

Classifications, Characterization and Applications of Metallic Alloys

EI Said Gouda¹

Abstract

An alloy is a homogeneous mixture of two or more metallic elements. Their structures features may be one or more of the following phases: solid solution, intermediate phases, and phase mixture depending on the types of the metals presented in the alloy. In regard to the composition, metallic alloys are classified as either ferrous or nonferrous. In regard to the base metal, alloys could be classified as: copper alloys, aluminum alloys, Magnesium alloys and Titanium alloys. In regard to the distinctive characteristic, alloys could be classified as; shape memory alloys, shielding blocks alloys, fusible alloys, and joining alloys. In regard to the joining alloys, alloys could be classified as welding, brazing and soldering. In regard to the soldering alloys, alloys could be classified as lead-tin solders and Lead-free solders.

1. Introduction

The physics of metals is a part of the wider field of material science which includes in addition to metal physics, parts of chemistry, solid state physics, and electrical engineering. In fact, it is easy to say that metals have played a key role in the development of societies. Stages in history of mankind have been named as: the Stone Age, Bronze Age and the Iron Stages. Of today, the advance of our technology depends critically upon the contribution of the advanced materials and its composites.

The study of the chemical nature of metal alloys, the discovery of purification processes and the evolution efficient production processes constituted most of the early progress in the field of metallic materials.

¹ Solid State Physics Department, Physics division, National Research Center, Cairo, Egypt.
Physics Department, College of Science, Jazan University, Gizan, KSA. E-mail: gouda.el73@yahoo.com

The early contributions from the physics were primarily from two directions: the field of elasticity and the external symmetry of crystals.

Real success in this area had to await the development of a modern view of atoms contained in the science of quantum mechanics, which gave a satisfactory understanding of atoms about 1930. By the end of the 1930, an outline was available which provided a remarkable synthesis of the general properties of metals from the physical view. Finally by the end of 1945, a second phase of work began. It is the study of crystalline imperfections and their effects upon the physical properties of solid metals. In the present section we will discuss; production, structure features, types, properties and applications of metallic alloys.

2. Solidification

Solidification phenomenon plays an essential role in many of the processes used in field of the production engineering to solid state physics that is because most of fabrication processes for the production of the semi-finished and finished products involving melting of metals and their alloys then casting them into molds of different shapes according to the applications. It is a phase transformation from liquid to solid state or it can be described as the transformation form more open structure to a closely packed configuration with strong inter-atomic binding forces and fixed atomic sites.

Pure metal solidifies at a constant temperature called solidification temperature which is the same as the melting point as shown in Fig.1. The solidification process [1] could be followed by inserting a thermocouple into a melt contained in a small crucible and recording the change in temperature with time. If no heat is supplied, the melt gradually cools by releasing sensible heat or internal energy until at T_m very small crystalline bodies called nuclei form at several points in the melt. At this point the temperature remains constant while nuclei grow by the deposition of further atoms in the same crystallographic orientation, and the heat of fusion is removed. When all melt is solidified, temperature drops again, and the solid releases its sensible heat energy. Fig.2 represents the two processes of the nucleation and growth. The solidified body is polycrystalline, i.e., it consists of many randomly oriented crystals called grains.

The situation for the alloys is completely differing than pure metals, in which the solidification occurs over a range of temperature called solidification range as shown in Fig.3. The alloy in this range has a pasty form that consists of solid, tree-like structures called dendrites and liquid metals. The size and the shape of the dendrite depend on the cooling rate and the alloy composition. The liquid metals existing among these three dimensional dendritic structures eventually solidify to form completely solid structure that is called grain structure.

An alloy is a macroscopically homogenous substance, which possesses metallic properties. It is a combination of two or more metals or metals and non-metals. It may consist of a single phase or mixture phases, depending only on the composition of the alloy and temperature provided at the equilibrium. The pressure on the alloy is another effective variable, but it is usually held constant. The changes in the constitution of the alloy produced by given changes in composition or temperature may be conveniently shown by means of a phase diagram. It is a common way to represent the various phases of a substance and the conditions under which each phase exists. It is a graph between temperature and composition that illustrates the phase's constituents of an alloy at a certain temperature and certain composition, so that the phase diagram is therefore of great importance in metal physics and metallurgy [2].

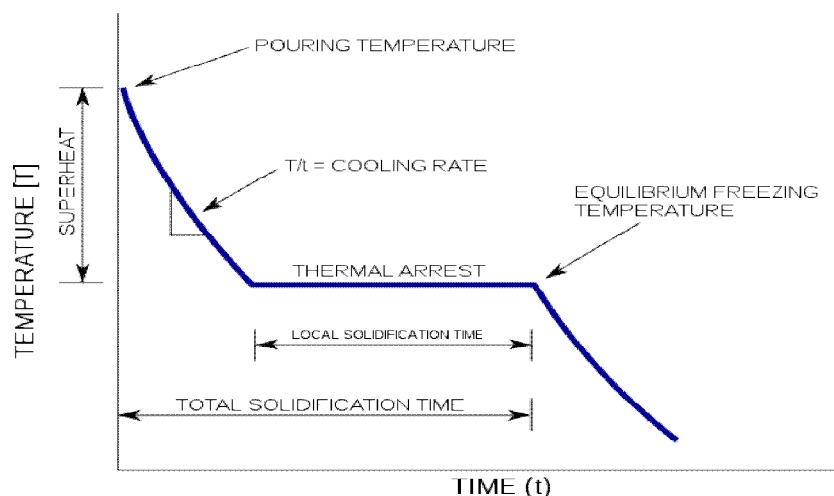


Fig.1 Cooling Curve of Pure Metal

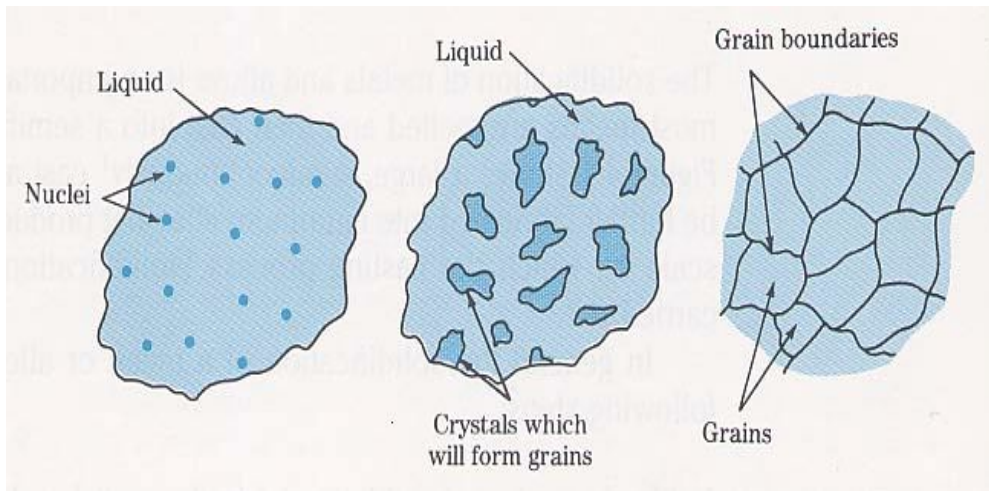


Fig.2: Nucleation and Growth of the Solidified Body

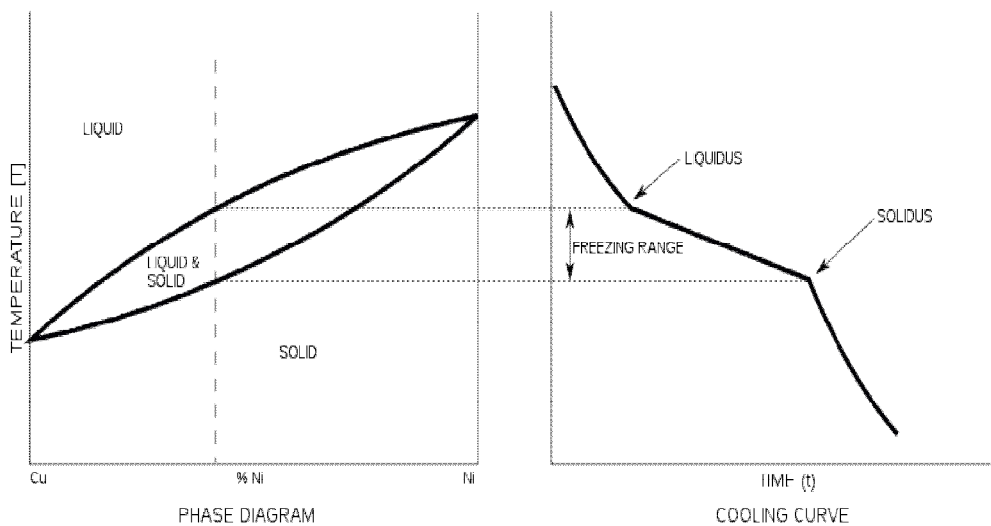


Fig.3 Cooling Curve of an Alloy

Special case of an alloy is the eutectic system as illustrated in Fig.4. Many binary alloy systems have components that limited solid solubility in each other as for example, in the lead-tin system. The regions of the restricted solid solubility at each ends of the Pb-Sn diagram are designed as alpha and beta phases and are called terminal solid solutions since they appear at the ends of the diagram [2]. The alpha phase is a lead-rich solid solution and can dissolve in solid solution a maximum of 19.2 wt. % Sn at 183 °C.

The beta phase is a tin-rich solid solution and can dissolve a maximum of 2.5wt.% Pb at 183 °C. As the temperature is decreased below 183 °C, the maximum solid solubility of the solute elements decreased according to the solvus lines of the Pb-Sn phase diagram. The eutectic system is a mixture of chemical compounds or elements has a single chemical composition that solidifies at a lower temperature than any other compositions in the alloy. This composition is known as the eutectic composition and the temperature is known as the eutectic temperature. When liquid of eutectic composition is slowly cooled to the eutectic temperature, the single liquid phase transforms simultaneously into two solid phases. This transformation is known as the eutectic reaction and could be written as:



On the phase diagram, the intersection of the eutectic temperature and the eutectic composition gives the eutectic point. Compositions to the left of the eutectic composition are called hypoeutectic compositions while, the compositions to the right are called hypereutectic compositions.

Solidification can occur by two methods:

- 1) Slow at rates lower than 10^4 K/sec.
- 2) Rapid at rates higher than 10^4 K/sec.

It has been known that, rapid solidification from molten state means to develop unusual even novel microstructures, which frequently exhibit beneficial properties. The structure of alloys rapidly solidified from the liquid state is always unusual in some respects. Under ordinary casting conditions, with cooling rate of about 1K/s, the microstructure typically is very coarse and exhibits a high degree of chemical segregation. In passing from ordinary casting practice to cooling rates $>10^2$ K/s, there is a progressive refinement in the solidification microstructure, i.e., dendrites, eutectics and other micro constituents are all reduced in scale. This is because with increasing cooling rate there is much less time available for coarsening of the microstructure.

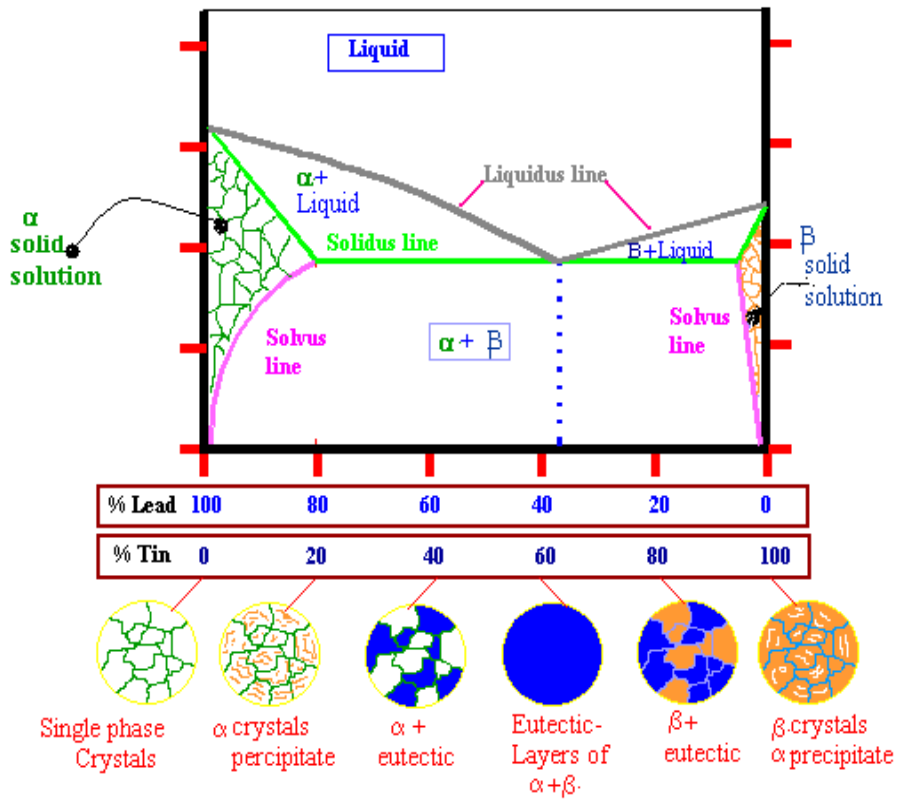


Fig.4: Eutectic Lead-Tin System

3. Structure of Alloys

Consider an alloy consists of two kinds of elements mixed in the liquid state and allowed to be solidified. The following structures may be obtained [3].

3.1 Solid Solution

A solid solution is a solid that consists of two or more elements atomically dispersed in a single-phase structure. It represents by the two symbols α and β at the two ends of Fig.4. In general there are two types of solid solutions: substitutional and interstitial.

a) **Substitutional Solid Solution:** In which, the two elements, solute atoms can substitute for parent solvent atoms in a crystal lattice as illustrated in Fig.5. The following conditions are favorable for extensive solid solubility of one elements in another:

- The diameters of the atoms of the elements must not differ by more than about 15 percent.
- The crystal structures of the two elements must be the same.
- There should be no appreciable difference in the electronegativity of the two elements so that compounds will not form.
- The two elements should have the same valence.

b) **Interstitial Solid Solution:** In which, the solute atoms fit into the spaces between the solvent or parent atoms as in Fig.6. These spaces or voids are called interstices. It can form when one atom is much larger than another. An important example of an interstitial solid solution is that formed by carbon in α iron that is stable between 1185 K and 1667 K. The atomic radius of α iron is 0.129 nm and that of carbon is 0.075 nm, and so there is an atomic radius difference of 42 percent.

It is important to realize that, atoms are not immovably tied to their lattice position. If, for example, there is a vacancy, one of the adjacent atoms may move in, and the previously occupied site now becomes vacant. By a repetition of these events, atoms can move, diffuse within the lattice. This case called vacancy diffusion or substitutional atom diffusion. Interstitial solute atom can also move into an adjacent space between the solvent atoms by diffusion since no vacancy is required and the diffusion occurs fast.

If the solute atoms are not distributed evenly in a solid solution, they will diffuse until concentration gradients are eliminated. According to Fick's first law, the flux of the atoms, (J) in units of atoms/m².s, is proportional to the concentration gradient $\frac{dC}{dx}$, over a distance Δx .

$$J = -D \frac{dC}{dx}$$

Where D is diffusivity or diffusion coefficient and its value is larger at higher temperatures according to the equation

$$D = D_0 \exp(-Q/RT)$$

D_0 is a constant for a given material, Q is activation energy and R is the gas constant (7.937 J/mol.K).

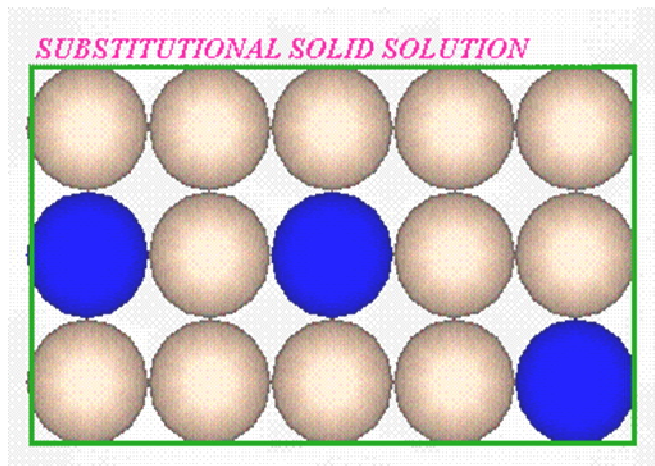


Fig.5: Substitutional Solid Solution

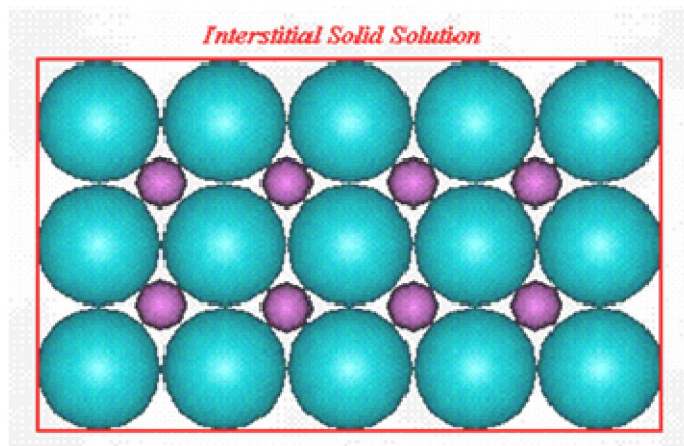


Fig.6 Interstitial Solid Solution

3.2 Intermetallic Phases

In many alloy systems, phases with distinct properties are formed. Their composition is characterized by a more or less fixed ratio of the two elements. In intermetallic compounds, the ratio is stoichiometric and can be denoted as A_mB_n . The two atomic species A and B occupy fixed sites. They can be classified broadly into:

a) Electrochemical Compounds

Electrochemical compounds are formed between several electropositive and electronegative elements such as: Mg_2Si , and Mg_3Sb_2 . Their compositions satisfy the valence laws.

b) Size Factor Compounds

In size factor compounds, the composition and the crystal structure are chosen in such a way as to allow the component atoms to pack together well. The composition of this type is based on the chemical formula such as $MgCu_2$ and $MgAg_2$.

c) Electron Compounds

In many alloy systems, phases of similar crystal structures are formed at certain ratios of valence electrons to atoms. The ratios concerned are $3/2$, $21/13$ and $7/4$. For examples, compounds of the ratio ($3/2$) are: $CuZn$, $AgZn$, Cu_3Al and Cu_5Sn . Examples of compounds with the ratio ($21/13$) are: Cu_9Al_4 , Cu_5Zn_8 and Ag_5Zn_8 . Examples of compounds with the ratio ($7/4$) are: $CuZn_3$, $AgZn_3$, Cu_3Sn , and Ag_5Al_3 . These electron concentrations are based on the following numbers of valence's electrons assumed to be contributed by each atom: Cu, Ag: 1, Zn: 2, Al: 3 and Sn: 4.

3.3 Phase Mixture

Alloys often exist in heterogeneous equilibrium as a phase mixture in which homogenous and distinct crystal grains of two or more different phases are mixed together and joined to one another. Fig.7 illustrates an example of this type of composition, in which the two phases mixed in one another.

In practice, very few truly pure or binary alloys are used. Even if only on the order of a few parts per million, contaminants are always present, while intentional additions may reach such high proportions that it becomes difficult to classify a material according to its base metal. Such ternary, quaternary, etc., alloys still exhibit the distinct phases found in binary alloys.

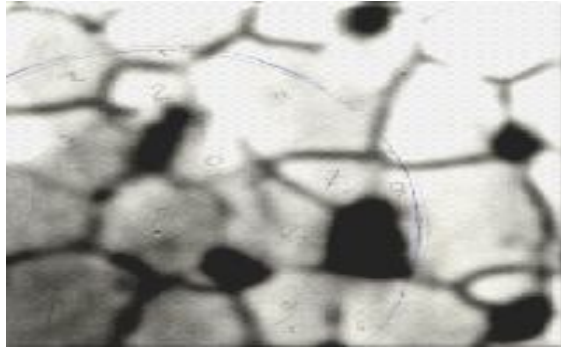


Fig.7: Two Phase Mixture Alloy [4]

4. Types of Metallic Alloys

Since there are more than 70 metallic elements in the periodic table, there are many thousands of metallic alloys being exist. Alloys can be classified according to their various categories [5]. One of them is that classified according to their compositions as follows;

4.1 Ferrous Alloys

A group of alloys in which iron is the prime constituent. They are produced in larger quantities than any other metallic material. Three factors account for it: (a) availability of abundant raw materials combined with economical extraction, (b) ease of forming and (c) their versatile mechanical and physical properties. One main drawback of ferrous alloys is their environmental degradation i.e. poor corrosion resistance. Other disadvantages include: relatively high density and comparatively low electrical and thermal conductivities. In ferrous materials the main alloying element is carbon (C). Depending on the amount of carbon present, these alloys will have different properties, especially when the carbon content is either less/higher than 2.14%. This amount of carbon is specific; as below this amount, material undergoes eutectoid transformation while above that limit, ferrous materials undergo eutectic transformation.

Thus the ferrous alloys with less than 2.14% C are termed as *steels* and the ferrous alloys with higher than 2.14% C are termed as *cast irons*. Fig.8 shows a scheme summarizes the different types of the ferrous alloys.

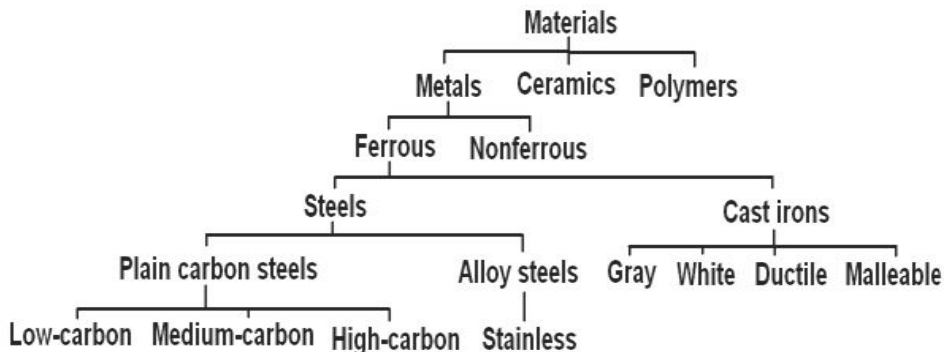


Fig.8: Classification Scheme for the Various Ferrous Alloys

4.1.1 Steels

Steels are alloys of iron and carbon plus other alloying elements. In steels, carbon present in atomic form, and occupies interstitial sites of Fe microstructure. Alloying additions are necessary for many reasons including: improving properties, improving corrosion resistance, etc. Arguably steels are well known and most used materials than any other materials. Mechanical properties of steels are very sensitive to carbon content. Hence, it is practical to classify steels based on their carbon content. Thus steels are basically three kinds: low-carbon steels (wt % C < 0.3), medium carbon steels (0.3 < wt % C < 0.6) and high-carbon steels (wt % of C > 0.6). The other parameter available for classification of steels is amount of alloying additions, and based on this steels are two kinds: (plain) carbon steels and alloy-steels.

i. Low Carbon Steels: These are arguably produced in the greatest quantities than other alloys. Carbon present in these alloys is limited, and is not enough to strengthen these materials by heat treatment; hence these alloys are strengthened by cold work. Their microstructure consists of ferrite and pearlite, and these alloys are thus relatively soft, ductile combined with high toughness. Hence these materials are easily machinable and weldable. Typical applications of these alloys include: structural shapes, tin cans, automobile body components, buildings, etc.

A special group of ferrous alloys with noticeable amount of alloying additions are known as HSLA (high-strength low-alloy) steels. Common alloying elements are: Cu, V, Ni, W, Cr, Mo, etc.

These alloys can be strengthened by heat treatment and at the same time, they are ductile and formable. Typical applications of these HSLA steels include: support columns, bridges, pressure vessels.

ii. Medium Carbon Steels: These are stronger than low carbon steels. However these are of less ductile than low carbon steels. These alloys can be heat treated to improve their strength. Usual heat treatment cycle consists of austenitizing, quenching and tempering at suitable conditions to acquire required hardness. They are often used in tempered condition. As hardenability of these alloys is low, only thin sections can be heat treated using very high quenching rates. Ni, Cr and Mo alloying additions improve their hardenability. Typical applications include: railway tracks & wheels, gears, other machine parts which require good combination of strength and toughness.

iii. High Carbon Steels: These are the strongest and hardest of carbon steels, and of course their ductility is very limited. These are heat treatable, and mostly used in hardened and tempered conditions. They possess very high wear resistance, and capable of holding sharp edges. Thus these are used for tool applications such as knives, razors, hacksaw blades, etc. With addition of alloying elements like; Cr, V, Mo, W which forms hard carbides by reacting with carbon present, wear resistance of high carbon steels can be improved considerably.

iv. Stainless Steels: The name of this kind comes from their high resistance to corrosion i.e. they are rust-less (stain-less). Steels are made highly corrosion resistant by addition of special alloying elements, especially a minimum of 12% Cr along with Ni and Mo. Stainless steels are mainly three kinds: ferritic & hardenable Cr steels, austenitic and precipitation hardenable (martensitic, semi-austenitic) steels. This classification is based on prominent constituent of the microstructure. Typical applications include cutlery, razor blades, surgical knives, etc.

Ferritic stainless steels are principally Fe-Cr-C alloys with 12-14% Cr. They also contain small additions of Mo, V, Nb, and Ni.

Austenitic stainless steels usually contain 18% Cr and 8% Ni in addition to other minor alloying elements. Ni stabilizes the austenitic phase assisted by C and N. Other alloying additions include Ti, Nb, Mo (prevent weld decay), Mn and Cu (helps in stabilizing austenite).

Ferritic and austenitic steels are hardened and strengthened by cold work because they are not heat treatable. On the other hand martensitic steels are heat treatable. Austenitic steels are most corrosion resistant, and they are produced in large quantities. Austenitic steels are non-magnetic as against ferritic and martensitic steels, which are magnetic. Table 1 summarizes the main applications of carbon steel [6].

Table 1 Composition, Mechanical Properties, and Typical Applications of Austenitic, Ferritic, and Martensitic Stainless-Steels.

Composition (wt%)	Condition	Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	Typical Applications
Ferritic					
0.08 C, 11.0 Cr, 1.0 Mn, 0.50 Ni, 0.75 Ti	Annealed	380 (55)	205 (30)	2 0	Automotive exhaust components, tanks.
0.20 C, 25 Cr, 1.5 Mn	Annealed	515 (75)	275 (40)	20	Valves (high temperature), glass molds, combustion chambers.
Austenitic					
0.08 C, 19 Cr, 9 Ni, 2.0 Mn	Annealed	515 (75)	205 (30)	40	Chemical and food processing equipment, cryogenic vessels.
0.03 C, 17 Cr, 12 Ni, 2.5 Mo, 2.0 Mn	Annealed	485 (70)	170 (25)	40	Welding construction
Martensitic					
0.15 C, 12.5 Cr, 1.0 Mn	Annealed	485 (70)	275 (40)	20	Rifle barrels,
	Q & T	825 (120)	620 (90)	12	cutlery, jet engine parts.
0.70 C, 17 Cr, 0.75 Mo, 1.0 Mn	Annealed	725 (105)	415 (60)	20	Cutlery, bearings
	Q & T	1790 (260)	1650 (240)	5	Surgical tools.
Precipitation Hardenable					
0.09 C, 17 Cr, 7 Ni, 1.0 Al, 1.0 Mn	Precipitation hardened	1450 (210)	1310 (190)	1–6	Springs, knives, pressure vessels.

4.1.2 Cast Irons

Though ferrous alloys with more than 2.14 wt % C are designated as cast irons, commercially cast irons contain about 3.0-4.5% C along with some alloying additions. Alloys with this carbon content melt at lower temperatures than steels i.e. they are responsive to casting.

Hence casting is the most used fabrication technique for these alloys. Table 2 illustrates the main applications of cast iron [6]. Hard and brittle constituent presented in these alloys, cementite is a meta-stable phase, and can readily decompose to form α -ferrite and graphite. In this way disadvantages of brittle phase can easily be overcome. Tendency of cast irons to form graphite is usually controlled by their composition and cooling rate.

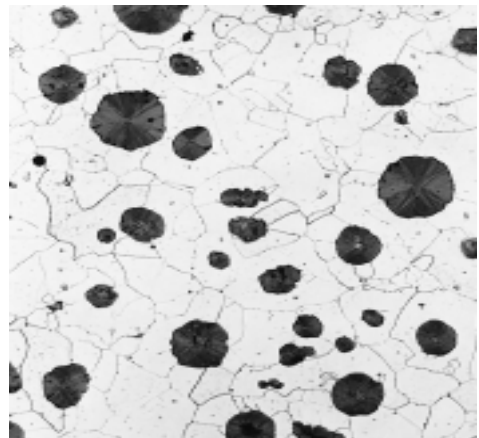
Based on the form of carbon present, cast irons are categorized as gray, white, nodular and malleable cast irons. Fig.9 illustrates the optical photomicrographs of various cast irons.

i. Gray Cast Irons: These alloys consist of carbon in form graphite flakes, which are surrounded by either ferrite or pearlite. Because of presence of graphite, fractured surface of these alloys look grayish, and so is the name for them. Alloying addition of Si (1-3w. %) is responsible for decomposition of cementite, and also high fluidity. Thus castings of intricate shapes can be easily made. Due to graphite flakes, gray cast irons are weak and brittle. However they possess good damping properties, and thus typical applications include: base structures, bed for heavy machines, etc. they also show high resistance to wear.

ii. White Cast Iron: When Si content is low (< 1%) in combination with faster cooling rates, there is no time left for cementite to get decomposed, thus most of the brittle cementite retains. Because of presence of cementite, fractured surface appear white, hence the name. They are very brittle and extremely difficult to machine. Hence their use is limited to wear resistant applications such as rollers in rolling mills. Usually white cast iron is heat treated to produce malleable iron.



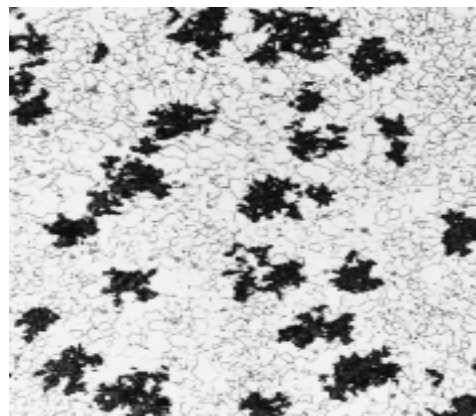
(a)



(b)



(c)



(d)

Fig.9 Optical photomicrographs of various cast irons. (a) Gray iron: the dark graphite flakes are embedded in an-ferrite matrix. 500. (Courtesy of C. H. Brady, National Bureau of Standards, Washington, DC.) (b) Nodular(ductile) iron: the dark graphite nodules are surrounded by an-ferrite matrix. 200. (Courtesy of C. H. Brady and L. C. Smith, National Bureau of Standards, Washington, DC.) (c) White iron: the light cementite regions are surrounded by pearlite, which has the ferrite-cementite layered structure. 400. (Courtesy of Am cast Industrial Corporation.) (d) Malleable iron: dark graphite rosettes (temper carbon) in an-ferrite matrix. 150. (Reprinted with permission of the Iron Castings Society, Des Plaines, IL.)

iii. Nodular (or ductile) Cast Iron: Alloying additions are of prime importance in producing these materials. Small additions of Mg /Coe to the gray cast iron melt before casting can result in graphite to form nodules or sphere-like particles. Matrix surrounding these particles can be either ferrite or pearlite depending on the heat treatment. These are stronger and ductile than gray cast irons. Typical applications include: pump bodies, crank shafts, automotive components, etc.

iv. Malleable Cast Iron: These formed after heat treating white cast iron. Heat treatments involve heating the material up to 800-900 °C, and keep it for long hours, before cooling it to room temperature. High temperature incubation causes cementite to decompose and form ferrite and graphite. Thus these materials are stronger with appreciable amount of ductility. Typical applications include: railroad, connecting rods, marine and other heavy-duty services.

4.2 Nonferrous Alloys

All other alloys fall within the non ferrous category. They have specific advantages over ferrous materials. They can be fabricated with ease, high relatively low density, and high electrical and thermal conductivities. However different materials have distinct characteristics, and are used for specific purposes. So that, the nonferrous alloys can be subdivided according to the base metal or specific characteristic that is shared by a group of alloys;

4.2.1 According to the Base Metal

Alloys within this category are classified according to the main constituents as follows:

i. Copper Alloys

Copper and copper-based alloys, possessing a desirable combination of physical properties, have been utilized in quite a variety of applications. Unalloyed copper is so soft and ductile that it is difficult to machine; also, it has an almost unlimited capacity to be cold worked. Furthermore, it is highly resistant to corrosion in diverse environments including the ambient atmosphere, seawater, and some industrial chemicals. The mechanical and corrosion-resistance properties of copper may be improved by alloying.

Most copper alloys cannot be hardened or strengthened by heat-treating procedures; consequently, cold working and/or solid-solution alloying must be utilized to improve these mechanical properties.

Table 2 Compositions, Mechanical Properties and Typical Applications of Various Gray, Nodular, and Malleable Cast-Irons

Composition (wt%) ^a	Matrix Structure	Tensile Strength [MPa (ksi)]	Yield Strength [MPa (ksi)]	Ductility [%EL in 50 mm (2 in.)]	Typical Applications
Gray Iron					
3.40–3.7 C, 2.55 Si, 0.7 Mn	Ferrite Pearlite	124 (18)	—	—	Miscellaneous soft iron castings in which strength is not a primary consideration.
3.2–3.5 C, 2.20 Si, 0.8 Mn	Ferrite Pearlite	173 (25)	—	—	Small cylinder blocks, cylinder heads, pistons, clutch plates, transmission cases
3.0–3.3 C, 2.0 Si, 0.8 Mn	Pearlite	276 (40)	—	—	Diesel engine castings, liners, cylinders, and pistons
Ductile (Nodular) Iron					
3.5–3.8 C, 2–2.8 Si, 0.05Mn, 0.20Ni, 0.10Mo	Ferrite	414 (60) 689 (100)	276 (40) 483 (70)	18	Pressure-containing parts such as valve and pump bodies.
	Pearlite	827 (120)	621 (90)	3	High-strength gears and machine components.
	Tempered martensite			2	Pinions, gears, rollers, slides.
Malleable Iron					
-2.7 C, 1–1.75 Si, 5Mn	Ferrite	345 (50)	224 (32)	10	General engineering service at normal and elevated temperatures
-2.7 C, 5–1.55 Si, 5Mn	Ferrite Pearlite	448 (65)	310 (45)	6	

The most common copper alloys are the brasses for which zinc, as a substitutional impurity, is the predominant alloying element. Some of the common brasses are yellow, naval, and cartridge brass, muntz metal, and gilding metal. The compositions, properties, and typical uses of several of these alloys are listed in table 3 [7]. Some of the common uses for brass alloys include costume jewelry, cartridge casings, automotive radiators, musical instruments, electronic packaging, and coins.

The bronzes are alloys of copper and several other elements, including tin, aluminum, silicon, and nickel. These alloys are somewhat stronger than the brasses, yet they still have a high degree of corrosion resistance. Table 3 contains several of the bronze alloys, their compositions, properties, and applications. Generally they are utilized when, in addition to corrosion resistance, good tensile properties are required.

The most common precipitation hardenable copper alloys are the beryllium coppers. They possess a remarkable combination of properties: tensile strengths as high as 1400 MPa, excellent electrical and corrosion properties, and wear resistance when properly lubricated; they may be cast, hot worked, or cold worked. High strengths are attained by precipitation-hardening heat treatments. These alloys are costly because of the beryllium additions, which range between 1.0 and 2.5wt .%.

ii. Aluminum Alloys

Aluminum and its alloys are characterized by a relatively low density, high electrical and thermal conductivities, and a resistance to corrosion in some common environments, including the ambient atmosphere. Many of these alloys are easily formed by virtue of high ductility; this evidenced by the thin aluminum foil sheet into which the relatively pure material may be rolled. The mechanical strength of aluminum may be enhanced by cold work and by alloying; however both processes tend to diminish resistance to corrosion. Principal alloying elements include copper, magnesium, silicon, manganese, and zinc. There are two principal classifications, namely casting alloys and wrought alloys, both of which are further subdivided into the categories heat-treatable and non-heat-treatable. About 85 % of aluminum is used for wrought products, for example rolled plate, foils and extrusions. Cast aluminum alloys yield cost effective products due to the low melting point, although they generally have lower tensile strengths than wrought alloys.

Table 3. Compositions, Mechanical Properties and Typical Applications of Cu Alloys

Alloy name	Composition (wt.%)	Condition	Tensile Strength MPa	Yield Strength MPa	Ductility [% EL in 50mm]	Typical Applications
<i>Wrought Alloys</i>						
Electrolytic tough pitch	0.04O	Annealed	220	69	45	Electrical wire, rivets screening.
Beryllium copper	1.9Be, 0.2 Co	Precipitation hardened	1140-1310	690-860	4-10	Spring, bellows, firing pins.
Cartridge brass	30 Zn	Annealed Cold working	300 525	75 435	68 8	Automotive radiator cores, ammunition components.
Phosphor bronze, 5%A	5Sn, 0.2 P	Annealed Cold working	325 560	130 515	64 10	Bellows, clutch disks, diaphragm, fuse clips, welding rods.
Copper-Nickel, 30%	30 Ni	Annealed Cold working	380 515	125 485	36 15	Condenser and heat exchanger component.
<i>Cast Alloys</i>						
Leaded yellow brass	29Zn, 3Pb, 1Sn	As cast	234	83	35	Furniture hardware, radiator fittings, battery clamps.
Tin bronze	10Sn, 2Zn	As cast	310	152	25	Bearings bushings, piston rings, steam fittings.
Aluminum bronze	4Fe, 11Al	As cast	586	241	18	Bearings, gears, bushings valve seats, pickling hooks.

aluminum alloy system is Al-Si, where the high levels of silicon (4.0 % to 13%) contribute to give good casting characteristics. Aluminum alloys are widely used in engineering structures and components where lightweight or corrosion resistance is required. Table 4 summarizes the compositions, properties, and applications of the several Al alloys [7]. Aluminum alloy surfaces will keep their apparent shine in a dry environment due to the formation of a clear, protective layer of aluminum oxide. In a wet environment, galvanic corrosion can occur when an aluminum alloy is placed in electrical contact with other metals with more negative corrosion potentials than aluminum.

iii. Magnesium Alloys

Perhaps the most outstanding characteristic of magnesium is its density, 1.7 g/cm^3 , which is the lowest of all the structural metals; therefore, its alloys are used where light weight is an important consideration (e.g., in aircraft components). Magnesium has an HCP crystal structure, is relatively soft, and has a low elastic modulus: 45 GPa. At room temperature magnesium and its alloys are difficult to deform; in fact, only small degrees of cold work may be imposed without annealing. Consequently, most fabrication is by casting or hot working at a temperature between 200 and 350 °C. Magnesium, like aluminum, has a moderately low melting temperature (651 °C). Chemically, magnesium alloys are relatively unstable and especially susceptible to corrosion in marine environments. On the other hand, corrosion or oxidation resistance is reasonably good in the normal atmosphere; it is believed that this behavior is due to impurities rather than being an inherent characteristic of Mg alloys. Fine magnesium powder ignites easily when heated in air; consequently, care should be exercised when handling it in this state.

These alloys are also classified as either cast or wrought, and some of them are heat treatable. Aluminum, zinc, manganese, and some of the rare earths are the major alloying elements. A composition–temper designation scheme similar to that for aluminum alloys is also used. Table 5 lists several common magnesium alloys, their compositions, properties, and applications [7]. These alloys are used in aircraft and missile applications, as well as in luggage. Furthermore, in the last several years the demand for magnesium alloys has increased dramatically in a host of different industries. For many applications, magnesium alloys have replaced engineering plastics that have comparable densities in as much as the magnesium materials are stiffer, more recyclable, and less costly to produce. For example, magnesium is now employed in a variety of hand-held devices (e.g., chain saws, power tools, hedge clippers), in automobiles (e.g., steering wheels and columns, seat frames, transmission cases), and in audio-video-computer-communications equipment (laptop computers, TV sets, cellular telephones).

iv. Titanium Alloys

Titanium and its alloys are relatively new engineering materials that possess and extraordinary combination of properties.

The pure metal has a relatively low density (4.5 g/cm^3), a high melting point and an elastic modulus of 107 GPa. Titanium alloys are extremely strong; room temperature tensile strengths as high as 1400 MPa are attainable, yielding remarkable specific strengths. Furthermore, the alloys are highly ductile and easily forged and machined. Table 6 summaries the compositions, mechanical properties, and typical applications for several common titanium alloys [7].

Table 4: Compositions, Mechanical Properties and Typical Applications of Al Alloys

Composition (wt.%)	Condition	Tensile Strength MPa	Yield Strength MPa	Ductility [% EL in 50mm]	Typical Applications
Wrought , Nonheat-treatable Alloys					
0.12 Cu	Annealed (O)	90	35	35-45	Food/Chemical handling and storage equipment, Heat exchangers light reflectors.
0.12 Cu, 1.2Mn, 0.1Zn	Annealed (O)	110	40	30-40	Cooking utensils, pressure vessels and piping.
2.5Mg, 0.25 Cr	Strain hardened	230	195	12-18	Aircraft fuel and oil lines, Fuel tanks appliances.
Wrought , heat-treatable Alloys					
4.4Cu, 1.5Mg, 0.6Mn	Heat-treated	470	325	20	Aircraft structures, rivets, truck wheels, screw machine products.
1.0Mg, 0.6Si, 0.3Cu, 0.2Cr	Heat-treated	240	145	22-25	Trucks, canoes, railroad cars.
5.6Zn, 2.5Mg, 1.6Cu, 0.23Cr	Heat-treated	570	505	11	Aircrafts structural parts and other highly stressed applications.
Cast, heat-treatable Alloys					
4.5Cu, 1.1Si	Heat-treated	221	110	8.5	Flywheel and rear-axle housings.
7.0 Si, 0.3Mg	Heat-treated	228	164	3.5	Aircraft pump parts automotive transmission cases.
Aluminum-Lithium Alloys					
2.7 Cu, .25Mg, 2.25Li, 0.12Zr	Heat-treated, cold worked	455	455	5	Aircraft structure and cryogenic tankage structures.
1.3 Cu, .95Mg, 2.0Li, 0.1Zr	Heat-treated, cold worked	465	360	-	Aircraft structures that must be highly damage tolerant.

Table 5: Compositions, Mechanical Properties and Typical Applications of Mg Alloys

Composition (wt.%)	Condition	Tensile Strength MPa	Yield Strength MPa	Ductility [% EL in 50mm]	Typical Applications
Wrought Alloys					
3.0Al, 1.0Zn, 0.2Mn	As extruded	262	200	15	Structures and tubing, cathodic protection.
3.0 Th, 0.6Zr	Strained hardened, partially annealed	255	200	9	High strength to 315 °C.
5.5Zn, 0.45Zr	Artificially aged	350	285	11	Forgings of maximum strength for aircraft.
Cast Alloys					
9.0 Al, 0.15Mn, 0.7Zn	As cast	230	150	3	Die-cast parts for automobiles luggage, and electronic devices.
6.0 Al, 0.13Mn	As cast	220	130	6	Automotive wheels.
4.3Al, 1.0Si, 0.35Mn	As cast	210	140	6	Die castings requiring good creep resistance.

Table 6: Compositions, Mechanical Properties and Typical Applications of Ti Alloys

Composition (wt.%)	Condition	Tensile Strength MPa	Yield Strength MPa	Ductility [% EL in 50mm]	Typical Applications
99.5 Ti	Annealed	484	414	25	Jet engine shrouds, corrosion resistance equipment for marine and chemical processing industries.
5Al, 2.5Sn	Annealed	826	784	16	Gas turbine engine casings and rings, chemical processing equipment requiring strength to temperatures of 480 °C.
8Al, 1Mo, 1V	Annealed (duplex)	950	890	15	Forgings for jet engine components.
6Al, 4V	Annealed	947	877	14	High strength prosthetic implants, chemical-processing equipment, airframe structural components.
6Al, 2Sn, 6V, 0.75Cu	Annealed	1050	985	14	Rocket engine case airframe applications and high strength airframe structures.
10V, 2Fe, 3Al	Solution + aging	1223	1150	10	Best combination of high strength and toughness of any commercial titanium alloys, high strength airframe components.

4.2.2 According to Some Specific Characteristics [8]:

This category includes some groups of alloys that shared in specific characteristic, which make them suitable for certain application not for the others.

i. Shape Memory Alloys: A group of alloys that have the ability to recover a previously defined shape when subjected to an appropriate heat treatment procedure. In reverting back to their original shapes, they can also apply force. There are a number of metallic alloys that exhibit such behavior, including Au-Cd, Cu-Zn-Al, Cu-Al-Ni, and Ni-Ti alloys. The most practical applications are for those SMAs that have the ability to recover a significant amount of strain (super elasticity) or those that can apply large forces when reverting back to their original shapes.

The shape-recovery effect in SMAs is a result of the solid-solid phase transformation between two material structures, i.e., austenite and martensite. In the martensitic state, the SMAs are very easy to deform by the application of stress. If at this stage the load is removed, the deformation in the martensite remains, giving the appearance of a plastic deformation. However, after in the martensitic state, heating will cause a martensite-austenite transformation with the component reverting back to its original shape. The change in structure does not occur at a discrete temperature but over a range of temperatures depends on the alloy system. Upon cooling the transformation starts at M_s (100 percent austenite) and ends at M_f (0 percent martensite) while upon heating the transformation starts at A_s (100 percent martensite) and ends at A_f (0 percent martensite) as shown in Fig.10. Additionally, the transformations during cooling and heating do not overlap, i.e., the system exhibits hysteresis. There are two ways for recovery named as:

One-Way Memory Effect: When a shape-memory alloy is in its cold state (below A_s), the metal can be bent or stretched and will hold those shapes until heated above the transition temperature. Upon heating, the shape changes to its original. When the metal cools again it will remain in the hot shape, until deformed again.

Two-Way Memory Effect: The two-way shape-memory effect is the effect that the material remembers two different shapes: one at low temperatures, and one at the high-temperature shape. A material that shows a shape-memory effect during both heating and cooling is called two-way shape memory.

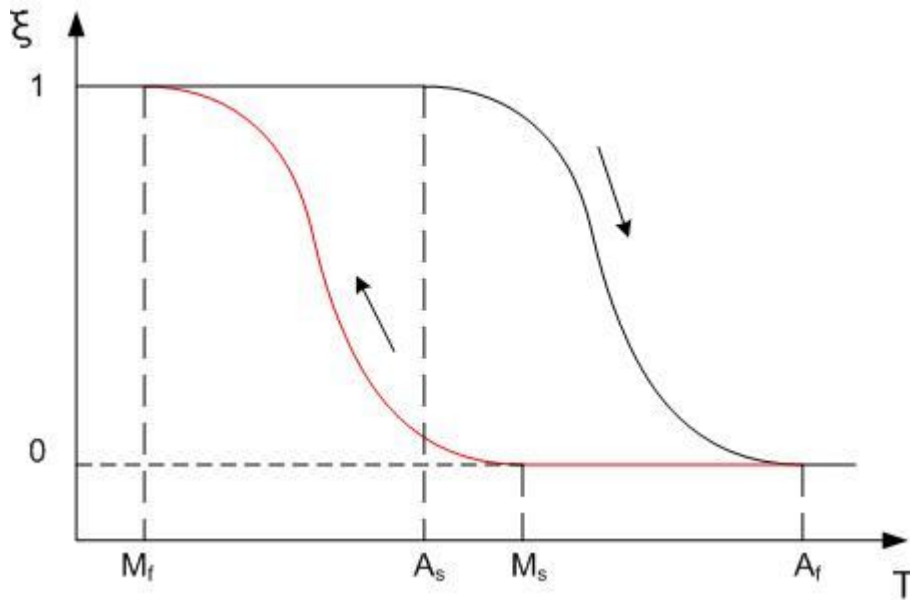


Fig.10 Martensite-Austenite Transformation

ii. Shielding Blocks Alloys: A group of alloys that have the property of a higher absorption coefficient of radiation and there is no transmission occurs. It is used in radiotherapy to construct shielding blocks. This group includes bismuth with about 20% to 25% lead and 10% cadmium.

iii. Fusible Alloys: A group of alloys that have melting point ranging from 150 °C to a temperature below the boiling point of water. Electrical uses are the main application of these alloys. The main alloys of this type are the Bi-Pb-Sn alloys.

iv. Joining Alloys: A group of alloys are used for joining separate parts in the engineering products. It is an inclusive term covering processes such as; welding, brazing, and soldering...etc. In this work, I will deal with the soldering alloys with more details.

5. Soldering Alloys

Soldering process is one of the oldest methods that have been used in the interconnection. It is very important in the field of electronics. While, advances in transistors, diodes, capacitors and some special integrated circuits have been revolutionized the world. These components are of very little values as individual components and to be used, they must be electrically connected to each other and mechanically to the printed circuits boards by the so called solder alloys.

The reliability of soldered joint in comparison to other joining processes as well as its lower cost per joint, lower initial investment, ease of estimation and serviceability have resulted in great success of the modern electronic and computer technology. The process of soldering is divided into two types, soft and hard depending on the strength required from the finished joint [9]. Soldering alloys mainly could be classified into two main types [10]:

5.1 Lead-Tin Solders

Lead/Tin eutectic solder is the most widely utilized soldering alloy. The popularity of this alloy is due to its relatively low melting point, aggressive bonding characteristics, good wicking tendencies, good electrical continuity, and low cost. That is due to lead provides many technical advantages, which includes the following to Sn-Pb solders;

- a) Pb reduces the surface tension of pure tin [11].
- b) Lead serves as a solvent metal, enabling the other joint constituents such as Sn and Cu to form intermetallic bonds rapidly by diffusing in the liquid state.

These two factors, combined with Pb being readily available and a low cost metal, make it is an ideal alloying element with tin. While, there are some studies indicated that lead has many adverse effects on human health such as; The Environmental Protection Agency (EPA) announced lead and its compounds as one of the 17 chemical poisons that threat human life and environment. When lead accumulates in the body for a long time, it will produce adverse health effects. The Environmental Protection Agency (EPA) announced lead and its compounds as one of the 17 chemical poisons that threat human life and environment. When it accumulates in the body for a long time, it has the following effects;

- *-It binds strongly with the proteins in the body and inhibits normal processing and functions .
- *-It causes disorders in nervous and reproductive system, delays in neurological and physical developments.
- *-Reduces production of hemoglobin resulting in anemia and hypertension, strokes and heart attack.
- *-Pregnant women exposed to lead are at risk of complications in their pregnancies.
- *-It damage kidneys, liver, blood and central nervous system.

Owing to these adverse effects, there are many studies tend to reduce and eliminate the use of lead from industries [12], which it is still in use until today.

- 1- U.S. Congress in 1990 was the first consider amount of legislations restricting and taxing the use of lead in all areas of manufacturing.
- 2- European Union has certain dangerous substances in electrical and electronic equipment starting in 2006 to minimize their threat to human health [13].
- 3- Japan Electronic Development Association planed to reduces 80 % of Pb by 2008 and eliminate it by 2013.

5.2 Lead-Free Solders

There are some characteristics play the major role in consideration of substitute for lead-tin solders in electronic soldering:

- 1- The melting temperature of solder is a fundamental performance characteristic.
- 2- Adequate strength properties (fatigue resistance, stress-coupling ability etc.) enable solder to bond materials with different levels of thermal coefficients of expansion.
- 3-Availability in sufficient quantities depending on whether of the base metal.
- 4- Good electrical/thermal conductivity.
- 5- Easy reparability.
- 6- Low cost.
- 7-Compatibility with existing and future materials and processes to allow smooth transition.
- 8-The environmental issues related to the toxicity and waste disposal play important role for the selection of the alternatives metal.

Because of its low melting point and its ability to wet and spread on a wide range of substrates using mild fluxes, tin becomes the principal component of most solder alloys used for electronic applications. It combined with one of silver, zinc, bismuth, copper, indium or antimony as follows [14]:

i. Sn-3.5Ag Alloy

This alloy exhibits adequate wetting behavior and strength and is used in electronics as well as plumbing.

Several sources have also reported good thermal fatigue properties as compared to Sn/Pb. The alloy is easily worked to various shapes, and is supplied in many forms, including bars, wire, paste, cored wire, ball and performs. Potential problems include the higher melting temperature, (about 38 °C higher than Pb/Sn solder alloy), in addition to the silver content that means more expensive.

ii. Sn-0.7Cu Alloy

Due to its low cost, the Sn-Cu alloy began to find popular application in flow soldering of single sided printed-circuit boards that consume large amount of solder. There are some studies have been conducted on this alloy with trace levels of Ni, P and Ge to improve its oxidation characteristics. These elements; however tend to react negatively with other elements on the solder surface. As a result, their amount tends to decrease as the amount of oxides increases. Adding Ge makes control of the alloy composition even more difficult. But the major problems associated with this alloy are its high melting temperature, poor wettability, low resistance to thermal stress and poor creep factor which resist its uses.

iii. Sn-58Bi Alloy

The Sn-Bi eutectic alloy has a low melting temperature of 139 °C and is therefore well suited for mounting parts having low heat resistance. Bismuth however is not very ductile and a case has been reported in which strong impact caused the soldered area to peel off. Examination of the peeled surface revealed a dimpled appearance of the Sn-Ag-Cu alloy, indicating that peeling is a form of ductile fracture caused by a force exceeding the materials ductile limits. In the Sn-Bi alloy, wall-to-wall fracture, which is apparently a form of brittle fracture, has been observed. Though all solders based on this alloy do not have the same problem, the used of a Sn-Bi alloy should consider this when deciding to use it.

iv. Sn-9Zn Alloy

The most noteworthy benefit of this alloy is its melting temperature. Although there are many lead free solders on the market, the melting temperature of the Sn-Zn alloy is closest to that of Pb-Sn alloy.

The melting point of the Sn-Zn eutectic is 199 °C. Wettability is a problem with Zn because it forms strong and stable oxide film.

v. Sn-52In Alloy

The melting point of this alloy makes it suitable to low temperature applications. With regard to indium, it displays good oxidation resistance, but is susceptible to corrosion in a humid environment. It is also a very soft metal and has a tendency to cold weld. In addition, the 52In/48Sn alloy displays rather poor high temperature fatigue behavior, due to its low melting point. The high indium content limits the widespread use of this alloy due to cost and availability constraints.

vi. Sn-5Sb Alloy

The 95Sn-5Sb solder is a solid solution of antimony in a tin matrix. The relatively high melting point of this alloy makes it suitable for high temperature applications. The antimony imparts strength and hardness. Formation of the intermetallic compound SnSb is possible at these levels of Sb. This phase has a cubic structure with a high hardness. The wetting behavior was measured on a wetting balance in air using a standard RMA flux. The wetting force at 2 seconds for 95Sn/5Sb on a Cu wire is significantly less than Sn/37Pb alloy. In addition to marginal wetting performance, the toxicity of Sb has also raised concerns.

Although, one of these binary alloys did not meet the entire requirement for lead free solder alternative, there are many studies tend to improve the properties of these alloys by small ternary or quaternary additions.

5.3 Historical Review

The effects of Bi additions and cooling rate on thermal and mechanical properties of Sn-Zn near eutectic alloy were studied and analyzed [15]. The results showed that adding Bi up to 8 % to Sn-8% Zn, decreased melting temperature from 198.4 to 186.1 °C, but the pasty range increased from 2.36 to 6.72 °C. It was also confirmed that the difference of cooling rates significantly affected the microstructure and mechanical properties of Sn-Zn-Bi alloys. In the case of fast cooling, the alloys have fine Sn, Zn, and Bi phases with smooth surfaces. But in the case of slow cooling, Sn-Zn alloys exhibited coarse dendrite structure and large needle or rod-like Zn-rich precipitates with rough surface and voids and extensive segregation of massive Bi toward the surface.

The effect of Ga addition to Sn-Zn eutectic system in order to improve the melting point and wetting abilities was studied and analyzed [16]. The results showed that, addition of Ga decreased the melting point of Sn-Zn eutectic system, and wetting angle while increased the wetting rate .

The effect of small additions of Ag, Bi, Cu and Sb on structure, melting temperature, wettability and electrical resistivity of the Sn-9Zn lead free solder alloy were studied and analyzed [17]. The results showed that, the Sn-9Zn-1Bi alloy has better properties for use as solder such as low melting point, lower electrical resistivity and lower temperature coefficient of resistivity. But the wettability is still the most important problem for applications of this alloy.

The effect of Al on the electrochemical corrosion behavior of Pb-free Sn-8.5Zn-0.5Ag-xAl-0.5Ga solder in 3.5% NaCl solution was studied [18]. The x-content in the solder varied from 0.1 to 3wt. %. Polarization studies revealed that, an increase in Al content up to 1.5 wt.% decreased the corrosion current density (I_{corr}), corrosion rate of the solder and shifted the corrosion potential (E_{corr}) towards more noble values. However, higher content of Al, i.e. 3(wt.%) in the five-element solder enhanced the corrosion rate and resulted in a significant increase in the E_{corr} towards more negative values.

The effects of La, Ti, Al, and Cr on oxidation resistance, wetting and tensile properties of Sn-9Zn alloy were studied and analyzed [19]. The results showed that, addition of Ti, Al, and Cr improved the oxidation resistance of Sn-9Zn solder, while have no effects on the wetting properties. Addition of Cr improved ductility while maintaining tensile strength.

Corrosion behavior of lead-free $Sn_{88.7}Ag_{2.3}In_{9.0}$, $Sn_{86.6}Ag_{3.0}Bi_{10.4}$, $Sn_{96.1}Ag_{3.1}Cu_{0.8}$ and $Sn_{90.4}Ag_{2.9}Cu_{6.7}$ solder alloys in 0.1M NaCl solution and compared with that of the $Sn_{73.9}Pb_{26.1}$ solder was studied [20]. The results showed that, $Sn_{88.7}Ag_{2.3}In_{9.0}$ and $Sn_{86.6}Ag_{3.0}Bi_{10.4}$ solders exhibited poor corrosion behavior compared to that of $Sn_{73.9}Pb_{26.1}$. On the contrary, copper addition enhanced corrosion resistance of Sn–Ag solder alloys which exhibit improved passivity behavior compared to $Sn_{73.9}Pb_{26.1}$ solder. Moreover, increasing the copper content from 0.8 to 6.7 at% improved corrosion behavior of Sn–Ag solders.

The effect of minor Bi additions on the interfacial morphology between Sn-9Zn solder and Cu layer was studied [21]. The results showed that, addition of minor amount of Bi into Sn-Zn solder reduced the tendency to form cracks at the solder/Cu interface. This is because alloying with Bi reduced the mismatch of the coefficient of thermal expansion (CTE) between the solder alloys and the Cu plate. Moreover, the Sn-Zn solder with Bi reduced the melting temperature of the solder alloy.

The microstructures, wettability and mechanical properties of Sn-9Zn-xAg (x = 0, 0.1, 0.3, 0.5, 1wt. %) lead-free solders were studied [22]. The results showed that, when the quantity of Ag added to the solder is 0.3wt. %, the microstructure of the solder becomes finer and more uniform than Sn-9Zn, and when the quantity of Ag is exceeded 0.3 wt.% (up to 0.5-1wt. %), the AgZn₃ intermetallic compounds appeared in the solder. In particular, adding 0.3 wt. % Ag improved the wettability due to the better oxidation resistance of the Sn-9Zn-0.3Ag solder. Results also indicated that adding 0.3wt. % Ag to the solder enhanced mechanical property of soldered joint, while the properties at 1wt. % Ag were decreased.

The effect of Bi content on the microstructure, thermal, and mechanical properties of the eutectic Sn-Zn alloy was studied [23]. The results showed that, addition of Bi decreased the melting point and heat of fusion of the solders. 1% Bi addition enhanced the solid solution effect and raised the tensile strength.

The effect of 1, 3, 5 and 10wt. % Bi additions on structure, melting and mechanical properties of rapidly solidified Sn-3.5Ag alloy was studied [24]. The results showed that, Bi precipitation in Sn matrix was only observed in Sn-3.5Ag-5Bi and Sn-3.5Ag-10Bi alloys. Also, addition of Bi decreased continuously the melting point of the eutectic Sn-3.5Ag alloy to 202.6 °C at 10wt. % Bi. Vickers hardness number of Sn-3.5Ag alloy increased with increasing Bi content up to 3wt% due to supersaturated solid solution strengthening hardening mechanism of Bi phase in Sn matrix, while the alloys contain 5 and 10 % Bi exhibited lower values of Vickers hardness.

The effect of a third element addition of Al and Cu on the microstructural and mechanical properties as well as thermal behavior of Sn-9Zn eutectic alloy was studied [25]. The results indicated that, both Al and Cu refined the microstructure and formed intermetallic compounds with the eutectic solder alloy.

The microstructures of the newly developed ternary Sn–9Zn–X solder alloys were composed of fine needle-like α -Zn phase with some IMC dispersed in the β -Sn matrix. The relatively small and compact shaped $\text{Al}_6\text{Zn}_3\text{Sn}$ IMC was found to be uniformly distributed in the β -Sn phase causing an increase in the tensile strength, due to the second phase dispersed strengthening mechanism. On contrary, the large flower shaped of Cu_6Sn_5 and rod shaped of Cu_5Zn_8 IMCs developed some sort of weak interface with the parent β -Sn matrix results in a decrease in the tensile strength. The microhardness of the Sn–9Zn–0.5Al ternary solder alloys was also higher than that of the Sn–9Zn–0.5Cu alloy.

The tensile properties of the Sn–3.7Ag–0.9Zn– x Al ($x = 0, 0.5$ and $1.0\text{wt.}\%$) solders were studied [26]. The results suggested that, addition of Al in the Sn-3.7Ag-0.9Zn solder decreased both the tensile strength and ductility. Moreover, a brittle fracture occurs instead of a ductile fracture with increasing Al content.

The effect of alloying elements such as rare earth, Bi, Sb, Fe, Co, Mn, Ti, In, Ni, and Ge on the properties of the SnAgCu alloy was studied [27]. The results showed that, small amount of RE elements can greatly enhance the properties of metals, such as microstructure refinement. In addition, a small amount of Zn addition has the ability to reduce undercooling efficiently and suppress the formation of massive primary Ag_3Sn plates, and Bi/Ga has the ability to enhance the wettability of SnAgCu alloys as well as Ni.

The effect of Ge additions (0.1–0.5at. %) on properties of Sn-13Zn-3Bi solder-alloys, specifically the anti-oxidation capability, electrical resistance, thermal expansion behavior, and mechanical strength were studied [28]. The results showed that, the Sn-Zn-Bi-Ge alloys have a melting point around 197°C . Electrical resistivity of Sn-Zn-Bi-Ge solder-alloys, $10\text{--}15\ \mu\Omega\ \text{cm}$, is much lower than that of Sn-37Pb solder. The microhardness up to 400 MPa with 0.5 at. % Ge addition, is 150 % that of Ge-free Sn₈₄Zn₁₃Bi₃, or 300 % that of Sn-37Pb solder. Moreover, it possesses better tensile strength, being 127 % that of Ge-free Sn₈₄Zn₁₃Bi₃, and 190 % that of Sn-37Pb solder.

The effect of adding 0.45 %Al on oxidation of 91Sn-9Zn solder was studied [29]. The studies were also extended to the 63Sn-37Pb, 91Sn-9Zn, and 99.4Sn-0.6Al alloys for comparison.

The weight gains per unit surface area descend in the order: 63Sn-37Pb > Sn > 91Sn-9Zn > 91Sn-8.55Zn-0.45Al > 99.4Sn-0.6Al. The initial weight gains of the materials investigated increase linearly with reaction time, while parabolic behavior existed after the linear stage.

The effect of silver (Ag) and bismuth (Bi) on corrosion resistance of Sn-9Zn alloy in 3wt.% NaCl solution using electrochemical techniques was studied [30]. The results showed that, additions of Bi and Ag increased corrosion rate and the corrosion potential E_{corr} was shifted towards less noble values. After immersion, X-ray diffraction (XRD), scanning electron microscopy (SEM) and energy dispersive of spectroscopy (EDS) analysis of the corroded alloy surface revealed the nature of corrosion products. EDS and XRD analyses confirmed the oxide of zinc (ZnO and $\text{Zn}_5(\text{OH})_8\text{Cl}_2\text{H}_2\text{O}$) as the major corrosion product formed on the outer surface of the tested three solder alloys.

The creep behavior of the Sn-5Sb-1.5Bi, Sn-5Sb-1.5Ag, and Sn-5Sb-1Ag-1Bi alloys by impression testing and compared to that of the Sn-5Sb base alloy was studied [31]. The tests were carried out under constant stress in the range 40-180 MPa and at temperatures in the range 298-373 K. The results showed that; Sn-5Sb-1.5Bi had the lowest creep rate, and thus the highest creep resistance among all materials tested. This is mainly due to the strong solid solution hardening effect of Bi in Sn, which decreased the minimum creep rate. The creep resistance of the Ag-containing alloys was higher than that of the binary base alloy, due to the formation of spherical and rod-shape Ag_3Sn particles along the grain boundaries and inside the grains.

The effect of trace addition of Cr on the mechanical properties and reliability on Sn-8Zn-3Bi solder alloys was studied [32]. It has been demonstrated that the microstructure of solder alloys was refined after doping traces of Cr. aging time of 0, 4, 9 and 16 days, mechanical property of Sn-8Zn-3Bi-0.3Cr alloy was improved slightly. It was found that the Sn-Zn-Cr phase was increased and Zn in alloy was consumed after aging, so that the amount of primary Zn phase was reduced and microstructure was improved.

The effect of minor alloying addition of Ni and Sb on the microstructure and solidification behavior as well as the creep properties of Sn-1.0Ag-0.5Cu (SAC105) alloys was studied [33]. The results showed that alloying of Ni and Sb resulted in considerably reduced undercooling, increased eutectic area and extended volume fraction of proeutectic Sn of which the dendritic size was refined.

Moreover, with the addition of Ni and Sb into SAC105, significant improvement in creep resistance of (210%) and (350%) is realized when compared with the SAC105 solder alloy. Likewise, the creep life time of SAC105 alloys was remarkably enhanced (2–3 times) with the minor alloying additions. An analysis of the creep behavior at elevated temperatures suggested that the presence of hard Ni_3Sn_4 IMC particles and the solid solution hardening effects which appeared, respectively, in the Ni-doped and Sb-doped alloys could increase the resistance to dislocation movement, which improved the creep properties.

6. Summary

1. Solidification process plays an essential role in producing metallic alloys.
2. There are two types of solidification; slow (at rates lower than 10^4 K/s) and rapid (at rates higher than 10^5 K/s).
3. With regard to the structure of alloys, one or more of the following phases could be obtained: solid solution, intermediate phases, and phase mixture depending on the types of the metals presented in the alloy.
4. With regard to composition, metallic alloys are classified as either ferrous or nonferrous:
 - Ferrous alloys (steels and cast irons) are those in which iron is the prime constituent depending on the amount of carbon in these alloys. Alloys containing carbon less than 2.14 % are termed as steels, while containing carbon higher than 2.14 % are termed as cast irons.
 - Non-ferrous alloys in which all other alloys fall within them, which is further subdivided according to either the base metal or some distinctive characteristic that is shared by a group of alloys.
 - With regard to the base metal, alloys could be classified as: copper alloys, aluminum alloys, magnesium alloys and titanium alloys.
 - With regard to the distinctive characteristic, alloys could be classified as shape memory alloys; shielding blocks alloys, fusible alloys, and joining alloys.
5. With regard to the joining alloys, alloys could be classified as welding, brazing and soldering alloy.
6. With regard to the soldering alloys, alloys could be classified as lead-tin solders and lead-free solders.
7. Although there are many lead-free alloys were nominated as alternative to lead – tin solders, no one of them meet all the requirements of the alternative, which is still used so far.

7. References

- John A. Schey, Introduction to Manufacturing Processes, 3rd Edition, McGraw-Hill series in mechanical engineering and materials science, (2000).
- W. Callister and D. Rethwisch, Materials Science and Engineering, 8th Edition, (John Wiley & Sons, Ch.9, 2011).
- A. Cottrell, An Introduction to Metallurgy, Second Edition, (1971).
- M. Kamal and E. Gouda, Crystal Research and Technology, 41, (2005).
- W. Callister and D. Rethwisch, Materials Science and Engineering, 8th Edition, (John Wiley & Sons, Ch.11, 2011).
- ASM Handbook, Vol.1, Properties and Selection: Irons, Steels, and High-Performance Alloys, Reprinted by Permission of ASM International, Materials Park, OH, (1990).
- ASM Handbook, Vol.2, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, Reprinted by Permission of ASM International, Materials Park, OH, (1990).
- E. Gouda and M. Kamal, "Rapid Solidification Technology and Lead Free Solder Alloys", Lambert Academic Publishing Book, (2012).
- H. Manko, "Soldering Handbook for Printed Circuits and Surface Mounting", Van Nostr and Reinhold, New York, (1986).
- J. Glazer, "Metallurgy of Low Temperature Pb-free Solders for Electronic Assembly" Int. Mater. Rev., 40, 67, (1995).
- P. Vianco, "Development of Alternatives to Lead-Bearing Solders ", in: Proceedings of the Technical Program of Surface Mount International, 19 August-2 September 1993, San Jose, CA.
- B. Allenby, "An Assessment of the Use of Lead in Electronic Assembly," Proc. Surface Mount Int., San Jose, CA, (1992).
- P. Harris, M. Whitmore, "Alternative Solders for Electronics Assemblies: Part 1: Materials Selection", Circuit World, 19, 25, (1993).
- B. Huang and N. Lee, "Prospects of Lead-Free Alternatives for Reflow Soldering", in Proc. of IMAPS'99, Chicago, October 28, (1999).
- Y. Kim, K. Kim, C. Hwang and K. Sukanuma, Alloys and Compounds, 3
- Y. Zhang, T. Liang, and M. Jusheng, Non-Crystalline Solids, 336, 153, (2004).
- M. Kamal, and E. Gouda, Materials and Manufacturing Processes, 21, 740, (2006).
- U. Mohanty and K. Lin, Applied Surface Science, 252, 5907, (2006).
- X. Chen, M. Li, X. Ren, A. Hu, and D. Mao, Journal of Electronic Materials, 35, 1734, (2006).
- F. Rosalbino, E. Angelini, G. Zanichchi, R. Marazza, Materials Chemistry and Physics, 109, 2-3, (2008).
- J. Chen, J. Shen, D. Min, and C. Peng, Journal of Materials Science: Materials in Electronics, 20, 1112, (2008).
- W. Chen, S. Xue, H. Wang, J. Wang, Z. Han and L. Gao, Journal of Materials Science: Materials in Electronics, 21, 461, (2009).
- A. El-Daly, Y. Swilem, M. Makled, M. El-Shaarawy, and A. Abdraboh, Journal of Alloys and Compounds, 484, 134, (2009).
- M. Kamal, E. Gouda, and L. Marei, Crystal Research and Technology, 44, 12, 1308, (2009).
- S. Das, A. Sharif, Y. Chan, N. Wong, and W. Yung, Journal of Alloys and Compounds, 481, 1-2, 167, (2009).

- C. Wei, Y. Liu, L. Yu, H. Chen and X. Wang, *Microelectronic Reliability*, 50, 8, 1142, (2010).
- L. Gao, S. Xue, Zhang, Z. Sheng, F. Ji, W. Dai, S. Yu and G. Zeng, *Microelectronic Engineering*, 87, 11, 2025, (2010).
- S. Wang, T. Chin, C. Yang, S. Chen, and C. Chuang, *Journal of Alloys and Compounds*, 497, 428, (2010).
- K. Lin, and T. Liu, *Oxidation of Metals*, 50, 255, (2010).
- A. Ahmido, A. Sabbar, H. Zouihri, K. Dakhsi, F. Guedira, M. Serghini-Idrissi and S. El Hajjaji, *Materials Science and Engineering: B*, 176, 13, 1032, (2011).
- A. Geranmayeh, G. Nayeri, and R. Mahmudi, *Materials Science and Engineering: A*, 547, 15, (2012).
- T. Luo, A. Hu, j. Hu. M. Li and D. Mao, *Microelectronics Reliability*, 52, 3, 585, (2012).
- A. El-Daly, A. Hammad, A. Fawzy, D. Nasralh, *Materials & Design*, 43, 1, 40, (2013).