5

NONFERROUS METALS AND ALLOYS

5.1 INTRODUCTION

Nonferrous metals are those which do not contain iron as base. Their melting points are generally lower than that of ferrous metals. Nonferrous metals suffer generally from hot-shortness, posses low strength at high temperature, and their shrinkage is generally more than that of ferrous metals. Nonferrous metals are used for the following reasons :

1. Resistance to corrosion.
2. Special electrical and magnetic properties.
3. Softness and facility of cold working.
4. Fusibility and ease of casting.
5. Good formability.
6. Low density.
7. Attractive colour.

The principal nonferrous metals used in engineering purposes are : aluminium, copper, lead, tin, zinc, nickel, etc. and their alloys.

5.2 ALUMINIUM AND ITS ALLOYS

Aluminium is a white metal produced by electrical processes from the oxide (alumina), which is prepared from a clayey mineral called ***bauxite***. In India they are chiefly available in Bihar, Madhya Pradesh, Karnataka, Maharastra and Tamilnadu.

It is silvery-white in colour and extensively used where a light noncorrosive metal is desired as in aircraft and automobile components where the saving of weight is an advantage. In its pure state the metal would be weak and soft for most purposes, but when mixed with small amounts of other metals it becomes hard and rigid. So it may be blanked, formed, drawn, turned, cast, forged, and die-cast. Its good electrical conductivity is an important property and aluminium is used for overhead cables. The high resistance to corrosion and its non-toxicity make it a useful metal for cooking utensils ; under ordinary conditions, water and air have practically no effect on it. Since pure aluminium is more corosion resistant than any alloy of aluminium, a thin layout pure aluminium is generally cladded on the sheets of aluminium alloy to elimination corrosion. Again pure aluminium is not heat treatable. Aluminium alloy cladded by thin layer of aluminium can be heat treated. In this composite, the core containing aluminium alloy can be hardened. Roll bonding, a technique used for cladding sheets is shown in Fig. 5.1. Aluminium has the property of being beaten into foil and this aluminium foil is now widely used as silver foil. Aluminium metal of high purity have got high reflecting power and is, therefore, widely used for reflectors, mirror, and telescopes. The melting point of aluminium is 658°C and is having a specific gravity of 2.65.

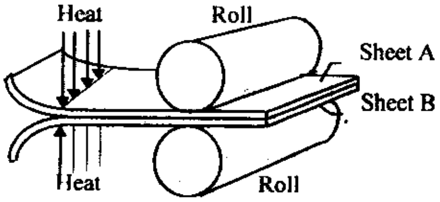


Figure 5.1 Roll bonding method

ALUMINIUM ALLOYS

Aluminium finds its widest uses when alloyed with small amounts of other metals. The addition of small quantities of other alloying elements converts this soft, weak metal into a hard and strong metal, while still retaining its light weight. Alloys can be classified as *cast* or *wrought*, both groups containing alloys that are age-hardened. The alloys in each of these two classes are further classified according to whether they respond to heat treatment of the strengthening type.

For the casting of general engineering use, aluminium is alloyed with small amounts of copper and zinc in the proportion of 12.5 to 14.5 per cent zinc and 2.5 to 3.0 per cent copper. An important series of casting and forging alloys having high strength have recently been developed for use in aeroplane construction. One example of such alloys is : zinc 5 per cent, magnesium 3 per cent, copper 2.2 per cent, nickel up to 1 per cent, aluminium the remainder.

An important and interesting wrought alloy is known as *duralumin*. This is composed of 3.5 to 4.5 per cent copper, 0.4 to 0.7 per cent manganese, 0.4 to 0.7 per cent magnesium, and aluminium the remainder. It is widely used in wrought condition for forging, stampings, bars, sheets, tubes and rivets. It is interesting because of its age-hardening property. After working if the metal is allowed to age for 3 or 4 days, it will be hardened. This phenomenon is called *age-hardening*. In the heat-treated and aged condition duralumin may have a tensile strength up to 40 kgf per mm^2 (400 Newton per mm^2).

Another alloy known as *Y-alloy* contains 3.5 to 4.5 per cent copper, 1.8 to 2.3 per cent nickel, and 1.2 to 1.7 per cent magnesium. This alloy has the characteristic of retaining good strength at high temperatures. *Y-alloy* is, therefore, useful for piston and other components of aero-engines. It is also largely used in the form of sheets and strips, and after proper heat treatment this may be brought to minimum tensile strength of about 35 kgf per mm^2 (350 Newton per mm^2).

Berrylium copper are solution heat treated and precipation hardened. Aging time is 2 to 3 hours at aound 325° C. Aluminium bronzes containing more than 10 per cent aluminium are quenched from 650° C and subsequently tempered at a low temperature.

Table 5.1 shows some of the common alloys of aluminium together with their mechanical properties and applications.

5.3 COPPER AND ITS ALLOYS

Copper is easily distinguished from all other metals on account of its red colour. It is not found in pure state under the earth. Copper is extracted from copper ores, the chief being copper *pyrites*. Copper ore is first ground and then smelted in a reverberatory or small blast furnace producing an impure alloy called *matte*. In the second step air is blown through the molten metal to remove sulphur and iron contamination to obtain *blister* copper in the converter. In the last stage further refinement is carried out to produce pure copper (99.9 per cent) using electrolysis. For pyrites ($CuFeS_2$) and copper glance (Cu_2S), the roasting / smelting process liberates fumes of sulphur and arsenic which are destructive for environment. Collection of these poisonous gases is mandatory for the smelting unit. In India, copper ore is found at Ghatsila in Bihar.

Copper is relatively soft and is very malleable, ductile and flexible, yet very tough and strong. A very efficient conductor of heat and electricity, being second only to silver, it is largely used in wire and sheet form for electrical purposes. Copper may be cast, forged, rolled and drawn into wires. It is non-corrosive under ordinary conditions and it resists weather very effectively. Copper in the form of tubes is used widely in

TABLE 5.1 MECHANICAL PROPERTIES AND APPLIANCES OF COMMON ALUMINIUM ALLOYS

Composition (Balance=A1)	*Condition* *	*Tensile Strength* ** MPa	*Yield* (0.2% proof stress) MPa	*% Elongation* 50 mm gl	*BHN Number*	*Shear Strength* MPa	*Endurance* # *Limit* MPa	*Charasteristic and uses*
1.2 % Mn	A	110	41	30	28	75	48	A non-heat-treatable work-hardening wrought alloy used for general sheet-metal applications and cooking utensils.
	W	200	186	4	55	110	69	
4.0% Cu, 0.5% Mg 0.5% Mn, 0.5% Si	A	180	69	20	45	124	90	Duralumin, an age – hardening wrought alloy, hardened by quenching and ageing; used for aircraft constriction in the form of Alclad.
	HT	425	275	20	105	262	125	
4.4% Cu, 0.8% Si 0.8% Mn, 0.4% Mg	A	186	96	12	45	124	75	A strong age-hardening alloy for forging and extrusion
	HT							
7.0% Cu, 2.0% Si 1.7% Zn	As Cast	165	105	1.5	70	–	–	General purpose sand-casting alloy that is not age-hardened and has low corrosion resistance
4.0% Cu, 1.5% Mg 2.0% Ni	As Cast	186	124	1.0	70	–	–	A sand-casting alloy capable of withstanding high temperatures.
12% Si	As Cast	270	145	2.7	–	–	–	A general purpose non-heat-treatable die-casting alloy having excellent corrosion resistance.
9.5 % Si, 0.5 % Mg	As Cast	300	186	3.0	–	–	–	A die-casting alloy having high strength and good corrosion resistance

*A=annealed, W=coldworked, HT=heat treated, # 500 million cycles in reverse bending.

mechanical engineering and also used in the making of munitions. The mechanical properties of copper depend upon its condition. Casting may have a tensile strength of 15 to 17 kgf per mm^2 (150 to 170 Newton per mm^2) which may be increased to 21.5 to 23.0 by working. The strength of hard-drawn copper wire may be as high as 38 to 46 kgf per mm^2. The melting point of copper is 1,083°C.

COPPER ALLOYS

Copper may be alloyed with a wide range of other elements to produce many different alloy groups of industrial importance. The most important are :

1. Copper aluminium (the aluminium bronzes).
2. Copper-tin-antimony (babbitt metal).
3. Copper-tin (the tin bronzes).
4. Copper-tin-phosphorus (the phosphor bronzes).
5. Copper-zinc (the brasses).
6. Copper-nickel (the cupro-nickels).

COPPER-ALUMINIUM ALLOY OR ALUMINIUM BRONZE

Copper alloys with aluminium gives aluminium bronze and the chief alloys are those containing 6 per cent and 10 per cent of aluminium and copper respectively. The aluminium gives the alloy lightness, while the addition of copper to pure aluminium increases its strength. The 6 per cent aluminium alloy has a fine gold colour, being used for imitation jewellery and decorative purposes.

Other copper alloys are described in the sections in **5.7** and **5.8**.

5.4 LEAD AND ITS ALLOYS

Lead is the heaviest of the common metals. It is extracted from lead ore called *galena*, which is a sulphide of lead. India is having very little lead ores. Lead has a bluish-grey colour and a dull, metallic lustre, but this is lost on exposure to the air, the surface becoming a dull grey.

Lead is a very soft, malleable and ductile metal and can be rolled easily. It is resistant to corrosion and many acids have no chemical action on it. Because of this it is used for water-pipes, roof covering, the sheathing of electric cables and for construction material of chemical plants. The melting point of lead is 327°C.

LEAD ALLOY

Lead alloyed with tin forms *solders* and alloyed with other metals makes bearing white metals and *type metal*. Alloyed with small percentage of arsenic, lead is used to produce shots for munitions.

5.5 TIN

Tin is obtained from *tin stone*, and oxide by a refining process carried out in a reverberatory furnace. In India, its sources are quite negligible. It is a brilliant white metal with a yellowish tinge. The melting point of tin is 232°C.

Soft, malleable and ductile, it can be rolled into very thin sheets. Tin does not corrode in wet and dry climates, making it useful as a protective coating for iron and steel. It is also used for tinning copper wire before the latter is made into cables.

5.6 BEARING METALS

Bearing metals may be classified into following groups :

1. Copper-base bearing metals containing copper, tin and lead.
2. Tin-base bearing metals containing tin, antimony, and copper.
3. Lead-base bearing metals containing lead, tin, and antimony.
4. Cadmium-base bearing metals containing cadmium and nickel.

Those alloys in which tin, lead, and cadmium are predominating elements are designated as *white-metal bearing alloys*. They have the properties of high plasticity combined with the low hardness and comparatively low melting point, which facilitates the formation of bearings by casting the metal directly in place and usually require no machining.

The *copper-base alloys* are harder and stronger than the white metals and are used for bearings which are required to resist heavier pressures. *Tin-base white metals* are used where bearings are subjected to high pressure and load, whereas for light loads and pressure *lead-base alloys* are used. Of the lead-base alloys, the alloys which contain 80 per cent lead and 20per cent antimony is generally used. *Cadmium-base bearing metals* have more favourable properties, especially at elevated temperatures, than the tin-base alloys. The compressive strength of the cadmium-base bearing alloys are greater than those of the tin-base alloys.

To give an efficient bearing combinations the following conditions are necessary :

1. That the shaft and bearing be dissimilar in their nature with bearing softer than the shaft.
2. That the most efficient bearing metal is one consisting of small pieces of a comparatively hard metal embedded in the softer body of another metal.
3. That the bearing metals should have sufficient compressive strength to carry the bearing pressure, should wear to smooth surfaces as they rub together, and should develop a minimum of friction when they actually come in contact, as for example, when a shaft is starting or stopping.

5.7 COPPER-TIN-ANTIMONY ALLOY (BABBITT METAL)

Babbitt metal is a tin-base white metal and it contains 88 per cent tin, 8 per cent antimony and 4 per cent copper. It is a soft material with a low coefficient of friction and has little strength.

Babbitt metal makes a fine bearing and does not scour the shaft very easily when the lubricant fails. It is the most common bearing metal used with cast iron boxes when the bearings are subjected to high pressure and load.

5.8 COPPER-TIN ALLOY

Bronzes, gun metal and bell metal are important copper-tin alloys.

BRONZE

Bronze is an alloy composed mainly of copper and tin. The useful range of composition in 5 to 25 per cent tin and 75 to 95 per cent copper.

The alloy is comparatively hard, resist surface wear and can be cast into shape or rolled into wire, rods and sheets very easily. In corrosion resistant properties bronzes are superior to brasses.

It is used in hydraulic fittings, pump linings, in making utensils, bearings, bushes, sheets, rods, wires, and many other stamped and drawn articles.

Some of the more common types of bronze and the special purposes for which they are used are given below :

PHOSPHOR BRONZE

When bronze contains phosphorus, it is called phosphorus bronze. The compositions of this metal varies according to weather it is to be forged and wrought or weather made into castings. A common type of wrought phosphor bronze has copper 93.7, tin 6, and phosphorus 0.3 per cent.

Phosphorus increases the strength, ductility, and soundness of castings. The alloy possesses good wearing quality and high elasticity. The metal is resistant to salt water corrosion.

It is used for all average bearings in which wearing qualities are desired. Pump parts, linings, and propellers are examples of cast manufacture. A variety of phosphor bronze suitable for casting contains 11 per cent tin and 0.3 per cent phosphorus alloyed with copper. This is used for bearings which must carry heavy loads, worm wheels, gears, nuts for machine lead screws, springs and many other purposes.

SILICON BRONZE

Silicon bronze has an average composition of 96 per cent copper, 3 per cent silicon, and 1 per cent manganese or zinc.

It has the good general corrosion resistance of copper, combined with higher strength, and in addition can be cast, rolled, stamped, forged, and pressed either hot, or cold and can be welded by all the usual methods.

Silicon bronze finds application in parts for boilers, tanks, stoves, or wherever high strength and good corrosion resistance are required.

MANGANESE BRONZE

Manganese bronze is an alloy of copper, zinc, lead, and a little percentage of manganese. The metal is highly resistant to corrosion. It is stronger and harder than phosphor bronze.

It is generally used for preparing bushes, plungers and feed pumps, rods, etc. Worm gears are frequently made from this bronze.

GUN METAL

Gun metal contains 10 per cent tin, 88 per cent copper, and 2 per cent zinc. The zinc is added to clean the metal and increase its fluidity.

It is not suitable for being worked in the cold state but may be forged when at about 600°C. The metal is very strong and resistant to corrosion by water and atmosphere. Originally, it was made for casting boiler fittings, bushes, bearings, glands, etc.

BELL METAL

It contains 20 per cent tin and the rest is copper. It is hard and resistant to surface wear. Bell metal is used for making bells, gongs, utensils, etc.

5.9 ZINC AND ITS ALLOYS

The chief ores of zinc are ***zinc blende*** (zinc sulphide) and ***calamine*** (zinc carbonate). In the extraction of the metal, the ore is first roasted in a reverberatory furnace to convert the sulphide to oxide, and in the case of calamine, to drive off carbonic acid and water. The roasted ore is then reduced either in a furnace or electrolytically.

Zinc is a fairly heavy, bluish-white metal used principally because of its low cost, corrosion resistance, and alloying properties. The melting point of zinc is 419°C.

The protection of iron and steel from corrosion is done more often with zinc than with any other metal coating. The oldest and most important methods of applying the zinc coating are known as ***galvanizing***. When rolled into sheets, zinc is used for roof covering and for providing a damp-proof noncorrosive lining to containers, etc. Zinc casts well and forms the base of various die-casting alloys. A typical high strength die-casting alloy would have the following composition and properties. (Table 5.2).

TABLE 5.2 TYPICAL DIE-CASTING ALLOYS

	Composition	
Cu = 1.25 per cent	Al = 4.0 per cent	Mg = 0.08 per cent
Fe = 0.10 per cent	Pb = 0.007 per cent	Cd = 0.0007 per cent
Sn = 0.007 per cent	Zn = remainder	

Properties

UTS = 32 kgf/mm^2 or 320 Mpa

per cent elongation = 7 per cent

Charpy Impact No. = 65 J or 6.5 kgm

Melting point = 425°C

5.10 COPPER-ZINC ALLOY

The most widely used copper-zinc alloys are brass and muntz metal.

BRASSES

This is fundamentally a binary alloy of copper with as much as 50 per cent Zinc. Various classes of brass, depending on the proportion of copper and zinc, are available for various uses. Suitable types of brass lend themselves to the following processes : casting, hot forging, cold forging, cold rolling, into sheets, drawing into wire and being extruded through dies to give special shaped bars. The melting point of brass ranges from 800°C to 1,000°C.

The alloy is noncorrosive and air, water and some acids do not appreciably affect it. It is soft, ductile and has tensile strength with good fusibility and surface-finish characteristic. It is non-magnetic and is poor conductor of electricity. By adding small quantities of other elements the properties of brass may be greatly changed, as for example, the addition of 1 or 2 per cent of lead improves the machining quality of brass. Small amounts of tin are sometimes added to brass to increase its hardness.

Brasses are used in hydraulic fittings, pump linings, in making utensils, bearings, bushes, etc.

MUNTZ METAL

It contains 40 per cent zinc and 60 per cent copper. Sometimes, a small per centage of lead is also included. It is stronger, harder, and more ductile than common brass. It is excellently suited for working at 700°C to 750°C but not for cold working.

Muntz metal is used for a wide variety of small components of machines, electrical equipment, fuses, ordnance works, and for bolts, rods, tubes, etc. It is widely employed in making such articles which are to resist wear. Table 5.3 gives the properties and uses of some of the important brasses.

5.11 NICKEL AND ITS ALLOYS

Although some nickel is obtained commercially from oxide ores, arsenical ores, and the ores of copper, manganese and iron, at least 85 per cent of all nickel production is obtained from *sulphide ores*.

Pure nickel is tough, silver-coloured metal, rather harder than copper, and of about the same strength, but possessing somewhat less ductility. It closely resembles iron in several of its properties, being malleable and weldable, and perceptibly magnetic, but unlike iron it is little affected by dilute acids, is far less readily oxidisable, and deteriorates

TABLE 5.3 COMPOSITION, PROPERTIES AND USES OF BRASSES

Name	*Composition*		*Other elements*	*Microstructure*	*UTS, depending upon working (MPa)*	*Uses*
	Copper	*Zinc*				
Copper	100	–	–	Pure metal	150-480	Tubing, piping, sheet, wire, electrical conductors
Guilding metal	90	10	–	Alpha	280-505	Forgings, rivets, jewellery applications.
Tombac or French Gold Low brass	80	20	–	Alpha	325-825	Drawing and forging operations.
Cartridge or spinning brass	70	30	–	Alpha	365-635	Cartridge cases, condensor tube, sheet fabrication, a general purpose brass.
Admiralty brass	70	29	Sn=1	Alpha	365-635	Condensor tubes exposed to salt water (high corrosion resistance)
High metal	66	34	–	Alpha	365-860	Stamping and drawing operations.
Muntz metal	60	40	–	Alpha-beta	410-860	Suitable for many hot working operations; rolled also cast valves and marine fittings.
Naval brass	60	39	Sn=1	Alpha-beta	610-860	As above, but posses increased corrosion resistance.
Tobin "bronze"	60	38	Sn=1 Al=1	Alpha-beta	410-860	Brazing alloy for naval brasses, etc..
Manganese "bronze"	62	32	Al=4 Fe=1.5 Mn=2.25		410-1035	High tensile casting metal, yield point=510 MN/m^2, UTS=710 MN/m^2.
Brazing brass	50	50	–	Beta		Brazing rods.

much less rapidly under atmospheric influences. For this reason articles of iron and steel are frequently nickel-plated to protect them from rusting. Nickel is much used for cooking utensils, and other vessels for heating and boiling. Nickel enters as a constituent into a large number of ferrous and nonferrous alloys, and frequently finds application as a catalyst in important industrial processes.

Nickel alloys which are practicularly useful for general industrial purposes are described below.

MONEL METAL

It is an alloy of 60per cent nickel, 38per cent copper and a small amount of aluminium or manganese.

It is a white, tough, and ductile metal and can be readily machined. It welds without difficulty. It can be heat-treated. It is also resistant to corrosion by most agents and has high strength at elevated temperatures.

Monel metal is used in the forms of rod, sheet, wire, and welded tubing. It is widely employed for structural and machine parts which must have a very high resistance to corrosion and high strength as steam turbine blade, impeller of centrifugal pump, etc.

GERMAN SILVER

An alloy of copper (25 to 50 per cent), nickel (10 to 35 per cent), and zinc (25 to 35 per cent) is known as German silver. Sometimes, tin and lead are also added.

It is hard, white and ductile. This is usually of bright silvery colour, but may also assume various other pleasing colours by adjusting the proportions of copper, nickel and zinc. It has in addition to colour, good mechanical and corrosion resisting properties. It is also known Ni-silver.

German silver is used for making utensils and resistances in electrical work.

INCONEL

It contains 75 to 80 per cent nickel, 10 to 15 per cent chromium and the rest iron. It can be used for parts that are exposed to high temperature for extended period. It is less reactive than nichrome to acid.

NICHROME

This is an alloy of nickel with chromium and is used widely as resistance wire for electrical appliances.

NIMONICS

A new type of nickel alloy called nimonics are being developed, which by proper heat treatment attain excellent properties for very high temperature service as well as under intermittent heating and cooling conditions. They contain 15 to 18 per cent chromium, 15 to 18 per cent cobalt, 3.5 to 5 per cent molybdenum, 1.2 to 4.0 per cent titanium, 1.2 to 5.0 per cent aluminium, and the remainder nickel.

5.12 ALLOYS FOR HIGH TEMPERATURE SERVICE

Many components in jet and rocket engines, and in nuclear equipment have to withstand temperatures in excess of 1100°C. This has made to develop a number of highly specialized alloys. Nickel or cobalt forms the base metals in this range of alloys. Most of these alloys possess yield strength in excess of 70 MN/mm^2 or 700 kgf/mm^2 and 250 to 370 Brinell hardness number at room temperature. Table 5.4 shows some typical-high-temperature alloys.

TABLE 5.4 ALLOYS FOR HIGH TEMPERATURE SERVICE

	Types of alloy				
Composition	*Nimonic 80A*	*Inconel 713C*	*Incoloy 910*	*Hastelloy*	*Vitallium*
Nickel	Balance	Balance	42.0	45.0	2.5
Chromium	21.0	12.0	13.0	22.0	28.0
Cobalt	–	–	–	1.5	62.0
Tungsten	–	–	–	0.5	–
Titanium	2.5	0.5	2.4	–	–
Iron	–	–	Balance	Balance	1.7
Tantalum	–	2.0	–	–	–
Aluminium	1.2	6.0	–	–	–
Carbon	0.04	4.5	0.04	0.15	0.28
Molybdenum	–	–	6.0	9.0	5.5

5.13 METALS FOR NUCLEAR ENERGY

Recent nuclear power developments have created a demand for materials to withstand stringent condition imposed, and as a result some metals, previously considered "rare" are now coming in the use in a wide perspective. The various metals for producing nuclear energy are used as raw materials, moderators reflectors, fuel elements, fuel canning materials, control elements, and pressure vessel materials. Thus, uranium, thorium, plutonium, zirconium, beryllium, niobium and their alloys are primarily used for nuclear engineering purposes.

URANIUM

The most important metal found in nature and used for nuclear energy is uranium. This is used as a nuclear fuel and is radioactive, easily oxidized and exists in three allotropic forms. This has a poor resistance to corrosion and needs to be protected for use as fuel elements by roll cladding a thin aluminium or zirconium jacket. The metal in the pure condition is weak and is susceptible to severe irradiation damage and growth in the reactor environments. Addition of some alloying elements such as chromium, molybdenum, plutonium, zirconium, etc. are added to make the meterial highly suitable for nuclear power.

Uranium compounds, such as UO_2 as a dispersion in cermets or as ceramic slugs, have been found to give better service. Uranium oxide is highly refractory, shows no phase change in an inert atmosphere, possesses a good strength and a high corrosion resistance. But it has a low thermal shock resistance, poor thermal conductivity and a high coefficient of expansion. The melting point of uranium is 1850°C.

THORIUM

Thorium is another possible fuel and is free from phase changes below 1480°C. Thorium ($_{90}Th^{234}$) is also a radioactive metal like uranium and this can be converted into uranium ($_{92}U^{234}$) by beta decay. The mechanical properties of thorium which is soft and weak when pure, are drastically changed by small addition of impurities. Only 0.2 per cent of carbon raises its tensile strength from 14 to 38 kgf/mm^2 (140 to 380 MPa). Small additions of titanium, zirconium, and niobium decreases the strength and hardness of the metal. Uranium addition increases the strength of thorium.

Thorium like uranium is an emitter of alpha rays and releases considerable quantity of the radioactive products during processing, but this being a cubic metal (*fcc*) is less susceptible to irradiation damage. The melting point of thorium is 1845°C.

PLUTONIUM

This is a synthetic element and does not occur in nature. It is produced through neutron absorption by fertile U^{238} and subsequent beta decays. Plutonium melts at 640°C. It is extremely toxic and emits alpha rays. Due to its being naturally fissionable, plutonium continues to emit high energy gamma and other radiation. The metal is chemically more reactive than uranium and has a poor resistance to corrosion. It has six allotropic forms. The chief application of plutonium is in the production of atomic weapons and also in breeder reactors. Since some plutonium alloys and compounds emit neutrons, adequate health protection is necessary while using these materials.

ZIRCONIUM

Zirconium minerals contain 0.5 to 2 per cent hafnium which is a strong absorber of neutrons and must therefore be removed. The main use of zirconium is for cladding fuel elements and for structural components in water-cooled systems. So it must have increased corrosion resistance. Zircaloy-2 containing 1.5 % Zn, 0.1 % Fe, 0.05 % Ni, and 0.1 % Cr provides better corrosion resistance and is generally used in water-cooled reactors. Zirconium has a relatively poor resistance to CO_2 at elevated temperatures, but this is improved by the addition of 0.5 % Cu, 0.5 % Mo with an increase of tensile strength to 51 kgf/mm^2 (510 MPa) and improved creep resistance at 450°C. This zirconium is specially useful in gas cooled reactors. The melting point of Zirconium is 1750°C.

BERYLLIUM

Beryllium is a light metal and melts at about 1280°C. The metal is used as a moderator, reflector and neutron source. This is very reactive and forms compounds with the furnace atmospheres and refractories. Vacuum or inert gas are necessary during melting.

The cast metal is usually coarse grained and brittle, and powder metallurgy methods are employed in the fabrication of beryllium components.

Beryllium is a toxic metal. Its compounds are also very toxic. Safety measures are to be taken when handling this metal.

NIOBIUM (COLUMBIUM)

This has a high melting point 1950°C and good strength, ductility and corrosion resistance especially to liquid sodium coolants, and excellent capability of coexistence with uranium. Its oxidation resistance above 400°C is indifferent, but is greatly improved by alloying.

The metal niobium, titanium, hafnium, tantalium and zirconium alloys are all used in jet aircraft, reactors, missiles and for nuclear reactor.

REVIEW QUESTIONS

1. List and discuss some of the important properties of nonferrous metals and alloys.
2. Name the various alloys of copper and comment on their importance in industries.
3. Write shorts notes on : (a) Duralumin, (b) Phosphor bronze, (c) Babbitt metal, (d) Gun metal, (e) Muntz metal, (f) Monel metal, (g) Bronze.
4. What are the necessary properties of a bearing alloy ? Name some important bearing metals and give their approximate composition.
5. What are the demerits of the lead-base bearing alloys relative to the tin-base ones ?
6. Name the various nickel base alloys and list their various uses.
7. List the composition and properties of a die-casting alloy.
8. List the properties of aluminium that make it a useful engineering metal.
9. Write short notes on metals for nuclear energy.
10. List and write characteristics of some alloys for high temperature service.
11. Write short notes on alloying metals for aluminium alloy.

6

HEAT TREATMENT OF METALS AND ALLOYS

6.1 INTRODUCTION

Any solid metal normally has a definite cell (unit cell) shape and size at a certain energy state, but in some metals the shape as well as the size change from one energy state to another. The energy state is usually changed by adding or taking away heat. Such a process is called ***heat treatment***. It may therefore be defined as an operation or combination of operations involving the heating and cooling of metals or alloys in the *solid state* to produce certain desired properties. All heat treatment processes may be considered to consist of three main parts.

1. The heating of the meal to the predetermined temperature.
2. The soaking of the metal at that temperature until the structure becomes uniform throughout the mass.
3. The cooling of the metal at some predetermined rate to cause the formation of desirable structures within the metal/alloy for the desired purpose.

6.2 COOLING CURVE FOR PURE IRON

The melting point of pure iron is 1535°C. Iron may exist in several allotropic forms, e.g., α, β, γ, δ in the solid state. The existence of one form to the other depends upon the temperature to which the iron is heated. Fig. 6.1 illustrates the cooling curve for pure molten iron plotted in time *vs* temperature coordinates.

The first horizontal step appears on this curve at a temperature of 1535°C. It indicates that the transformation from the liquid state takes place at a constant temperature. Upon freezing the melt, delta iron is formed. This has a body centered cubic lattice constant a=2.93Å. (The lattice constants are measured in angstrom units, abbreviated Å and 1 Å =10^{-10} m).

The second temperature effect occurs at 1400° C (*Ar*) on the iron cooling curves and corresponds to the transformation of delta iron into a new allotropic form (Gamma iron). It has a face centered cubic lattice with a constant of 3.63 Å. Gamma iron is very weakly magnetic (paramagnetic), and it can dissolve carbon reaching a maximum value of 2 per cent at 1,130° C.

The third temperature effect occurs at 910° C (*Ar*). Here gamma iron is transformed into alpha iron with a body centered cubic lattice having a constant a=2.9 Å. It is nonmagnetic.

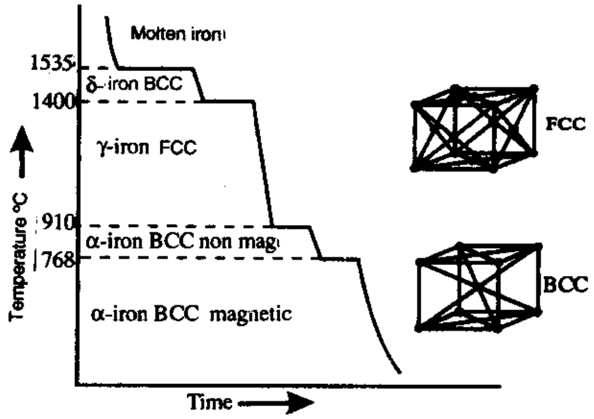


Figure 6.1 **Cooling curve for pure molten iron**

The last and the fourth retardation is observed at 768° C (*Ar*). It corresponds to alpha iron. The alpha form of iron is highly magnetic and is one that exists at room temperature. It can dissolve only a very small amount of carbon, the maximum being about 0.025 per cent at 723° C. At 20° C, the solubility is only 0.0025 per cent.

Thus it is evident from the illustration, there are actually two allotropic forms of iron–the low temperature modification, alpha iron ; and the high temperature form, gamma iron. These changes are reversible, i.e., same allotropic forms are observed during heating.

6.3 INVERSE-RATE CURVES FOR STEEL

If a piece of steel is slowly and uniformly heated and its temperature recorded at definite intervals of time a curve may be obtained. Such a curve is called an *inverse-rate curve*, the temperature as ordinate and time increments as abscissa. This is shown in Fig. 6.2

The curve is a vertical line except at those points where the heating and cooling rates show marked change.

It will be found that at certain points the temperature will tend to remain stationary, although the rate of heat input to the steel specimen has not been altered. During heating, these points are known as *decalescence points* which imply that the heat is being absorbed by the specimen. During cooling, however, these points are known as *recalescence points* where the steel is seen to take an extra glow as though heat has been imparted to it. Moreover, on heating a steel of specific composition, the temperature is arrested at always the same temperature points and the arrest at each point is apparent for constant time increment, within very fine margins of error for that point.

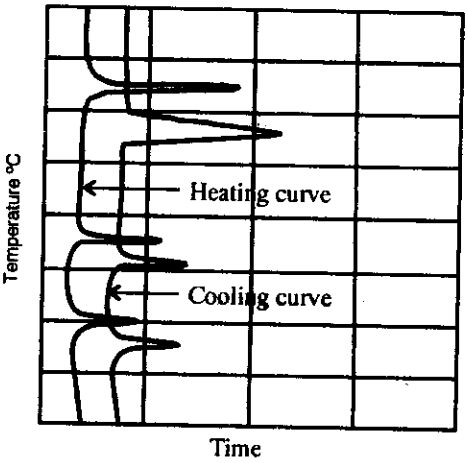


Figure 6.2 Inverse-rate curve

It can, therefore, be concluded that structural change takes place at these "arrest points" which are called *critical points*. The arrests that occur during cooling are denoted by the symbol Ar, 'A' standing for *arrest* and 'r' for *refroidissement* or *cooling* ; while arrests that occur during heating are denoted by Ac, 'c' being for *chauffage* or *heating*. The arrest points in the order in which they occur during heating or cooling are given numerals 1, 2, 3 and 4 such as Ac_1, Ar_1, etc. The arrest points are seen to take place about 20° to 30°C above or below each other during heating and cooling respectively. The range or temperature between two arrest or critical points is known as *thermal critical range*.

6.4 TRANSFORMATION IN STEEL

The binary iron-carbon equilibrium diagram, as said in Art. 2.12, and shown in Fig. 2.13 is the basis of steel treatment.

TRANSFORMATION ON HEATING

Hypoeutectoid steels containing less than 0.80 per cent carbon have a structure of ferrite and pearlite (Fig. 6.3) up to a temperature of 723°C (point Ac_1). When these steels are heated to a temperature between Ac_1 and Ac_3 the pearlite begins to transform into austenite (Fig. 6.3) and the steel consists of austenite and ferrite. Upon further heating above upper critical point Ac_3 all of the ferrite is dissolved in the austenite and the structure becomes purely austenitic (Fig. 2.13).

Eutectoid steel containing 0.80 per cent carbon consists of pearlite until it is heated to a temperature of 723° C (Ac_1). At point Ac_1 all the pearlite is transformed into austenite.

Hypereutectoid steels containing over 0.80 per cent carbon have a structure of pearlite and cementite upto the point Ac_1. As these steels are heated above Ac_1, the pearlite begins to transform into austenite, and the structure of hypereutectoid steels between points Ac_1 and Ac_m consists of austenite and cementite. At temperatures above Ac_m these steels acquire a purely austenitic structure.

TRANSFORMATION ON COOLING

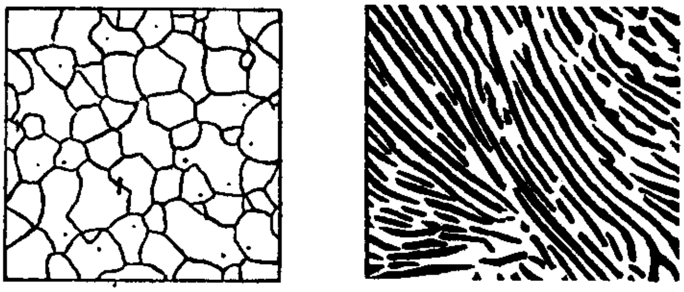
If austenite is obtained in a steel and then the heated steel is *slowly* cooled, the austenite will decompose below line PSK to form coarse-pearlite (Fig. 6.4), a mechanical mixture of ferrite and cementite.

An increased rate of cooling of the steel leads to the formation of a finely dispersed pearlite known as fine-pearlite (Fig. 6.4) or*sorbite*.

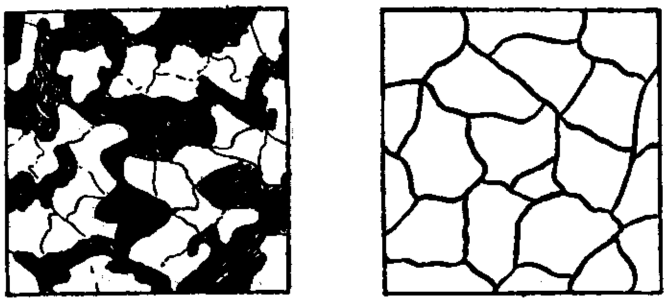
If the steel is cooled at a still higher rate, an even finer structure (Fig. 6.4) of austenite decomposition is obtained, which is called *troostite* or *bainite*.

Since the cementite in sorbite and troostite is in a finely divided state, the latter two constituents are harder than pearlite (coarse). While pearlite has a Brinell hardness of 180, that of sorbite is 350 and troostite–450.

When steel is cooled from the high-temperature region at a rate so high that the austenite does not have sufficient time to decompose into sorbite or troostite, the austenite is transformed into a new structure of acicular (needle-like) form, called *martensite* (Fig. 6.4). It is ferro-magnetic, very hard and brittle having Brinell hardness ranges from 650 to 750. The formation of martensite is accompanied by an increase in the volume of the steel by about 3 per cent. This results in internal stresses produced by rapid cooling (quenching).



Ferrite in pure iron × 200 Structure of pearlite × 1,000 approx



Structure of ferrite and pearlite Structure of austenite

Figure 6.3 **Normal microstructure of steel**

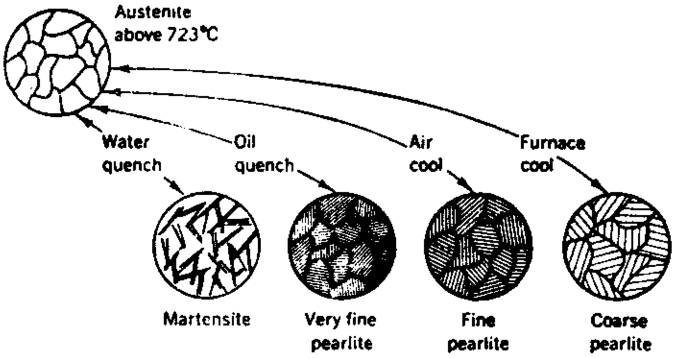


Figure 6.4 **Effect of cooling on austenite transformation**

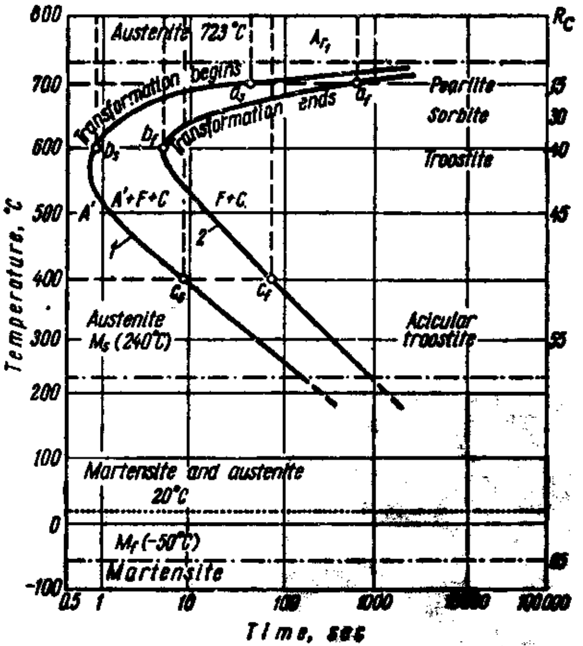


Figure 6.5 Isothermal austenite transformation

ISOTHERMAL TRANSFORMATION

The iron-carbon equilibrium diagram shows the types of phases present in the steel only under equilibrium conditions. However, equilibrium is not usually achieved, since the cooling rates, in practice, are made higher than those necessary to maintain an equilibrium. A diagram known as *TTT*-diagram is therefore used. It relates to the *transformation* of the austenite to the *time* and *temperature* conditions to which it is subjected. This is also called S-curve and C-curve due to their shapes. This is done by heating the steel above the critical points Ac_3, then rapidly cooling them to the desired temperatures to obtain austenite and, finally, holding the specimen at these temperatures for various lengths of time.

The various t_s and t_f in curve *1* and *2* respectively indicate the starting and finishing points of transformation at corresponding temperatures. The region to the left of curve *1* corresponds to supercooled austenite, denoted by *A'*. that to the right of curve *2*-to the complete transformation of austenite. The interval between them indicates conditions for the partial decomposition of austenite into ferrite and cementite denoted by *F*, and *C* respectively. This is shown in Fig. 6.5.

Austenite is stable above the dash line Ar_1. At temperatures in the vicinity of point Ar_1 (700°C) austenite decomposes and pearlite is formed ; at lower temperatures (600°C) *sorbite* is formed and at 500°–550°C–troostite. If the temperature is lowered from 550°C to 220°C acicular troostite or *bainite* is formed. In eutectoid steel, the *martensite* transformation begins at M_s (240°C) and ends at M_f (–50°C). The change in the hardness of the structure formed is shown in Rockwell units (Rc) at the right-hand side of the diagram.

SUMMARY OF THE MICROSTRUCTURE

Ferrite. It is the grain or crystal of solid solution of carbon in alpha-iron. It is relatively soft (50-100 Brinell), ductile and strongly magnetic.

Cementite. Cementite is a chemical compound of 93.33 per cent iron and 6.67 per cent carbon. It is identified as round particles in the structure. Being extremely hard (about 1400 Brinell) and brittle. It has no ductility. Cementite becomes ferro-magnetic below 210°C.

Pearlite. It is readily recognized by its pearly lustruous appearance and its structure of thin alternating plates of 13 per cent cementite in a matrix of 87 per cent ferrite. Pearlite is a strong metal having 180 Brinell.

Austenite. It is a solid solution of carbon in gama-iron. It is generally soft and ductile than ferrite, but denser than ferrite, and is non-magnetic.

Sorbite. It is a finely dispersed pearlite, and the properties are intermediate between those of pearlite and troostite. The Brinell hardness is 350.

Troostite or bainite. It is the most finer acicular (needle-like) structure of austenite decomposition; and is composed of two equilibrium phases of ferrite and cementite.

Martensite. Martensite is obtained by decomposition of austenite when it is very rapidly cooled. It is composed of needle-like crystals in angular arrangements. Martensite is very hard (650–750 Brinell), brittle, and magnetic.

6.5 PURPOSES AND METHODS OF HEAT TREATMENT

Heat treatment refers to a combination of heating and cooling of a metal or alloy in the solid state for the purpose of obtaining desired properties. Changes in properties result from micro structural changes in the material produced by heat treatment operations. However, these serve one or more of the following purposes :

1. Improve machinability.
2. Relieve internal stresses.
3. Improve mechanical properties such as ductility, strength, hardness, toughness, etc.
4. Change the grain size.
5. Increase resistance to heat and corrosion.
6. Modify electrical and magnetic properties.
7. Change the chemical composition.
8. Remove gases.

The aforesaid purposes of heat treatment may be served by one or more of the following processes of heat treatment :

1. Annealing
2. Normalizing.
3. Hardening.
4. Tempering.
5. Case hardening:
    (a) Carburising,
    (b) Cyaniding,
    (c) Nitriding.
6. Surface hardening :
    (a) Induction hardening,
    (b) Flame hardening.
7. Diffusion coatings.

6.6 ANNEALING

Annealing is one of the most important widely used operations in the heat treatment of steel.

The purpose of annealing is to obtain one or more of the following effects :

1. Soften the steel.
2. Improve machinability.
3. Increase or restore ductility and toughness.
4. Relieve internal stresses.
5. Reduce or eliminate structural inhomogeneity.
6. Refine grain size.

7. Prepare steel for subsequent heat treatment.

The various types of annealing that serve one or more of these problems are explained in the following discussions.

FULL ANNEALING

This process is known as full annealing because it wipes out all traces of previous structure by complete phase recrystallisation.

Full annealing consists of :

1. Heating the steel slightly above the critical point.
2. Holding it at this temperature for a considerable period.
3. Slowly cooling.

The annealing temperature is 30°C to 50°C above Ac_3 point (higher critical line GS in Fig. 6.6) for hypoeutectoid steels and about the same amount above Ac_1 point (lower critical line *PSK*) for hypereutectoid steel. A small excess of temperature above A_3 and A_1 points is provided to equalize the chemical composition of austenite which is formed after the steel is heated above critical points.

After the required heating temperature is achieved, the metal is held at that temperature for a certain time to enable the internal changes to take place throughout the mass of the workpiece. The holding time at the annealing temperature is not less than 3 to 4 minutes for each millimeter of section of the largest pieces being treated.

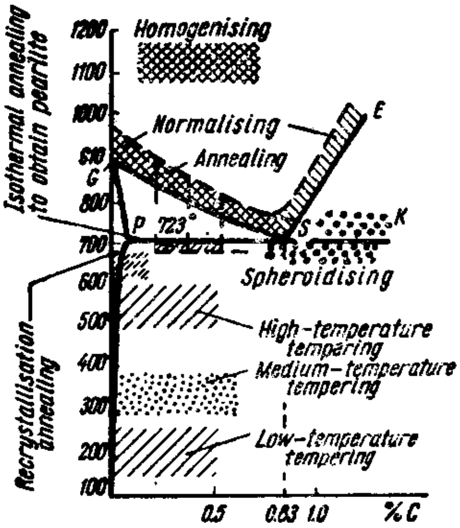


Figure 6.6 Temperature ranges for various heat treatment processes

The metal is slowly cooled, after heating and holding in and with the furnace, or it may be removed at high temperature and buried in a non-conducting material such as sand, lime or ashes. Carbon steels are cooled down at a rate of 150°C to 200°C per hour, while alloy steels, in which austenite is very stable, should be cooled much slower (30°C to 100°C per hour).

This slow cooling is required in annealing to enable austenite to decompose at low degrees of supercooling so as to form a pearlite and ferrite structure in hypoeutectoid steel, a pearlite structure in eutectoid steel, and a pearlite and cementite structure in hypereutectoid steel. In a successfully annealed steel, the grains of ferrite are large and regular while the pearlite consists of coarse plates of cementite and ferrite.

Hypoeutectoid hot worked steel (rolled stock, sheet, forgings, etc.) as well as castings of carbon and alloy steels, may undergo full annealing. Hypereutectoid steel requires full annealing only in cases when hot working (rolling or forging) is finished at high temperatures and the steel is, consequently, coarse grained. If hot working is finished at a normal temperature, slightly above Ac_3 point (line *GS*) incomplete annealing will be sufficient to ensure the required properties.

PROCESS ANNEALING

When a steel is cold-worked the hardness and elastic properties particularly considerably increase, while the ductility remarkably suffers and the steel becomes unsuitable for further plastic deformation. The ductility of a steel may then be restored by so-called recrystallisation or process annealing. Furthermore, the effect of process annealing is to relieve internal stresses resulting from any previous heat treatment.

Process annealing consists in heating the steel to a temperature below or close to Ac_1 point (line *PSK*) usually in the range of 500° C to 700°C (Fig. 6.6), holding at this temperature for a prolonged period and slow cooling. This causes the grains of steel, broken up or distorted in the process of deformation, to come back into their normal state (by recrystallisation). Process of recrystallisation annealing is frequently applied in the production of cold rolled steel which, in deep drawing, and in wire drawing operations is an *intermediate process* with the aim of increasing the plasticity of the steel. It should be pointed out that this process is applied to low carbon steels only. Medium and high carbon steels, however, require full annealing for recrystallisation.

In process annealing, new equiaxial grains gradually grows from the fragments of the original elongated grains, forming centres, or nuclei. These new grains become equiaxial. It must, therefore, be remembered that this process does not produce any new structure by phase transformations but produces only new crystals of the same structure.