Alloys and thermal equilibrium diagrams

Introduction to Alloys:

An alloy is a mixture of two or more elements, where at least one is a metal. Alloys are designed to have specific properties that pure metals cannot offer, such as enhanced strength, hardness, corrosion resistance, or better workability. Alloys are commonly used in various engineering applications, including aerospace, automotive, and construction.
There are two main types of alloys:
1. Ferrous alloys: Contain iron as the primary element (e.g., steel, cast iron).
2. Non-ferrous alloys: Do not contain iron as the main element (e.g., aluminum alloys, copper alloys).

Types of Alloys:

1. Solid Solutions:
   - One element (solute) dissolves into another (solvent), forming a single-phase mixture. The solute atoms are distributed throughout the solvent.
   - Example: Brass (copper and zinc) or Aluminum alloys.

2. Intermetallic Compounds:
   - Formed when two metals combine in a specific ratio to form a distinct phase with a definite stoichiometric composition.(The term stoichiometric composition refers to the specific ratio of elements or compounds in a material, particularly in alloys or chemical compounds)
   - Example: Titanium aluminide (TiAl).

3. Composite Alloys:
   - A mixture of multiple phases, including solid solutions and intermetallic compounds.
   - Example: Steel with carbides (e.g., tool steels).

Thermal Equilibrium Diagrams (Phase Diagrams):

A thermal equilibrium diagram (also known as a phase diagram) is a graphical representation of the phases and phase changes that occur in a metal or alloy as a function of temperature and composition. These diagrams provide valuable insights into the material's behavior during heating and cooling, aiding engineers in selecting the best processing conditions for a given alloy.

-In metallurgy, a phase refers to a distinct and homogeneous region of a material that has uniform physical and chemical properties throughout. Phases are typically separated by phase boundaries, where the material transitions from one phase to another. A phase can be a solid, liquid, or gas, and in the context of metallurgy, it usually refers to the arrangement of atoms or molecules and the way these structures interact within the material.

Common Types of Phase Diagrams:

1. Binary Phase Diagrams:
   - Represent systems with two components (e.g., two metals or a metal and a non-metal).
   - They show how the phases of the mixture change with temperature and composition.
   - Isomorphous and eutectic systems are the two main types.

An isomorphous system refers to a binary alloy system where the two components can mix in all proportions and form a single-phase solid solution over the entire range of compositions. In other words, both elements are mutually soluble in each other in the solid state at all compositions and temperatures.

A eutectic system is a binary system where one component (or phase) react to form a mixture of two solid phases at a specific composition and temperature. This reaction occurs at a particular temperature known as the eutectic point. At this point, the liquid phase cools and solidifies into a fine mixture of two solid phases simultaneously. The eutectic composition and temperature are unique for each system and are important in applications like casting and alloy design.

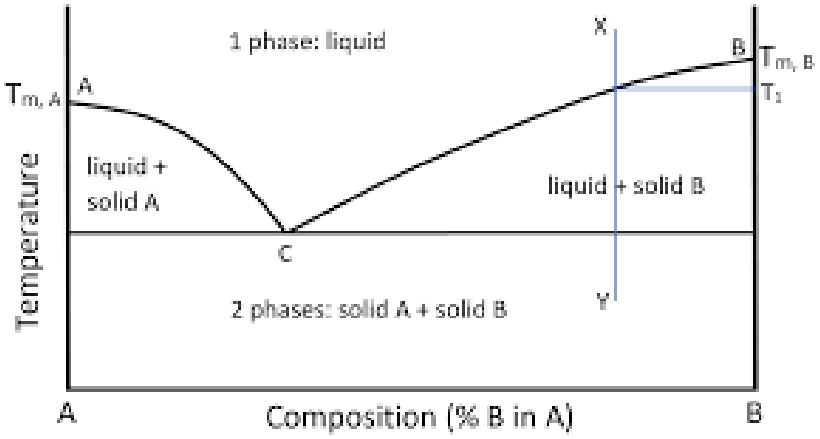
2. Ternary and Higher-Order Diagrams:
   - Represent systems with three or more components.
   - They are more complex and show the interaction between multiple components.

Key Features of a Binary Phase Diagram:

1. Temperature-Composition Relationships:
   - The x-axis represents the composition of the alloy, typically in terms of percentage of each element.
   - The y-axis represents the temperature.
2. Phases:
   - Different regions in the diagram represent different phases (solid, liquid, or mixed phases).
   - These phases may include solid solution phases, intermetallic compounds, and liquid

phases.

3. Phase Boundaries (Lines):
   - The lines or curves in the diagram represent the temperature-composition conditions under which phase transformations occur.
   - These boundaries are usually labeled with terms such as liquidus and solidus.
4. Solidus Line:
   - The line that defines the temperature below which the material is completely solid.
5. Liquidus Line:
   - The line that defines the temperature above which the material is completely liquid.
6. Eutectic Point:
   - The eutectic point represents the composition and temperature where a liquid phase transforms into two solid phases simultaneously. See fig. (1)



C is the eutectic point Fig.(1)

Types of Binary Phase Diagrams:

1. Isomorphous (Single-Phase Solid Solution) Systems:
   - In an isomorphous phase diagram, both components (e.g., copper and nickel) can form a single solid solution at all compositions.
   - Example: Copper-Nickel (Cu-Ni) system. See fig. (2)
   - The diagram shows a single solid solution phase and no distinct compounds.

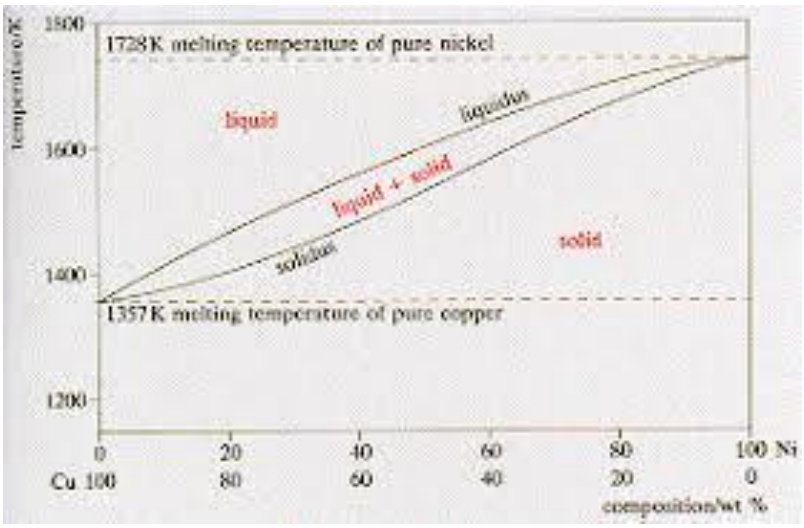


Fig. (2)

2. Eutectic Systems:

- A eutectic system involves a mixture of two phases that melts or solidifies at a single temperature, called the eutectic temperature.
- At the eutectic composition and temperature, the alloy undergoes a solidification process that results in the simultaneous formation of two distinct solid phases.
- Example: Lead-Tin (Pb-Sn) system.See fig. (3)
- In this diagram, when cooling from the liquid phase, the eutectic composition (at about 61.9% Sn and 38.1% Pb) solidifies into a fine mixture of two solid phases.

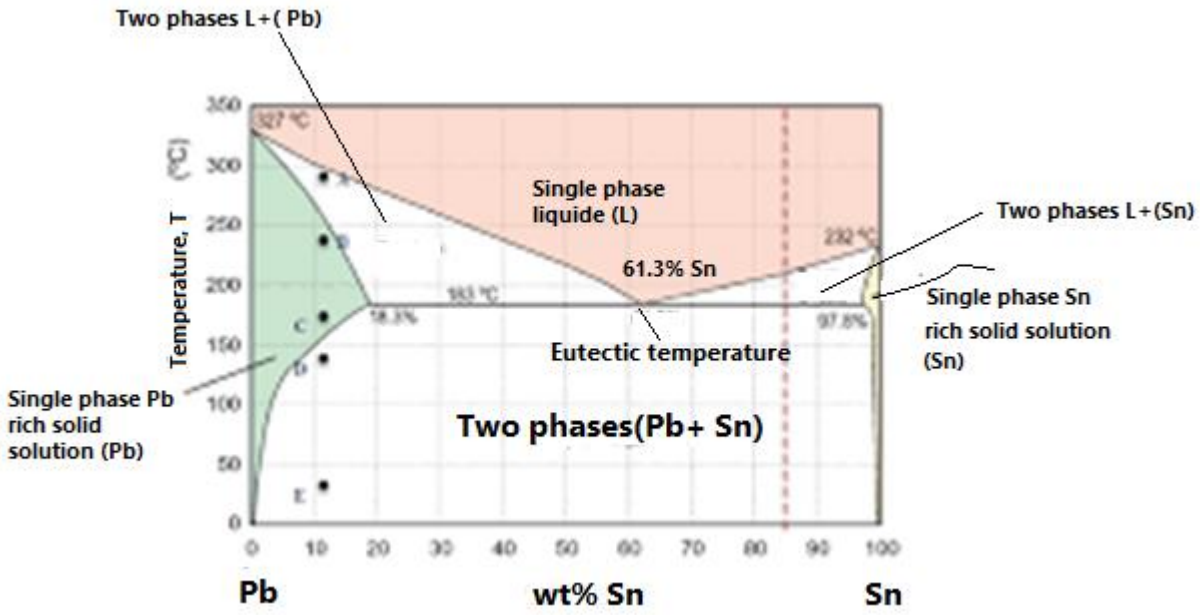


Fig.(3)

3. Eutectoid Systems:
   - Similar to eutectic systems, but instead of forming two solid phases from a liquid, a eutectoid system involves the transformation of one solid phase into two other solid phases.
   - Example: Steel (Fe-C) system. See Fig.(4)
   - In steel, the eutectoid composition (0.8% carbon) transforms from a single phase (austenite) to two distinct phases (ferrite and cementite) at the eutectoid temperature (around 727°C).

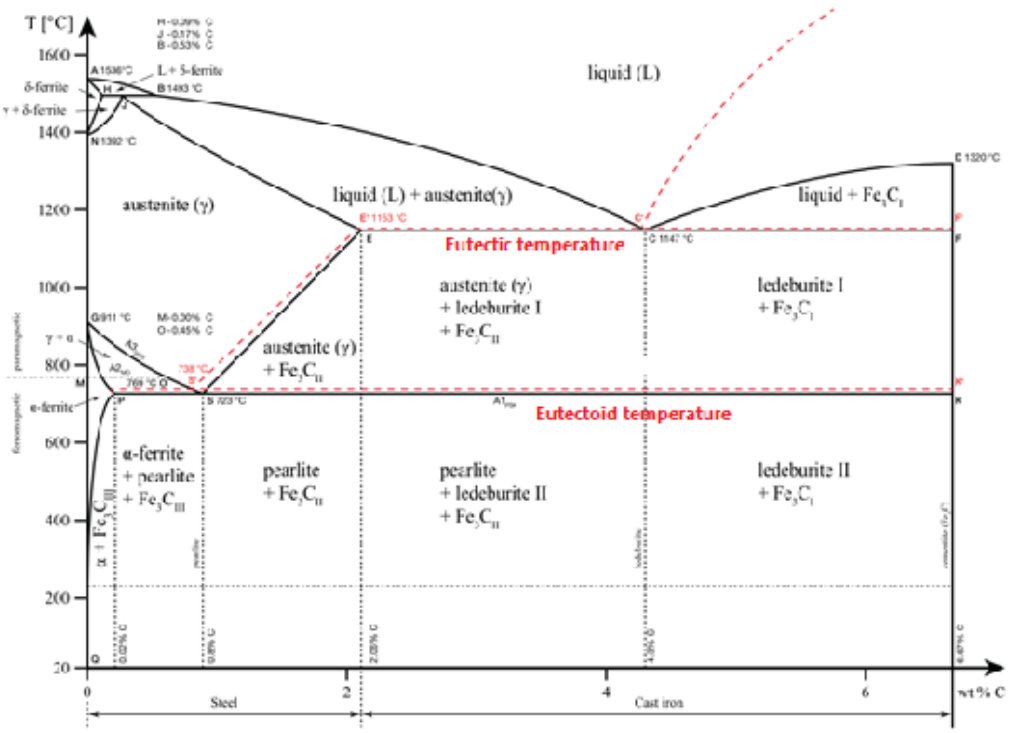


Fig. (4)

4. Peritectic Systems:
   - A peritectic reaction occurs when a solid and liquid phase react at a specific temperature to form a second solid phase.
   - Example: Iron-Carbon (Fe-C) system. See Fig (4) and Fig. (5)
   - This system is important in understanding the phase transformations that occur in steels and cast iron.

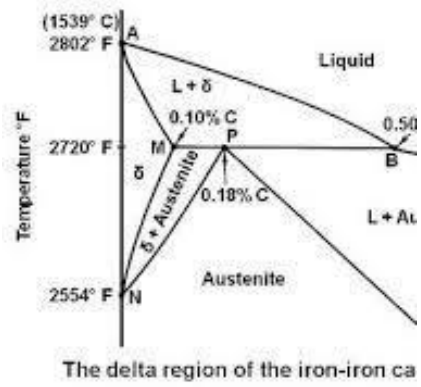


Fig. (5)

Phase Diagram of the Iron-Carbon (Fe-C) System:

The Fe-C phase diagram (Fig. 4) is one of the most important diagrams in metallurgy, as it describes the behavior of steel and cast iron at different temperatures and carbon compositions. The main phases in the Fe-C system include:

1. Ferrite (α-iron): A body-centered cubic (BCC) phase of iron with low carbon solubility.
2. Austenite (γ-iron): A face-centered cubic (FCC) phase of iron that can dissolve more carbon than ferrite.
3. Cementite (Fe_3C): An iron carbide phase with a fixed composition (6.7% carbon by weight).
4. Liquid: The molten phase of the alloy.

Key Regions and Lines:
- Solidus Line: Defines the temperature below which the alloy is entirely solid.
- Liquidus Line: Defines the temperature above which the alloy is entirely liquid.
- Eutectoid Point: At 0.8% carbon, where austenite transforms into pearlite (a mixture of ferrite and cementite) at 727°C.

Titanium Phase Diagram

The Titanium Phase Equilibrium Diagram is an important tool for understanding the different phases and phase transformations that occur in titanium and its alloys, which is crucial for designing and processing titanium-based materials, especially in biomedical and aerospace applications. Titanium alloy, such as Ti-6Al-4V, is commonly used in biomedical applications due to its excellent biocompatibility, strength, and corrosion resistance.

Key Phases in the Titanium Phase Diagram:

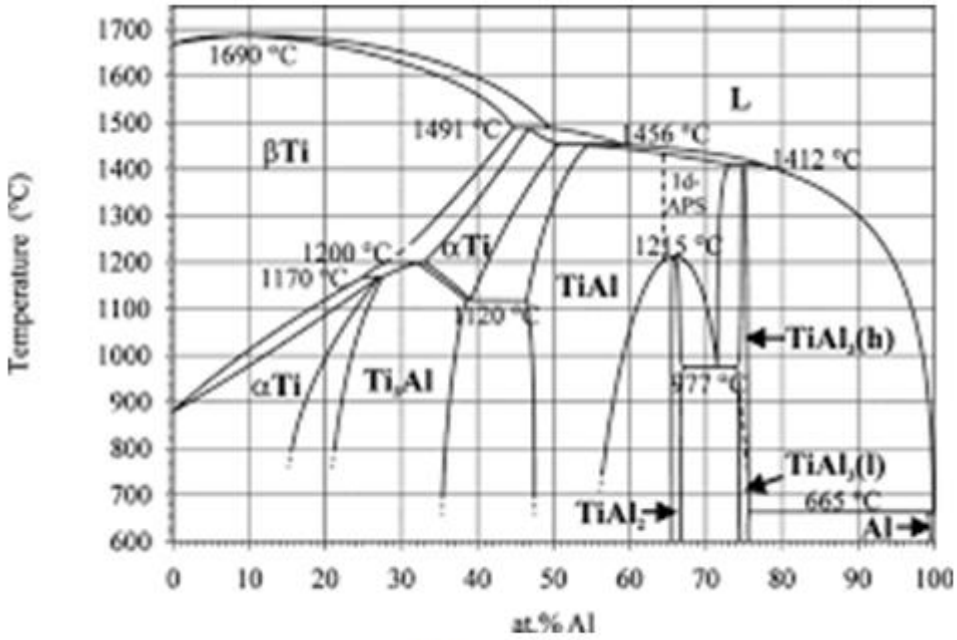
1. Alpha (α) Phase:
- The α-phase is a hexagonal close-packed (HCP) structure of titanium. It is stable at low temperatures and is known for its good strength and excellent corrosion resistance.
- The α-phase is the primary phase at room temperature and up to about 882°C.
- It is characterized by its relatively low ductility but good strength.

2. Beta (β) Phase:
- The β-phase has a body-centered cubic (BCC) structure and is more ductile and stronger than the α-phase.
- It is stable at higher temperatures, above 882°C.
- The β-phase is typically stabilized by elements such as vanadium (V), molybdenum (Mo), niobium (Nb), and iron (Fe), which increase the phase's temperature stability and strength.
- The β-phase can be transformed into the α-phase upon cooling, and the amount of β-phase depends on the composition and temperature.

3. Alpha-Beta (α+β) Phase:
- Between the temperature ranges of 882°C to around 1000°C, titanium alloys exist in a mixture of the α-phase and the β-phase, which is the α+β phase.
- The α+β phase is important for many titanium alloys because it allows for a balance between strength, ductility, and toughness.

Ti-Al (Titanium-Aluminum) Phase Diagram

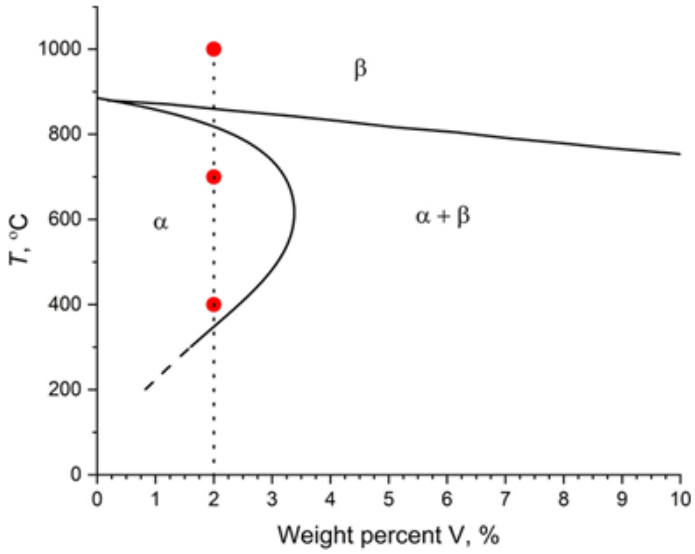
- The Ti-Al phase diagram shows the interaction between titanium (Ti) and aluminum (Al). Aluminum is the most common alloying element used to stabilize the α-phase in titanium.
  - Key Features:
    - The α-phase is stable at low temperatures.
    - The β-phase is stabilized at high temperatures by aluminum.
    - The diagram shows a eutectoid point where α+β forms.



Ti- Al phase digram

Ti-V (Titanium-Vanadium) Phase Diagram

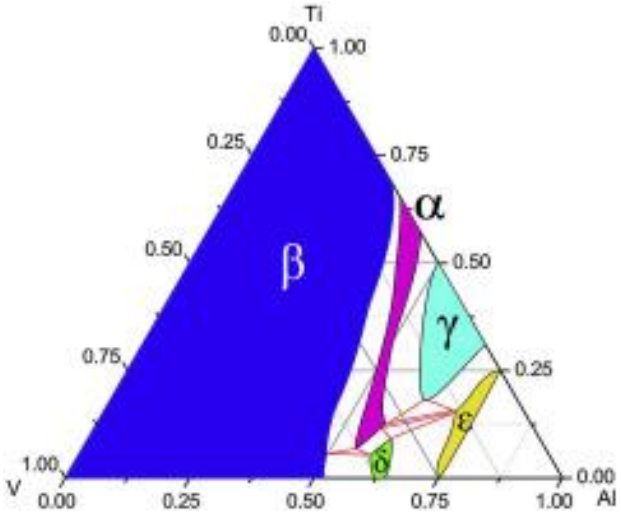
- The Ti-V phase diagram is important for understanding the properties of β-stabilized titanium alloys, such as Ti-6Al-4V, which has vanadium as a stabilizing element for the β-phase.
- Key Features:
- Vanadium stabilizes the β-phase and allows the alloy to remain in the β-phase at room temperature



Ti- V Phase diagram

Phase equilibria of Ti –Al- V system at1300 ºC

The transition from α+β to β occurs at temperatures above 882°C.



Applications of Phase Diagrams:

1. Alloy Design:
   - Phase diagrams help engineers design alloys with the desired properties by understanding how different compositions will affect the material's behavior during heating and cooling.

2. Heat Treatment:
 - Understanding phase transformations allows metallurgists to use heat treatments (e.g., quenching, annealing, and tempering) to control the microstructure and properties of metals.

3. Casting and Solidification:
   - Phase diagrams are used to predict how an alloy will solidify during casting, helping in designing processes for optimal casting.
4. Corrosion Resistance:
   - Phase diagrams can predict the formation of phases that might affect the corrosion behavior of alloys, which is crucial in selecting materials for marine environments, chemical processing, and aerospace applications.

Conclusion:

Alloys and their thermal equilibrium diagrams are essential tools for understanding the material behavior under various conditions. These diagrams help engineers and material scientists predict phase transitions, understand microstructure formation, and develop alloys with optimized mechanical properties. The study of phase diagrams is critical in alloy design, heat treatment, and improving the performance of materials in engineering applications.