Ceramics' densities are low. Ceramics have several uses due to these qualities. Ceramics are utilized as furnace refractories and durable building materials including bricks, tiles, cinder blocks, and others. They are also employed as electrical and thermal insulators in spark plugs, telephone poles, electronics, and spacecraft nose cones. However, ceramics are fragile. A big issue with ceramics is that tiny fractures grow until they break. Ceramic coatings are routinely applied to inexpensive crack-resistant materials to avoid cracking. To minimize heat transfer, engine parts are covered with ceramics. Ceramic fiber-embedded polymer composites feature low densities, corrosion resistance, and toughness without brittleness. Tennis rackets, bicycles, and cars use them. Composites can also be created from two ceramic materials as separate ceramic phases. Cracks won't spread between phases. Thus, the composite material resists cracking well. Spacecraft nose cones are built of composite ceramics from zirconium and hafnium diborides and carbides combined with silicon carbide. Break-resistant ceramic composite cookware has excellent thermal shock resistance.

Structure and Properties:

Ceramic materials' qualities depend on atom kinds, bonding, and atom packing. Known as atomic scale structure. Most ceramics are multi-element. This is compound. Alumina (Al_2O_3) is an aluminum-oxygen combination. Chemical bonds hold ceramic atoms together. Ceramic materials use covalent and ionic bonding most often. Chemical bonds in metals are called metallic bonds. Atoms link stronger in covalent and ionic bonds than metallic bonds. Metals are ductile and ceramics brittle because of this.

Microstructure affects a material's final properties. The microstructure of a material can be observed using a microscope but not by the human eye. Ceramic microstructures can be glassy, crystalline, or a mix of both. The glassy phase bonds tiny crystals in the last case. The atomic structure mostly affects chemical, physical, thermal, electrical, magnetic, and optical properties. The microstructure affects

these parameters, although mechanical properties and chemical reaction rate are most affected. Ceramic materials are used in many ways due to their versatility.

Ceramics are typically hard, wear-resistant, brittle, refractory, thermal and electrical insulators, nonmagnetic, oxidation-resistant, thermal shock-prone, and chemically stable.

There are several exceptions to these generalizations. For instance, borosilicate glasses, certain glass ceramics, and NZP ceramics are thermal shock-resistant and used in ovenware, stove tops, and kiln furniture. Some ceramics are good electrical conductors, and ferrites and their magnetic properties drive a commercial market.

Overview of Ceramic and Glass Manufacturing:

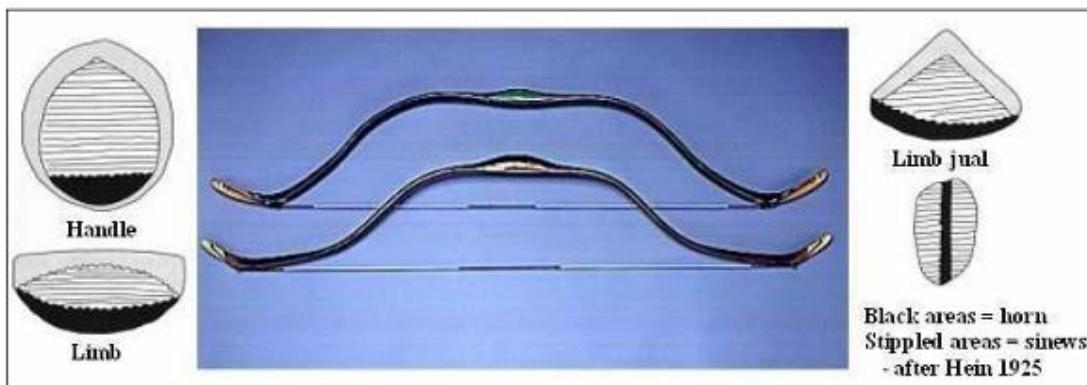
Ceramics are made by heating clays and other natural raw materials to make them stiff. Ceramic products made from natural rocks and minerals require particular processing to control purity, particle size, particle size distribution, and heterogeneity. These factors greatly affect ceramic characteristics. Some ceramics start with chemically produced particles. Controlling these synthetic materials produces powders with specific chemical compositions and particle sizes. The ceramic particles must be shaped next. After adding water and/or binders, the shape is formed. Common ceramic forming methods include extrusion, slip casting, pressing, tape casting, and injection molding. Fire or sintering turns "green" ceramic particles into stiff products. Glazing may be applied to electrical insulators, dinnerware, and tile. Advanced ceramics may be machined and polished to suit engineering design specifications. Glass and ceramics are processed differently. Glass is made by melting silica, lime, and soda ash in a furnace and shaping it into pressed plate, fibers, molded bottle, plate glass, etc. After molten glass is created, it is quickly cooled and "frozen" into the final product. Cutting, etching, coating, grinding, decorating, and heat treating are common glass processing steps. Ceramic and glass manufacturers and suppliers confront issues include raw material availability and cost, labor quality and cost,

changing markets, quality control, expansion capital, import pressure, and environmental, health, and safety norms.

Introduction to components:

Historical Overview / Historical Development:

Spinning continuous yarns, along with fire and the wheel, is a crucial development that allowed humans to thrive beyond tropical climates and spread throughout the Earth. Locally grown and spun fibers like cotton, flax, and jute provided for flexible textiles, surpassing animal skins. Increasing utilization of natural resources led to the creation of composites, straw-reinforced walls, bows, and chariots built of wood, bone, and horn layers (Figure below). Old composites were replaced by more lasting materials like wood and metal.



Present:

In the second half of the 20th century, lightweight composite structures again became popular for various technical solutions after years of neglect. Composites were popular in the latter two decades of the previous century for improving spacecraft and military aircraft structural performance after being utilized mainly for electromagnetic properties (insulators and radar-domes). With improved materials and rising expenses, cost reduction throughout manufacture

and operation is the key technical driver today. Composites are being used to protect humans from fire and impact (Figure below) and are becoming more environmentally friendly, resulting in the return of natural fibers in composite technology (Figure below). By volume and number, composites' success in applications is increasingly evaluated by accessibility and reproductivity of the applied manufacturing techniques.



Following figures both illustrate some examples of how natural fibers can be utilized in various applications.

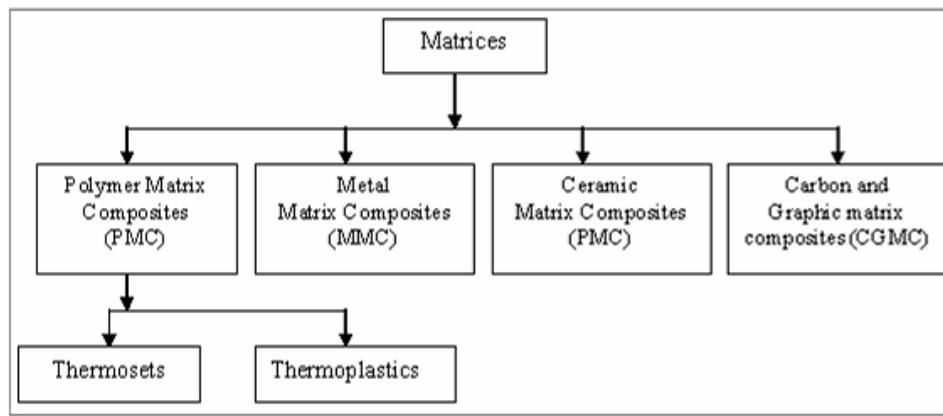


Concept of Composite:

Modern composite materials, which are largely structural, are best examples of fibers or particles embedded in matrix. Laminates are composite materials with distinct functions due to their layers. Fabrics lack a matrix, yet fibers of diverse compositions give them character. Reinforcing materials have desirable qualities and can bear maximum stress. Composite kinds are often identifiable, but no definite distinction may be made. The emphasis is typically changed to microscopic

or macroscopic levels to help define. The matrix in matrix-based structural composites binds the reinforcement phases and deforms to distribute stresses among the reinforcement components under strain. Matrixes face several demands. They may be temperature-sensitive, electrical conductors or resistors, or moisture-sensitive. This may offer weight advantages, convenience of handling, and other benefits depending on the purpose of matrices. Potential matrix materials comprise elements that can withstand stress and form strong connections with the reinforcing phase. Several inorganic minerals, polymers, and metals have been successful matrix materials for structural composites. These materials are elastic till failure and have low failure strain in tension and compression.

Composites cannot be created from divergent linear expansion elements. Interface is where reinforcing and matrix materials meet. Regions are sometimes added phases. Each side of an interphase must have two interphases with its neighboring constituent. Interphases form when contrasting elements interact in some composites. The selection of manufacturing method is influenced by matrix qualities and their impact on reinforcing properties. Selecting and making composites requires chemically inert, non-reactive elements. See Figure below for matrix classification.



Classification of Composites:

Composite materials are usually divided into two categories:

- The matrix constituent is usually classified first.

Three main composite classifications are Organic Matrix Composites (OMCs), Metal Matrix Composites (MMCs), and Ceramic Matrix Composites (CMCs). Organic matrix composites often relate to two types: Polymer Matrix Composites (PMCs) and carbon-carbon composites.

- The second classification level involves reinforcing forms: fiber-reinforced, laminar, and particulate composites. Fiber Reinforced Composites (FRP) can have discontinuous or continuous fibers.
- Fiber Reinforced Composites have fibers in matrix. A discontinuous fiber or short fiber composite has qualities that vary with fiber length. The composite is continuous fiber reinforced when the elastic modulus of the composite does not rise with fiber length. Despite their strong tensile qualities, fibers are tiny and bend easily when forced axially. To prevent bending and buckling, support these fibers.
- Laminar Composites are matrix-held layers of materials. Sandwich structures are included.
- Particulate composites consist of particles embedded in a matrix body. They may be flakes or powder. Wood and concrete particle boards are examples of this group.

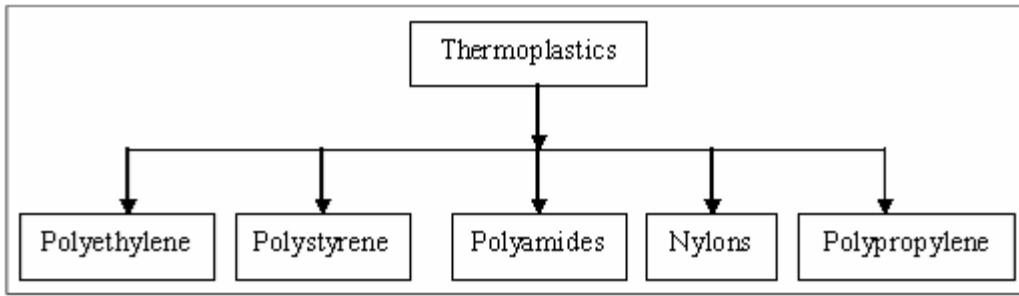
Organic Matrix Composites: Polymer Matrix Composites/Carbon Matrix Composites or Carbon-Carbon Composites:

Polymers are ideal materials due to their lightweight, easy processing, and good mechanical qualities. Thus, high-temperature resins are widely employed in aviation.

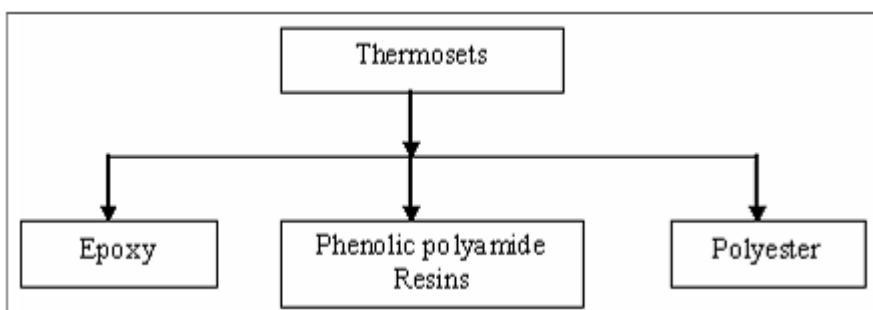
Polymers are mostly thermosets and thermoplastics. Thermosets exhibit a well-bonded three-dimensional molecular structure after curing. Decompose instead of dissolving when hardened. Changing the resin's basic composition changes curing conditions and other properties. Thermosets can remain partially cured for extended durations, making them highly flexible. Thus, they are ideal for advanced fiber reinforced composites as matrix bases. Thermosets are widely used in chopped fiber composites, especially when using premixed or molding compounds with precise fiber quality and aspect ratio, such as epoxy, polymer, and phenolic polyamide resins.

At high temperatures, thermoplastics have an increased melting point because to their one- or two-dimensional molecular structure. Advantages include the ability to reverse softening at high temperatures and restore characteristics during cooling, enabling traditional compression procedures to mold compounds.

Composites reinforced with thermoplastics were appearing. Most efforts in this area aim to improve resin base qualities and maximize functional benefits in innovative ways, such as replacing metals in die-casting processes. In crystalline thermoplastics, reinforcement greatly impacts morphology, enabling nucleation. Whether crystalline or amorphous, these resins can change creep over a wide temperature range. However, resin use is limited in this range, and reinforcing can improve failure load and creep resistance. Following figure depicts thermoplastics.



A little amount of shrinkage and the shape's tendency to preserve its shape must also be considered. However, reinforcements can change this. Plastics systems are better than thermosets since they don't produce gasses or heat through chemical reactions. Time spent heating, shaping, and cooling structures limits manufacturing. As molding compounds, thermoplastic resins are sold. Fiber reinforcement suits these resins. Randomly distributed fibers make the reinforcement practically isotropic. They can be oriented directionally during molding. Several methods can increase thermoplastic heat resistance. Fillers increase heat resistance. But all thermoplastic composites lose strength at high temperatures. However, thermoplastics' rigidity, toughness, and creep resistance make them valuable composite materials. In automobile control panels, electronic product encasing, etc. New breakthroughs promise thermoplastics' expanded applications. Massive sheets of reinforced thermoplastics can be sampled and heated to shape. This makes making big components easier, eliminating molding chemicals. Thermosets are the most prevalent fiber composite matrix, without which structural engineering research would suffer. Aerospace, automotive, and defense systems use these fiber composites extensively. PCBs and other applications use epoxy matrix materials. Some thermosets are shown in Figure below.



Most thermoset resins are produced through direct condensation polymerization and rearrangement processes to create heterocyclic units. Using water as a reaction product in both processes can hamper the creation of void-free composites. These voids reduce composite strength and dielectric characteristics. Polyesters phenolic and epoxies are major thermoset resins.

Prepress-moldable epoxy resins are popular in filament-wound composites. Despite chemical attacks, they are good adherents with modest shrinkage during curing and no volatile gas emissions. Due to these benefits, epoxies are pricey. Note that they cannot be predicted above 140°C. In high-tech sectors with greater service temperatures, their use is not recommended.

Polyester resins are available, affordable, and versatile in various applications. Liquid polyesters can be maintained at room temperature for months or years, and a catalyst can cure the matrix material quickly. They are utilized in cars and structures.

Curing polyester makes it translucent and hard or flexible. Polyesters resist chemicals and weather. These resins can be utilized up to 75°C or more, depending on their formulation or service requirements. Polyesters are compatible with few glass fibers and can be used with reinforced plastic accessories.

Aromatic polyamides are ideal for advanced fiber composites in structural applications requiring continuous exposure at 200-250°C for extended periods.

Metal Matrix Composites (MMC):

Metal matrix composites are popular in research but less popular in practice than plastic composites. Metal matrices give superior strength, fracture toughness, and stiffness compared to polymers. They can resist higher temperatures and corrosive environments than polymer composites. Many metals and alloys can serve as matrices, but they need stable reinforcement materials that are non-reactive and temperature-resistant. The selection process is mostly influenced by the matrix material. Light metals create the temperature matrix, and the reinforcements have high moduli together with the above causes. Most alloys

and metals are good matrices. Practically, low-temperature applications have few options. Only light metals are sensitive, and their low density helps. Current matrix metals include titanium, aluminum, and magnesium, which are helpful for aviation. High modulus reinforcements are needed for strong metallic matrix materials. Composites can have greater strength-to-weight ratios than most alloys. Composite service temperatures depend on their melting point, physical, and mechanical qualities. Low melting point alloy matrices work with most metals, ceramics, and compounds. Increased matrix material melting temperature limits reinforcing choice.

Ceramics Matrix Materials (CMM):

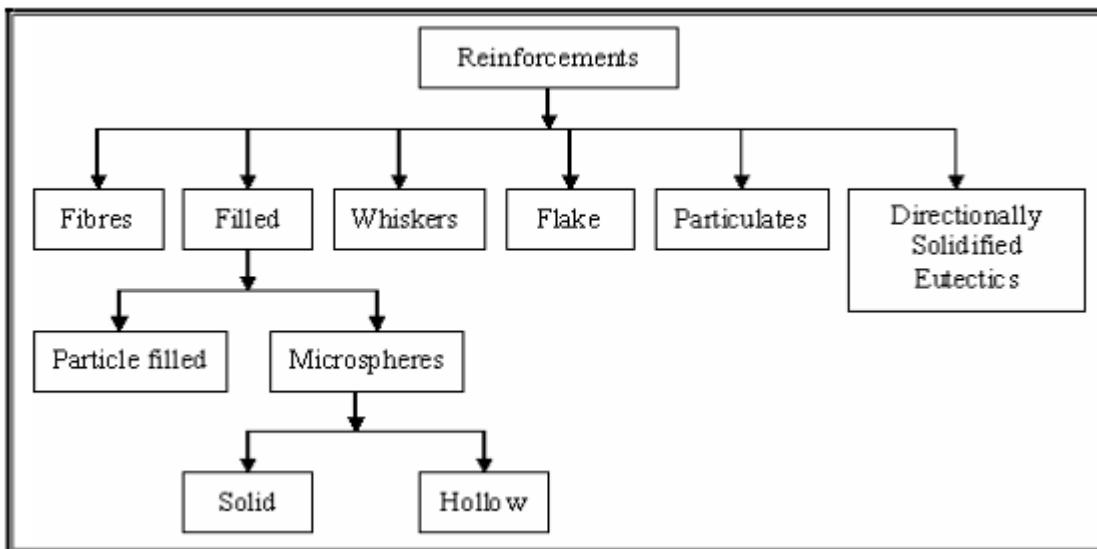
Ceramics are solid materials with strong ionic and occasionally covalent bonding. High melting points, corrosion resistance, stability at high temperatures, and high compressive strength make ceramic-based matrix materials ideal for structural applications over 1500°C. Ceramic matrices are ideal for high-temperature applications. Most ceramics have high modulus of elasticity and low tensile strain, making reinforcements ineffective. The matrix's insufficient elongation prevents the composite from transmitting an effective load to the reinforcement at stress levels where ceramics rupture, and the composite may fail unless the fiber volume % is high enough. Reinforcement uses fiber's increased tensile strength to boost matrix load bearing capability. High-strength fiber added to a weaker ceramic has often resulted in a weaker composite.

Using reinforcement with high modulus of elasticity may alleviate the issue, and pre-stressing the fiber in the ceramic matrix is becoming a more popular solution.

Composites made from ceramics with a higher thermal expansion coefficient than reinforcing materials are unlikely to be stronger. When cooled, the composite will strengthen within ceramic, causing microcracks from fiber to fiber in the matrix. Microcracking can diminish the tensile strength of a composite compared to the matrix.

Classification (Based on Reinforcement):

These include fibers, fabric particles, and whiskers. Fibers typically have one long axis and two circular or near circular axes. Neither particle orientation nor form is desired. Whiskers are shorter and narrower than fibers but have a preferred form. Composite reinforcement types are shown in Figure below.



Reinforcing elements in composites offer the strength that defines the composite. Additionally, they offer heat resistance, corrosion resistance, and stiffness. As needed, reinforcement can accomplish all or some of these functions. For reinforcement to enhance matrix strength, it must be stronger and stiffer than the matrix and capable of modifying failure mechanisms to benefit the composite. This means the composite should be brittle and have little ductility.

Fiber Reinforced Composites / Fiber Reinforced Polymers (FRP) Composites:

Fibers are crucial reinforcements because they meet the desired requirements and transfer strength to the matrix constituent, improving their

qualities. Glass fibers were the first reinforcement fibers. Ceramic and metal fibers were discovered and widely used to stiffen and heat-resistant composites. Several variables reduce fiber performance. Fiber composite performance is determined by fiber length, shape, orientation, composition, and matrix mechanical properties. Fiber orientation in the matrix determines composite strength, with longitudinal fiber orientation being strongest. This doesn't mean longitudinal fibers can take the same load in any orientation. For optimal performance, load longitudinal fibers along their direction. The tiniest loading angle change can greatly affect composite strength. Unidirectional loading is rare hence it's recommended to mix fiber orientations in composites, especially where the load is predicted to be the heaviest. Continuous or discontinuous monolayer tapes can be layered into plies with filaments aligned in the same direction. Today, computers can project more complex orientations for specific needs. Thus, planar composites can shift strength from unidirectional fiber-oriented composites with approximately isotropic characteristics.

Angle-plyed composites may exhibit non-isotropic properties depending on the number and direction of plies. Composite variables are believed to have a constant ratio, and matrices are weaker than fibers. Assuming equal volume percentage in all three axes, the fiber's strength in any one axis would be one-third the unidirectional fiber composite. Short fibers can be oriented by random sprinkling on a plane or by adding matrix in liquid or solid form before or after fiber deposition. Even three-dimensional orientations can do this. Several methods of random fiber orientations produce two-dimensional composites with one-third the strength of a unidirectional fiber-stressed composite in the fiber direction. The composite would have a comparable ratio of less than one-fifth in 3D. Moduli and strengths within strong matrices have not been seen.

The strength of composites with various matrices and orientations can be utilized. To compute longitudinal strength in composites with strong matrix and non-longitudinally oriented fibers, assume fibers have been reduced to their effective strength on approximation. Fiber composites can use continuous or short fibers. Continuous fibers (filaments) have better orientation, but not performance. Fibers have a high aspect ratio, meaning their lengths are several times larger than their effective diameters. Filaments are made continuously for this reason.

Well-known mass production of filaments matches with numerous matrices in winding, twisting, weaving, and knitting, which exhibit fabric qualities. Filaments and other fibers have low densities and high strengths; hence their fiber lengths affect composites' mechanical properties and processing responsiveness. Shorter fibers with suitable orientation can make composites of glass, ceramic, or multi-purpose fibers stronger than continuous fibers. The theoretical strength of short fibers is known. Composites commonly link continuous fibers using filament winding, where the matrix impregnated fiber is wrapped around a mandrel shaped like the part.

Short-length fibers incorporated by open or close molds are less efficient than filament winding, despite reduced input costs.

Most fibers in use are solids with a circular cross-section, making them easy to create and handle. However, a few non-conventional shaped and hollow fibers show promise for improving composite mechanical properties. Smaller diameters can increase fiber strength by minimizing or eliminating surface flaws, since the enormous difference in length and effective diameter are benefits to a fiber composite. Fibers with rectangular cross sections offer new choices for high-strength structures after the popularity of flat-thin filaments. Shaped fibers offer optimal packing, while hollow fibers improve structural efficiency for stiffness and compressive strength in composites. When the hollow section is greater than half the fiber diameter, hollow fibers have lower transverse compressive strength than solid fiber composites. They are difficult to handle and make.

Laminar Composites:

Laminar composites appear in as many material combinations as materials. They are layers of bound materials. These may have many layers of two or more metal components alternately or in a specified arrangement, in as many numbers as needed. Although clad and sandwich laminates follow the modulus and strength rule of mixes, they have numerous areas as they should. Other intrinsic metal-

matrix, metal-reinforced composite values are also well known. Roll bonding, hot pressing, diffusion bonding, brazing, and other powder metallurgical methods can be used to make sheet, foil, powder, or sprayed alloys. Unlike fiber, high-strength materials are impossible. Two-dimensional sheets and foils are easier to isotropic than fibers. Foils and sheets have high percentages by design. Strong sheets can use over 92% laminar structure, but such fibers are hard to manufacture. Laminates cannot exceed 75% strong fibers. Single-layered metal-metal laminates boast unique features and are cost-effective, but lack high strength or stiffness. They are usually pre-coated or clad.

A thin continuous film of pre-coated metal is generated by layering it on a substrate. Hot dipping and chemical plating or electroplating are used to achieve this. Clad metals are good for denser faces in intense situations. Many sheet-foil pairings are low-temperature adhesives. Plastics and metals can be mixed with a third ingredient. The most popular metal-organic laminate is pre-painted or pre-finished metal, which eliminates user finishing. Up to 95% of metal-plastic laminates are made from vinyl-metal laminates, organic films, and metals. Their construction involves adhesive bonding.

Particulate Reinforced Composites (PRC):

Particulate reinforced composites are metal-ceramic composite microstructures with particles of one phase dispersed in the other. Reinforcements are square, triangular, and circular, but their sides are about equal. Dispersoid size and volume concentration separate it from dispersion hardened materials. Particulate composites with volume concentrations over 28% and dispersion of a few microns. Comparatively, difference between particle composite and dispersion-strengthened materials is negligible. The mechanisms that strengthen them differ too. The dispersion-strengthen materials reinforce the matrix alloy by arresting dislocation motion and require significant forces to fracture the restriction. Particulate composites are strengthened by the hydrostatic pressure of fillers in matrices and their hardness. The three systematic orthogonal planes in three-dimensional reinforcement in composites provide

isotropic characteristics. As the array is not homogeneous, material qualities are sensitive to constituent properties, interfacial properties, and geometric shapes. Usually, particle diameter, inter-particle spacing, and reinforcing volume fraction determine composite strength. Matrix characteristics affect particle composite behavior.

Cermets/Ceramal:

Cermet stands for "ceramic" and "metal." CerMet is a ceramic-metal hybrid. Cermets combine the best qualities of ceramics and metals, including high temperature resistance, hardness, and plastic deformation. The metal binds oxides, borides, carbides, and alumina. Usually nickel, molybdenum, and cobalt are used. Cermets are usually less than 20% metal by volume, however they can be metal matrix composites depending on their physical structure. Resistances (particularly potentiometers), capacitors, and other high-temperature electronic components are made with it.

Some cermets are being evaluated for spaceship shielding because they withstand high-velocity micrometeoroids and orbital debris better than aluminum and other metals. Solar hot water systems use vacuum tube coatings made from these materials.

Cermets are utilized in dental fillings and prosthesis. Also used in cutting tool machining. Cermets, a leading particle-strengthened composite, contain ceramic grains of borides, carbides, or oxides. A scattered grain 20–85% of the volume is refractory ductile metal matrix. Ceramic and metal elements bond by a tiny mutual solution.

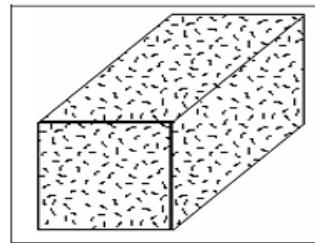
Metal oxide systems need bonding agents due to weak bonding. Cermet structures are typically made utilizing power metallurgy methods. Their characteristics vary according on the relative quantities and compositions of metal and ceramic elements. Cermets are also made by impregnating porous ceramic structures with metallic matrix binder. Cermet coatings can be power-based.

Power is sprayed through a gas flame to fuse a base material. Few cermets have commercial value, but many have been made on a modest scale.

Categories:

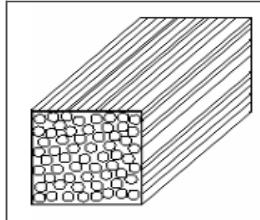
The classification is of Composite Materials based on Fiber length is as follow:

1. Fibers as the reinforcement (Fibrous Composites):
 - a. Random fiber (short fiber) reinforced composites



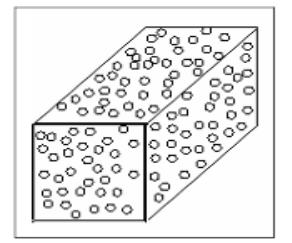
Short-fibre reinforced composites

- b. Continuous fiber (long fiber) reinforced composites



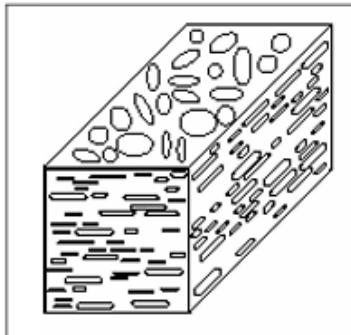
Long-fibre reinforced composites

2. Particles as the reinforcement (Particulate composites):



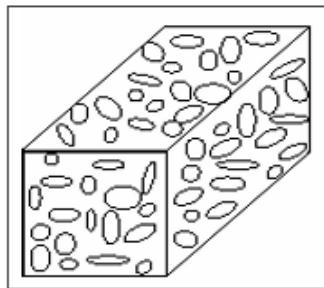
Particulate Composites

3. Flat flakes as the reinforcement (Flake composites):



Flake Composites

4. Fillers as the reinforcement (Filler composites):



Filler Composites

Role and Selection of Fibers:

When choosing reinforcements, it's important to think about how well they work with the core material, how stable they are at high temperatures, how dense they are, how hot they melt, and so on. How well discontinuously reinforced composites work depends on how strong they are and how dense the reinforcing stages are. It is important that the reinforcement and matrix material are compatible in terms of density, chemical and temperature stability, and how well they work together during the making of the material and in its final use. When thermal cycling is used, one important thing to look at is the thermal discord strain between the matrix and the support. The gap between the matrix's and reinforcement's coefficients of thermal expansion has to do with it. The crystal structure is changed by the production process and the reinforcement.

What kind of reinforcement is used also changes what part it plays in structural composites. The matrix is what holds most of the weight in powder and whisker-reinforced composites. The reinforcement's job is to make the composite stronger and stiffer by keeping the matrix from deforming through mechanical control. This restriction is usually based on the amount of the distance between particles to their diameter.

Matrix Materials:

Introduction:

The strength of composites is mostly attributable to fiber reinforcement, but matrix material is also crucial as it supports and helps bear loads. Additionally, it stabilizes composite materials. Resin matrix system binds fibers to structural components. When resin is overused, the part is resin rich. If there is insufficient resin, the part is called resin starved. A resin-rich part is more prone to breaking due to insufficient fiber support, while a resin-starved part is weaker due to voids and unsupported fibers.

Matrix Selection:

High-temperature metal matrix composites require thermodynamically stable dispersoids. An alloy dispersoid system minimizes solid state diffusivity, interfacial energy, and elemental solubility, minimizing coarsening and reactions. Aluminum and magnesium alloys are popular matrices for their low density and strong heat conductivity. Composites with low matrix alloying exhibit desirable ductility, toughness, and strength. Discontinuous reinforced metal matrix composites do not require minor alloying elements employed as grain refiners in wrought alloys. Avoid additives that cause coarse inter-metallic compounds during consolidation, limiting composite tensile ductility.

Advantages and Limitations of Composites:

Advantages of Composites:

Composite materials, used in aircraft, have these benefits:

- High fatigue and corrosion resistance.
- High 'strength or stiffness to weight'. Compared to standard metallic designs, weight savings are 25–45%.
- Greater reliability reduces inspections and structural repairs.
- Directional customization for design. The fibre pattern can be laid to efficiently support loads.

Fiber-to-fiber redundant load route.

- Dent resistance usually improves. Composite panels are less susceptible to damage than thin metal sheets.

Aerodynamic profiles are easier to smooth for drag reduction. One manufacturing operation can make complex double-curvature pieces with flat surfaces.

Composites improve torsional stiffness. This means high spinning speeds, fewer intermediate bearings, and structural support. So, part count and manufacturing & assembly costs decrease.

- High impact resistance.
- Rapid process cycles make thermoplastics ideal for high-volume commercial applications that sheet metals have historically served. Also, thermoplastics can be reformed.
- Like metals, thermoplastics stay forever.
- Composites are dimensionally stable with minimal thermal conductivity and expansion. Composite materials can be designed to meet several thermal expansion design criteria and reduce thermal stresses.
- Part integration simplifies manufacturing and assembly (joint/fastener reduction), lowering costs.
- Composites' corrosion resistance, durability, and marine weatherability save maintenance downtime.

No machining is needed for close tolerances.

- Composite components and structures are often constructed to shape rather than being machined like metals, saving material.
- Composites, notably Carbon-Carbon, are used in airplane brakes due to their lightweight and heat sink qualities.
- Better friction and wear.
- Tailoring Laminate material properties enables innovative aeroelastic flying structure design.

Limitations of Composites

The following are some downsides of advanced composites:

High raw material and production costs.

Composites are brittle and more quickly damaged than wrought metals.

Transverse characteristics may be poor.

Toughness is low due to weak matrix.

Disposal and reuse may be tricky.

Hard to attach.

Repair causes new issues because: Materials need refrigeration and limited shelf life.

- Hot curing often requires special tooling.
- Time-consuming curing.
- Difficulty in analysis.
- Matrix degrades in the environment.

However, good design and material choices can overcome many of these drawbacks. New technology offers a choice of reinforcing fibers and matrices that can be used to create composites with extraordinary qualities. As modern composites offer structural efficiency at lower weights than equivalent metallic constructions, they are becoming the principal materials for future use. Advanced fiber reinforced composites are used in floor beams, engine cowlings, flight control surfaces, landing gear doors, wing-to-body fairings, and vertical and horizontal stabilizer main torque boxes in aircraft.

Polymers:

Introduction:

Polymer comes from the Greek words poly (“many”) and meros (“parts” or “units”). Polymers are made of many monomers, tiny molecules. In polymerization, monomers are united end-to-end. Silicates and silicones can be used to produce polymers, but carbon compounds are the most prevalent. Naturally occurring polymers include protein, cellulose, resins, starch, shellac, and lignin. Their presence is prevalent in leather, fur, wool, cotton, silk, rubber, wood, and others. Synthetic polymers including polyethylene, polystyrene, nylon, Terylene, Dacron, and others fall under plastics, fibers, and elastomers. Their properties are better than natural ones. Thus, we focus on synthetic polymers, or plastics or resins.

Polymerization: Linking monomers to form macromolecules is called polymerization. This can be done through Addition Polymerization or Condensation Polymerization.

Plastics, fibers, and elastomers are polymers. Plastic products can be shaped in any desired shape since they acquire plasticity during manufacturing. Chemically, plastics are high polymers.

Engineering Plastics:

“Plastics” refers to compositions with high molecular compounds, fillers, plasticizers, stains, pigments, lubricants, and other components. Some plastics contain only resin. Plastics comes from the Greek term Plastikos, meaning molded. Plastics are easy to mold, manufacture, and join. Thus, engineering and home applications use plastics. Plastics come in rods, sheets, films, and tubes.

Types of Plastics:

(a) Thermosetting Plastics:

These harden permanently when heated and shaped with or without pressure. Heat softens the plastic, but adding heat or chemicals hardens it by "polymerization" and cannot be resoftened. Plastic thermosetting is phenol formaldehyde. Urea formaldehyde, epoxy, etc. Plastics used to make TV cabinets, phone receivers, camera bodies, and car parts are thermosetting.

(b) Thermoplastics:

Molding thermoplastics does not modify their chemical properties. While hot, they are soft till cooled. These polymers can be recycled by melting and remoulding. The most regularly used thermoplastics include polystyrene, polytene, PVC, nylon, and Teflon. Products created from thermoplastics include photographic films, insulating tapes, and hose pipes.

Properties of Plastics:

Plastics are widely used in engineering and other industries due to their diverse physical, chemical, and mechanical qualities and simplicity of production.

Plastics' low density, excellent mechanical strength, and anti-friction qualities make them a viable alternative to metals. Plastics can sometimes substitute ferrous metals with unique qualities. Their low melting temperatures and moldability are their key manufacturing advantages. Extracting machine parts is easy. There is typically only one production process needed to turn chemically generated plastic into a final product.

Product damping and finish are good. Plastics are used as dielectrics in radio and electrical engineering because to their superior thermal and electric insulation, replacing porcelain, ebonite, shellac, mica, and natural rubber. Plastics are valuable engineering materials in the automobile, tractor, shipbuilding, and other sectors due to their chemical stability against solvents and certain oxidizing agents, water resistance, gas and steam resistant qualities.

Comparison between Thermo plastics and Thermosetting Plastics:

Thermo Plastics	Thermosetting Plastics
<ol style="list-style-type: none">1. Heat does not soften them once hardened.2. Stronger and tougher.3. Plastics can be used at high temperatures.4. Monomeric or partly polymerized liquids or semisolids are given.5. These plastics make TV cabinets and car parts.	<ol style="list-style-type: none">1. Heat and cooling can repeatedly soften and harden them.2. They are weaker and softer.3. Heat softens thermo-plastics; thus, they cannot be used at higher temperatures.4. Granular material is frequently supplied.5. Plastics make insulating tapes and photo films.

Advantages of Plastics:

1. Lighter than metals.
2. Excellent finish.
3. Tight dimensions.
4. Rust- and moisture-resistant.
5. Easily molded.

Disadvantages of Plastics:

1. Weakness.
2. Low heat resistance.
3. Fade in sunlight.

Applications of Plastics:

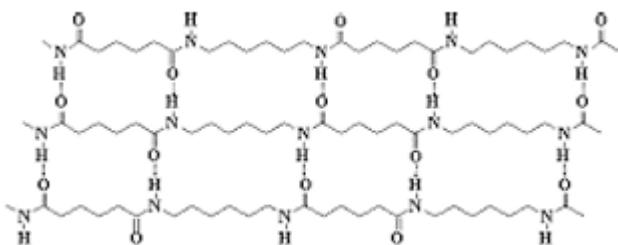
1. Film industry photo films.
2. Insulating tapes
3. Electrical components: plugs, switches, etc.
4. Radio, TV cabinets
5. Chairs and tubs

6. Telephone receivers
7. Camera parts
8. Gears, Bearings
9. Toys, bottles, buckets, etc.
10. Hosepipes
11. Automobile parts

Polymers of Commercial Importance:

Nylon:

Nylon is a synthetic polymer created in labs and by companies for commercial use. The textile and fabric industry uses it extensively. Nylon belongs to the linear polyamide family. Both nylon 6 and nylon 6,6 are popular. Nylon 6,6—a popular fiber—is manufactured from adipic acid and hexamethylene diamine. A tight molecular structure makes them abrasion-resistant. Hydrogen bonding links monomers. Nylon is valuable due to its strength, sheen, elasticity, and oil and chemical resistance.

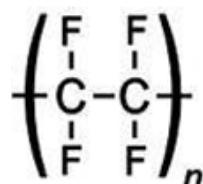


Nylon Fiber:

Nylon fiber is commonly used in clothing such as shirts, underwear, raincoats, and lingeries. Nylon is used in manufacturing conveyor belts, nets, ropes, parachutes, and tents.

Polytetrafluoroethylene:

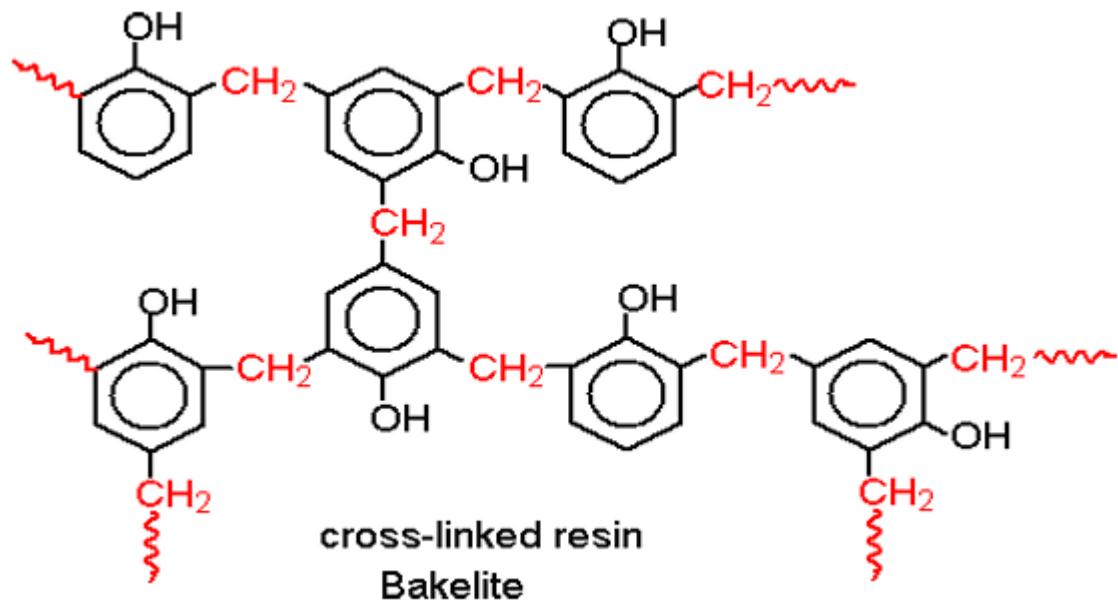
PTFE is a synthetic tetrafluoroethylene fluoropolymer. Its carbon and fluorine content makes it heavy. Teflon, used in non-stick pans, is the most famous PTFE-based compound.



Structure of PTFE

Bakelite:

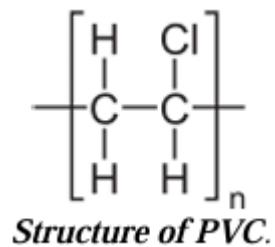
Bakelite is one of the oldest man-made polymers. This thermosetting polymer is strong and holds its shape after molding. It was one of the first lab-made polymers/plastics. The polymer is created by condensing formaldehyde and phenol. Its chemical formula is $(C_6H_6O \cdot CH_2O)_n$. Bakelite is most often used to make electrical switches because it resists heat and chemicals and has limited electrical conductivity. Many utensil handles are made of Bakelite. It is one of the most widely used polymers for producing parts and components. This polymer is also used in pipe stems.



Polyvinyl Chloride (PVC)

Discussion of commercial polymers must include PVC. One of the most frequently used polymers on Earth. PVC is widely utilized in building, transport, packaging, electrical, and other industries due to its versatility.

PVC is long-lasting and durable. It's thermoplastic. Polymerization of vinyl chloride monomer creates it. It can be rigid or flexible, white, black, or a variety of colors, and is exceedingly sturdy and long-lasting. Commercial items using polymer PV Care include window frames, drainage pipe, medical equipment, cable, and wire insulation. PVC is used to make credit cards and vinyl records. Recently, PVC has entered the textile sector.



Structure of PVC.

Elastomers:

Elastomers (rubbers) are elastic polymers. These materials are amorphous and minimally cross-linked, having a glass transition temperature much below ambient temperature. They form a big macroscopic molecule. Polymer chains have weak intermolecular forces. Crosslinks prevent irreversible flow, but chains remain flexible above the glass transition, causing significant deformation with modest forces. Unlike other polymers, elastomers have a low Young's modulus and significant elongation at break. Elastomers and rubber are commonly used interchangeably, however vulcanized rubbers are better. Elastomeric pieces are made by injection, transfer, or compression molding. The molding method selection depends on criteria such as part shape, size, tolerance, quantity, elastomer type, and raw material cost. The right elastomeric product for the

application depends on many factors, including mechanical and physical service requirements, chemical exposure, operating temperature, service life, part manufacturability, and raw material and manufacturing cost, as with most materials.

Liquid Crystal Polymers:

Liquid Crystal Polymers (LCPs) are thermoplastics with unusual characteristics. They are highly heat-, electrical-, and chemical-resistant in severe settings. LCPs are highly anisotropic in solid and liquid crystal phases, unlike ABS or nylon. This causes one direction to have higher strength, stiffness, and thermal expansion. Other LCPs are possible, but PET copolyester, copolyamide, and polyester-amide are the most prevalent. Unlike ABS and nylon, LCPs have a highly crystalline molecular chain. The semi stiff, nearly linear, stacking orientation of molecules keeps them highly organized even in liquid crystal phase (Fig. 1 (a)). In contrast, ABS and nylon contain interweaving molecular chains (Fig. 1(b)). Anisotropic tendencies in LCPs' layered molecular architecture give them numerous intriguing features. The main bonds of the molecule cause anisotropy by increasing its attractive force. Less attractive secondary bonds make the molecules more prone to separation. Applied transversely to the molecular orientation, secondary bonds receive most of the load, making separation easier. The main bonds of molecules are more highly loaded in the longitudinal direction, making separation harder.

LCPs are typically injection molded, but other processing methods can be used to accommodate the material. LCP melt temperatures range from 280-330°C, while mold temperatures should be 70-130°C. Melt molecular chains are substantially aligned along resin flow. To produce resin flow, which determines molecule orientation and anisotropic characteristics, mold gating positions must be carefully considered. This affects the final part because anisotropic qualities including tensile strength, thermal expansion, and elastic modulus can be three times stronger in the longitudinal direction than in the transverse direction. High melt flow and moderate thermal expansion in molecular orientation provide LCPs

exceptional cycle repeatability. This makes molding thin-walled pieces easy without warping. LCPs resist heat, fire, weather, and UV radiation and provide good electrical insulation. LCPs resist hydrolysis, weak acids and bases, alcohols, aromates, chlorinated hydrocarbons, esters, and ketones at many temperatures. They also have excellent mechanical qualities, including high strength, modulus of elasticity, and toughness. Table 1 compares LCP thermal expansion to two other common polymers and shows the difference between longitudinal and transverse thermal expansion. Table 1 gives the thermal expansion coefficient in meters per degree Celsius per meter.

Conductive Polymers:

Applying a voltage causes charges in a substance to move orderly and generate an electric current. Positive charges follow the electric field, while negative charges go in the opposite direction. The flux of electrons, known as electric conduction, creates a current in most materials. These materials have conjugated chains, or alternating single and double bonds between atoms. Conjugated bonds simplify the doping procedure for conductive polymers. Polymeric chain flaws and deformations result from this process. Polarons—electrons-deformation pairs or electron-phonon cloud pairs—control polymer conductivity. The conductivity mechanism also involves quasi-particles like bipolarons and solitons. Dopants determine soliton, bipolaron, or polaron formation. The meaning and physics behind them are beyond the scope of this topic. Charges from doping in conductive polymers contribute to their high conductivity. Constant movement of double bonds stabilizes charge in neighboring atoms, leading to charge mobility and conductivity. Resonance describes delocalized electrons in a molecule by moving double bonds (see [d] of "Links" Section). A π bond electron shared by three or more atoms is called a delocalized electron. Polaron production changes the band structure of conductive polymers. It forms polaronic conduction bands, permitted bands in the band gap, reducing band gap energy and allowing the polymer to conduct (see figure).

High Performance Fibers:

High-performance fibres are new. These fibers differ from normal ones and can meet certain technical requirements due to their unique features. High-performance fibers like Kevlar, Nomex, carbon, and glass offer superior tensile strength, heat and flame resistance, and chemical resistance compared to traditional materials like steel. Metal car bodies have been replaced with fiber composites. The aerodynamic design and weight reduction have improved. Sportswear uses textured nylon fiber for strength and breathability. Additionally, high-performance fibers are utilized in aerospace, metals, and medical industries. These fibers can be customized to offer versatile properties such as dyeability, adhesion, absorbance, conductivity, flame retardance, and a variety of special surface characteristics.

Fibers with high performance require special qualities such as

1. Exceptional strength and modulus.
2. Stiffness.
3. Resistance to heat.
4. Chemical-resistant.

Examples of fibers include carbon, glass, aramid, kevlar, nomex, PBO, and chlorinated fibers like PVDV.

List of High Performance Fibers:

1. Glass Fiber.
2. Carbon Fiber.

3. Aramid Fiber.

4. Spandex Fiber.

Glass Fiber:

One of the oldest and most popular high-performance fibers is glass. It has been produced since the 1930s. Early versions were strong yet rigid, making them unsuitable for textile uses. SiO₂ is the building block of glass fibers. Polymer (SiO₂)_n is its pure form. Despite having no melting point, it softens about 1200 °C.

Modern glass fibers have many characteristics and are used in numerous applications.

- Mat-making material.
- Thermal insulation fabric
- Sound insulation fabric • Heat and corrosion resistant fabric.



Carbon Fiber:

One of the strongest and lightest materials available, carbon fiber is commonly employed in high-performance applications. Carbon fiber, one-third the weight of steel and roughly five times stronger, is utilized in aerospace, aviation, civil engineering, military, vehicle and automobile, and sports applications. Carbon fiber, also known as graphite fiber, is a material made of carbon atoms and has filaments of 5-10 µm in diameter. Carbon fibers vary in elasticity, electrical conductivity, heat, and chemical resistance. Carbon fibers are

produced by extruding pre-made materials like rayon, PAN, and pitch into filaments, then carbonizing them because carbon cannot be easily formed into fibers.

Carbon fiber applications include

1. aerospace.
2. Sporting goods.
3. Wind turbine blades.
4. Auto.

Biomedical Applications of Polymers:

Containers:

Many polymer devices are utilized to package medications and devices. PVC with DEHP is commonly used in extracorporeal perfusion tubes for drug delivery, blood leading tubes for dialysis, and oxygenation. Also, polymer bags are used to keep blood donations and merchandise. Since the plasticizer is lipophilic, it moves from the polymer surface to red blood cell lipids and membranes. Alternative polymers like polyolefins and polyethylene and polyurethane tubings are employed for platelet storage. The peristaltic pump tubing is usually silicone.

Vascular Catheters:

Mechanical flexibility and non-collapsing qualities are needed. Long-lasting central venous catheters typically contain antimicrobial fittings that prevent bacterial biofilm growth and adhesion. Plasticized PVC was an early catheter polymer. Today, plasticizers make it unpopular and utilized only for short-term peripheral venous catheters. In catheters, thermoplastic polyurethanes are used since they don't need plasticizers.

Urinary Catheters and Ureteral Stents:

For patient comfort, catheters and stents must be strong and gentle. The surface must have low-friction. Generally, coating technologies are used. Silicone is the least encrustation-prone biocompatible material, but its poor mechanical rigidity and high friction make application challenging. Polyurethane and PMMA/pharma co-polymers have been optimized to have better mechanical characteristics than silicone. Stents are coated with GAGs, heparin, phosphoryl choline, PVP, or hydrogels to minimize bacterial colonization, encrustation, and improve patient comfort.