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**Definition of alloys, binary alloys, phase diagrams (equilibrium thermal diagrams), eutectic; solid solution**

1. **Definition of alloys**

An alloy is homogeneous substance formed by mixing two or more elements , at least one of them being a metal. For example, in a copper–zinc brass alloy, the components are Cu and Zn. Iron–carbon system , system refer to series of possible alloys consisting of the same components but without regard to alloy composition. Alloys are of three types:

1. Alloys formed by two or more metals, example: brass ( Cu-Zn )
2. Alloys formed between a metal and a non-metal Steel is an alloy made of a metal and a non-metal. The components of steel are iron (metal) and carbon (non-metal).
3. Alloys ( Amalgam) formed between mercury and another metal, example: Zinc amalgam.
4. **Importance of making alloys**

The properties of some materials are influenced by the presence of imperfections, and The physical properties of alloys are different from that of constituent elements .Consequently, it is important to have a knowledge about the roles that they play in affecting the behavior of materials. The reasons behind making alloys are:

1. Pure metals are very soft and weak and therefore cannot be used for making strong articles . Therefore alloying them increases their strength .
2. Two or more metal can be mixed in different proportions to produce alloys of desirable character (Hardness, electrical conductivity , colour , casting property , resist the corrosion, etc.) for definite applications .
3. The use of alloys instead of expensive pure metals promotes economy in the manufacture and use of components .
4. **Types of alloys**

Alloys are classified in a number of ways:

1. Based on the principal metal in the alloy, examples: copper(Cu) alloys , lead(Pb) alloys , iron (Fe) alloys , etc., copper alloy has copper as major constituent (ex.: Brass, Bronze**)**
2. Based on Phases :
* Single phase alloys consist of a uniform face (Brass( 30% Zn + 70 % Cu )).
* Double phase alloys consist of two different phases (muntz metal ( 60% Cu + 40% Zn )
1. Based on iron content : Ferrous alloys contain Fe as constituent(example: Stainless steel (Fe +Cr) ), while Non-ferrous alloys do not contain iron, example: Solder ( Pb + Sn ) is a non-ferrous alloy .



Figure 1 (Cu-Zn) alloy phase diagram

1. **Solid Solubility**

Certain rules govern the limits of solubility known as Hume Rothery rules. Unlimited solubility occur if they satisfy the following four criteria.

 1. The atomic diameters of the two metals should be within ±15% known as (size factor).

 2. The two metals must have identical crystal structure.

 3. The metals must have the same valance.

 4. The electro‐negativity difference between two atoms should not be greater than 0.4e.u.

1. **Binary alloys**

There are several binary alloys belonging to either simple isomorphous or simple eutectics.

**5.1 Binary isomorphous system**

Copper - Nickel (Cu-Ni) system (figure 2) is binary isomorphous system, satisfy Hume Rothery rules. Therefore the two have unlimited solubility in the liquid state.



Figure 2 (Cu-Ni) system

The strength of metals increases with increasing alloy content. This is known as solid solution strengthening. The figure also displays the effect of composition on the UTS (Ultimate Tensile Strength). It attains the highest value at an intermediate composition. The increase in strength is accompanied by loss of ductility. It is commonly used in heat exchangers, condenser tubes. The constantan wire in thermocouples is made of Cu‐46Ni.

**5.2 Binary simple eutectic system**

One of the examples of a binary eutectic is that Aluminum(Al)-silicon(Si) alloy, Aluminum is a soft and ductile metal, it has FCC structure. Si on the other hand is hard and brittle. Its crystal structure is diamond cubic. Therefore the two have very limited solubility, and form a simple binary eutectic system. Figure 3 shows a sketch of the Al‐Si phase diagram.

The eutectic composition is around 11.8% Si. Si expand on solidification. Therefore, hyper eutectic Al‐Si alloys having around 12% Si does not shrink on solidification, and easy to cast. Al–Si eutectic consists of coarse Si plates in Al matrix. Such a structure is brittle, modified by adding Na or NaCl or by rapid solidification.



Figure 3 Al-Si alloy

1. **Phase diagrams (equilibrium thermal diagrams)**

The understanding of phase diagrams for alloy systems is extremely important because there is a strong correlation between microstructure and mechanical properties, and the development of microstructure of an alloy is related to the characteristics of its phase diagram. In addition, phase diagrams provide valuable information about melting, casting, crystallization, and other phenomena. The term components refer to pure metals and/or compounds of which an alloy is composed. For example, in a copper–zinc brass, the components are Cu and Zn. Other terms called solute and solvent. Other example is iron–carbon phase diagram.

**6.1 Phases**

A **phase** defined as **homogeneous portion of system that has uniform physical and chemical characteristics**. Every pure material is considered to be a phase; so also is every solid, liquid, and gaseous solution. Also there are two phases, each has different physical properties when present in a system. when a substance can exist in two or more polymorphic forms (e.g., having both FCC and BCC structures), each of these structures is a separate phase because variation of physical characteristics. Most metallic alloys , ceramic, polymeric, and composite systems are heterogeneous. Typically, the phases interact in such a way that the property combination of the multiphase system is different from, and more desirable than, either of the individual phases.

**6.2 Microstructure**

The physical and mechanical behavior of material depend on the microstructure, microstructure is subject to direct microscopic observation using optical or electron microscopes (figure 4) ; In metal alloys, microstructure is characterized by the number of phases present, their proportions, and the manner in which they are distributed or arranged. The microstructure of an alloy depends on the alloying elements, their concentrations, and heat treatment of the alloy. The specimen must be prepare for microscopic examination, appropriate polishing and etching, the different phases may be distinguished by their appearance. For example, for a two-phase alloy, one phase may appear light and the other phase dark. When only a single phase or solid solution is present, the texture is uniform, except for grain boundaries that may be revealed.

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Figure 4 (a) Section of a grain boundary and its surface groove; the light reflection characteristics in the vicinity of the groove. (b) Photomicrograph of the surface of after polished and etched specimen of iron–chromium alloy in which the grain boundaries appear dark.

**6.4 One-Component Phase Diagrams**

One-component system, in which the phase diagram for pure substance; this means that pressure and temperature are the variables. This one-component phase diagram also called a pressure–temperature [or P–T] diagram).

**6.5 Binary Phase Diagrams**

Another type in which temperature and composition are variable and pressure is constant(1 atm.) , contain two components. Represent the relationships between temperature , compositions and quantities of phases at equilibrium, which influence on the microstructure. Many microstructures develop from phase transformations due to altered of temperature, transition from one phase to another. The easiest type of binary phase diagram is copper–nickel system (Figure 5). Temperature – composition(%nickel) curve of the alloy, the composition ranges from 0 wt% Ni (100 wt% Cu) to 100 wt% Ni (0 wt% Cu). Three different phase regions appear on the diagram: alpha (α) field, liquid (L), and two-phase (α + L).



Figure 5 The copper–nickel phase diagram.

The liquid L is a homogeneous liquid solution composed of both copper and nickel. The α phase is a substitutional solid solution consisting of both Cu and Ni atoms and has FCC crystal structure. At temperatures below about 1080°C, copper and nickel are mutually soluble in each other in the solid state for all compositions(Cu and Ni have same crystal structure (FCC), nearly identical atomic radii and electro-negativities, and similar valences). The copper–nickel system is termed isomorphous because of complete liquid and solid solubility of the two components.

The line separating the L and α + L phase fields is termed liquidus line, the liquid phase is present at all temperatures and compositions above this line. The solidus line is located between the α and α + L regions, below which only the solid α phase exists.

The melting temperatures of pure copper and nickel are 1085°C and 1455°C, respectively. Heating pure copper ( moving vertically up). Copper remains solid until its melting temperature is reached. The solid-to-liquid transformation takes place at the melting temperature.

 For any composition other than pure components, melting phenomenon occurs over the range of temperatures between the solidus and liquidus lines; both solid α and liquid phases are in equilibrium within this temperature range. For example, upon heating of an alloy of composition (50 wt% Ni–50 wt% Cu), melting begins at approximately 1280oC (2340oF); the amount of liquid phase continuously increases with temperature until about 1320oC (2410oF), at which point the alloy is completely liquid.

**6.6 Determination of Phase Compositions**

The first step in the determination of phase compositions (in terms of the concentrations of the components) is to locate the temperature–composition point on the phase diagram. Different methods are used for single- and two-phase regions. For example, consider the 60 wt% Ni–40 wt% Cu alloy at 1100°C (point A, Figure 6 ). At this composition and temperature, only the α phase is present, having a composition of 60 wt% Ni–40 wt% Cu. For an alloy having composition and temperature located in a two-phase region, the situation is more complicated. In all two-phase regions, to compute the equilibrium concentrations of the two phases, the following procedure is used:

1. A line is constructed across the two-phase region at the temperature of the alloy.

2. The intersections of the line and the phase boundaries.

3. Perpendiculars are dropped from these intersections to the horizontal composition axis, from which the composition of each of the respective phases is read.

For example, consider again the 35 wt% Ni–65 wt% Cu alloy at 1250°C, located at point B lying within the α + L region. Thus, the problem is to determine the composition (in wt% Ni and Cu) for both the α and liquid phases. The line is constructed across the α + L phase region, the perpendicular from the intersection of the line with the liquidus boundary meets the composition axis at 31.5 wt% Ni–68.5 wt% Cu, which is the composition of the liquid phase, CL. At solidus–line intersection, we find a composition for the α solid-solution phase, Cα, of 42.5 wt% Ni–57.5 wt% Cu.



Figure 6 copper–nickel phase diagram

**6.7 Determination of Phase Amounts**

The amounts of phases have been determined by using the lever rule, which is applied as follows:

1. The line is constructed across the two-phase region at the temperature of the alloy.

2. The overall alloy composition is located on the line.

3. The fraction of one phase is computed by taking the length of line from the specified point to the phase boundary for the other phase and dividing by the total line length.

4. The fraction of the other phase is determined in the same manner.

5. If phase percentages are desired, each phase fraction is multiplied by 100.

Also can be used the mass (or weight) of a specific phase divided by the total alloy mass (or weight). The mass of each phase is computed from the product of each phase fraction and the total alloy mass.

The example shown in Figure 6 , in which at 1250oC both α and liquid phases are present for 35 wt% Ni–65 wt% Cu alloy. The problem is to compute the fraction of each of α and liquid phases. Let the overall alloy composition be located along the line and denoted as C0, and let the mass fractions be represented by WL and Wα for the respective phases. From the lever rule, WL may be computed according to



Composition need be specified in terms of only one of the constituents for a binary alloy; for the preceding computation, weight percent nickel is used (i.e., C0 = 35 wt% Ni, C𝛼 = 42.5 wt% Ni, and CL = 31.5 wt% Ni), and



Similarly, for the α phase:



Examples:

1. A copper–nickel alloy of composition 70 wt% Ni–30 wt% Cu is

slowly heated from a temperature of 1300°C (2370°F).

(a) At what temperature does the first liquid phase form?

(b) What is the composition of this liquid phase?

(c) At what temperature does complete melting of the alloy occur?

(d) What is the composition of the last solid remaining prior to complete melting?

1. Is it possible to have Cu–Ni alloy that, at equilibrium, consists of an 𝛼 phase of composition 37 wt% Ni–63 wt% Cu and liquid phase of composition 20 wt% Ni–80 wt% Cu?

If so, what will be approximate temperature of the alloy? If this is not possible, explain why.

1. Derive the lever rule.



**DEVELOPMENT OF MICROSTRUCTURE IN ISOMORPHOUS ALLOYS**

At this point it is instructive to examine the development of microstructure that occurs for isomorphous alloys during solidification (figure 7 ).



**Figure 7** Schematic representation of the development of microstructure during

the equilibrium solidification of a 35 wt% Ni–65 wt% Cu alloy.

1. **Eutectic**

Another type of common and relatively simple phase diagram found for binary alloys is shown in Figure 8 for the copper–silver system; this is known as a **binary eutectic phase diagram**. A number of features of this phase diagram are important and worth noting. First, three single-phase regions are found on the diagram: 𝛼, 𝛽, and liquid. The 𝛼 phase is a solid solution rich in copper; it has silver as the solute component and an FCC crystal structure. The 𝛽-phase solid solution also has an FCC structure, but copper is the solute. Pure copper and pure silver are also considered to be 𝛼 and 𝛽 phases, respectively

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Figure 8 The copper–silver phase diagram.

Thus, the solubility in each of these solid phases is limited, in that at any temperature below line *BEG* only a limited concentration of silver dissolves in copper (for the 𝛼 phase), and similarly for copper in silver (for the 𝛽 phase). The solubility limit for the 𝛼 phase corresponds to the boundary line, labeled *CBA*, between the 𝛼/(𝛼 + 𝛽) and 𝛼/(𝛼 + *L*) phase regions; it increases with temperature to a maximum [8.0 wt% Ag at779°C (1434°F)] at point *B*, and decreases back to

zero at the melting temperature of pure copper, point *A* [1085°C (1985°F)]. At temperatures below 779°C (1434°F), the solid solubility limit line separating the 𝛼 and 𝛼 + 𝛽 phase regions is termed a solvus line; the boundary *AB* between the 𝛼 and 𝛼 + *L* fields is the solidus line.

**7.1 The eutectic reaction**

Liquid phase is transformed upon cooling into the two solid α and β phases at the temperature TE; the opposite reaction occurs upon heating. This is called a eutectic reaction and point E on the diagram is called the eutectic point; furthermore, CE and TE represent the eutectic composition and temperature, respectively.

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at TE, the solid product of eutectic solidification is always two solid phases, whereas for a pure component only a single phase forms. Because of this eutectic reaction, phase diagrams termed **eutectic phase diagrams**; components exhibiting this behavior make up a **eutectic system**.