7. FERROUS AND NON-FERROUS ALLOYS

- Introduction
- Classification
- Properties, Composition and applications of
  - Steel
  - Cast Iron (grey cast iron, malleable iron, SG iron)
  - Copper alloys (brasses and bronzes)
  - Aluminium alloys (Al-Cu, Al-Si, Al-Zn alloys)
  - Magnesium alloys
  - Titanium alloys

7.1 INTRODUCTION

Iron is the most abundantly used metal for engineering applications because of its availability, ease of production and excellent properties in its alloyed form. About 80 to 90% of the metals cast today are iron based. Hence, with the prominence of iron, the alloys used for engineering materials are broadly classified as ferrous and non-ferrous materials. In this section of the module you will study these materials, their types, composition, properties and applications.

7.2 FERROUS ALLOYS

The ferrous (iron-base) alloys are classified as *steels* and *cast irons* based on their carbon composition.

- Steels (up to 2% carbon)
- Cast iron (beyond 2% carbon)

The addition of carbon has a remarkable influence on the microstructure of iron. The ferrite (solid solution of iron) has a limited solubility for carbon at room temperature, when carbon is present slightly in excess to this solubility it appears as *iron carbide* or *cementite*. Iron with a carbon composition of 0.8% upon normal cooling forms a complete lamellar structure comprising alternate layers of ferrite and cementite, this structure is known as *pearlite.* At carbon percentages less than this amount, ferrite and pearlite appear in separate patches where ferrite is a soft and ductile phase and the cementite is hard and brittle. This variation in microstructure is responsible for the difference in properties of cast steel from 0 to 0.8%.

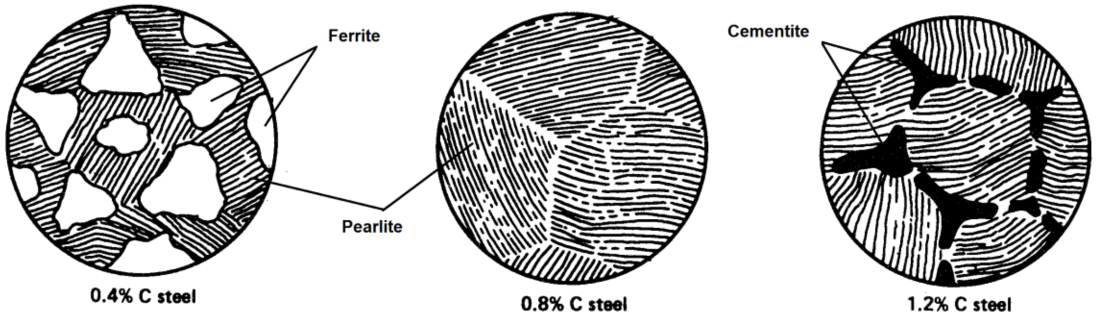


Figure 7.1: Microstructure of Steel

Beyond 0.8% carbon, cementite is present with pearlite and becomes more prevalent as the carbon increases; hence there is an enhanced strength and hardness characteristic at the expense of ductility. Although steels are marked to have a carbon percentage up to 2%, the commercially viable steels contains not more than 1 to 1.5% carbon. Iron with more than 2% carbon is called as cast iron; it is very hard and brittle.

7.2.1 STEEL

7.2.1(a) Types of Steel

Steels are broadly classified as,

- Plain carbon steel
- Alloy steel

Steel with only carbon as the alloying constituent is termed as *plain carbon steel* and it may be further classified as;

1. Low-carbon steel (carbon less than 0.2%)
2. Medium-carbon steel (carbon between 0.2 and 0.5%)
3. High-carbon steel (carbon above 0.5%)

In addition to carbon, steel may also contain other alloying constituents such as manganese, silicon, phosphorus, sulphur. Small percentages of other residual metals such as nickel, chromium and copper may also be present. Based on the quantities of these alloying additives, steel may also be classified as;

1. Low-alloy steel (alloy content totaling less than 8%)
2. High-alloy steel (alloy content totaling more than 8%)

7.2.1(b) Properties & Applications

A. PLAIN CARBON STEEL

Characteristics and properties:

- Carbon content less than 1.5 %
- They are tough and ductile
- Offer very good weldability
- Good response to heat treatment

Applications:

- Automotive industries – gears, engines housings, cylinder blocks, etc.
- Electrical equipments – frames, housings, rotors, etc.
- Marine works – anchors, rudders, etc.
- Transportation – couplings, brake shoes, etc.
- Rolling mill rolls.

B. ALLOY STEEL

Characteristics and properties:

- High yield point and high strength
- Stronger, tougher and fatigue resistant
- Good formability, ductility, and weldability
- Corrosion and abrasion resistant

Applications:

- Structural applications, transmission towers, high rise building columns
- Railroads, lighting poles
- Agricultural and earthmoving machinery parts
- Surgical instrument, chemical plant, and cutlery
- Bearings, gears, shafts, Cutting tools, Pressure vessels, Hand tools (spanners, hammers, etc.)

7.2.2 CAST IRON

Cast iron is an alloy of iron, carbon (up to about 4%) and silicon (up to about 3.5%) which ordinarily is not usefully malleable as-cast. Carbon in cast iron is present in two forms, elemental carbon in the form of graphite and combined carbon as Fe_3C (iron carbide). The presence of silicon promotes graphitization. Several forms of graphite may occur in cast iron; flaky graphite or aggregates of graphite or a spheroidal graphite, etc., and accordingly based on the shape and form of carbon, the cast irons are classified as,

1. *Gray cast iron* (carbon is present as graphite flakes)
2. *White cast iron* (carbon is present in a chemically combined form as cementite)
3. *Malleable cast iron* (nodular shaped graphite aggregates obtained by heat treating white cast iron)
4. *Ductile cast iron* (nodular or spheroidal graphite obtained by treating the iron melt with magnesium, cerium and other agents)
5. *Compacted graphite iron* (vermicular graphite)

The amount, size, shape and distribution of the graphite in cast irons greatly influence their properties. Cast irons offer a wide range of fair/excellent metallic properties in terms of strength, wear resistance, hardness, machinability, abrasion resistance, corrosion resistance, etc.

The cast iron may also be classified based on the matrix type as ferritic, pearlitic, austenitic, martensitic and bainitic. However, the most common are ferritic and pearlitic matrix cast iron. The evolution of the matrix phase depends on the rate of cooling or heat treatment. The figure 7.2 shows the possible microstructure for few cast irons.

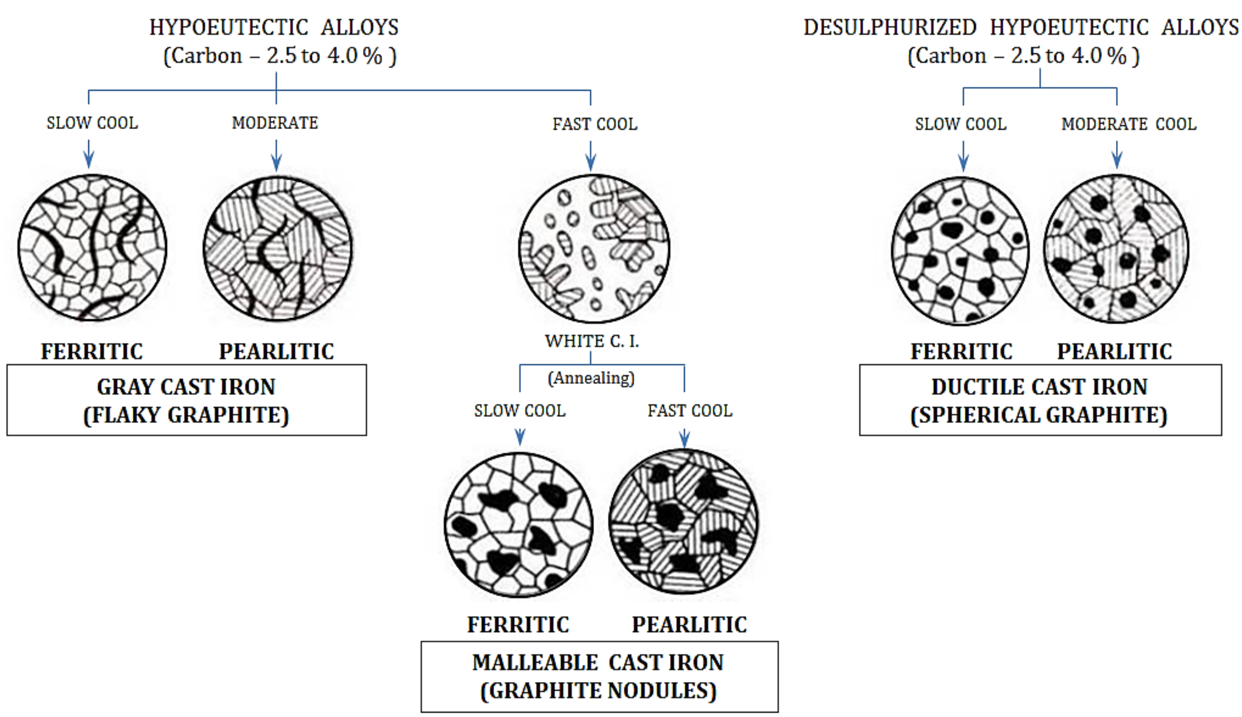
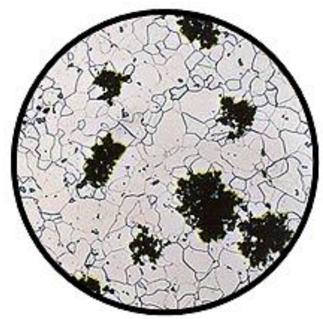
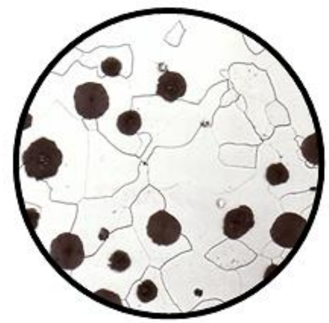


Figure 7.2: Effect of cooling rate on the microstructure of Cast Iron

Table 7.1: Composition & microstructure of cast irons

Gray cast iron	**White cast iron**	**Malleable cast iron**	**Ductile cast iron**	**Compacted graphitic iron**
C – 2.5 to 4% Si – 1 to 3 % Mn – 0.2 to 1 % P – 0.002 to 1 % S – 0.02 to 0.25 %	C – 1.8 to 3.6 % Si – 0.5 to 1.9 % Mn – 0.25 to 0.8 % P – 0.06 to 0.2 % S – 0.06 to 0.2 %	C – 2.2 to 2.9 % Si – 0.9 to 1.9 % Mn – 0.15 to 1.2 % P – 0.02 to 0.2 % S – 0.02 to 0.2 %	C – 3 to 4 % Si – 1.8 to 2.8 % Mn – 0.1 to 1 % P – 0.01 to 0.1 % S – 0.01 to 0.03 %	C – 2.5 to 4 % Si – 1 to 3 % Mn – 0.2 to 1 % P – 0.01 to 0.1 % S – 0.01 to 0.03 %
				
Gray cast iron has flaky graphite	Prearlite present in a white interdendritic network of cementite	Malleable cast iron has graphitic nodular aggrgates	Ductile cast iron has graphite has round particles	The graphite shape is vermicular (intermediate to spheroidal and flake)

7.2.2(a) Gray cast iron

Gray cast iron is characterized by the presence of graphite flakes in a matrix of ferrite, pearlite or austenite. The flakes occupy about 10% of the metal volume. Graphite is very soft and weak material and hence the graphite filled spaces behave similar to empty spaces.

Gray cast irons are comparatively cheap, abundantly available and feature lowest melting point among the ferrous alloys. They present a gray sooty surface when fractured and hence the name.

Properties:

- Better machinability – graphite acts as solid lubricant
- High fluidity – easy to obtain complex shapes
- High vibration damping capacity – graphite gives cushion effect
- High resistance to wear
- High compressive strength
- Low ductility and low impact strength – sharp ends of graphite flakes acts as fracture nucleation sites
- Excellent casting qualities

Applications:

- Gas or water pipes for underground purposes, manhole covers, sanitary wares
- Piston rings, Cylinder blocks and heads for I.C. Engines
- Electric motor frames
- Flywheels and machinery parts
- Household appliances

7.2.2(b) Malleable cast iron

Gray cast iron being brittle has a low resistance to shock on the other hand malleable cast iron offers good ductility along with excellent casting qualities.

It is a ferrous alloy featuring temper carbon which is obtained by heat treating the white cast iron as shown in figure 7.3. White cast iron is basically very hard but brittle material due to the presence of excessive carbides which can be eliminated by annealing treatment; resulting in a malleable cast iron with carbides transformed into free carbon in the form of graphitic nodular aggregates. Malleable iron can be of ferritic type (machinable & ductile) or pearlitic type (stronger & harder).

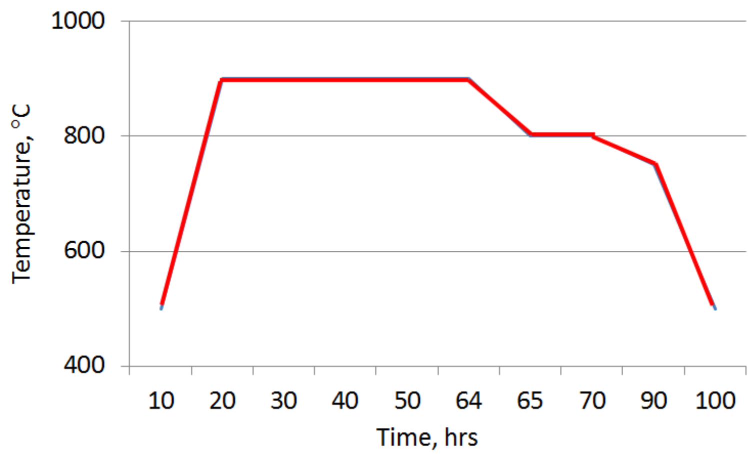


Figure 7.3: Annealing treatment for white cast iron

Properties:

- High yield strength
- Good wear resistance
- Good vibration damping capacity
- Good impact resistance at low temperature
- High strength and corrosion resistance – presence of chromium and nickel
- High young's modulus and low coefficient of thermal expansion
- Castability with good toughness and machinability
- Thin section castability

Applications:

- Agricultural implements, rail roads
- Electrical line hardware
- Automotive crankshaft, gear case, automobile axle assembly parts
- Universal joint yoke
- Conveyor chain links

7.2.2(c) Ductile cast iron

Ductile cast iron also known as nodular or spheroidal graphite cast iron is characterized by the presence of graphite as rounded particles. The spheroidizing elements such as magnesium or chromium are added to melt to eliminate sulphur and oxygen from the melt, which change solidification characteristics and possibly account for nodulation. The nodular graphite inhibits the formation of cracks as compared to flaky graphite.

Properties:

- Very good machinability
- Intermediate damping capacity between cast iron and steel
- High resistance to wear
- Excellent castability

Applications:

- I.C. Engines,
- Pipes, valves and fittings
- Pumps and compressors
- Power transmission equipment
- Paper industry machinery
- Farm implements and tractors
- Construction machinery

7.2.2(d) Compacted graphite iron

Compacted graphite (CG) irons are characterized by vermicular graphite, i.e., a shape intermediate between spheroidal and flake. Consequently, most of the properties of CG irons lie in between those of gray and ductile iron. Compacted graphite structure can be obtained either by a controlled under-treatment with magnesium-containing alloys.

Example: treating a spheroidal graphite-type base iron with magnesium-iron-silicon alloy, when residual magnesium is controlled in the range of 0.013 to 0.022%.

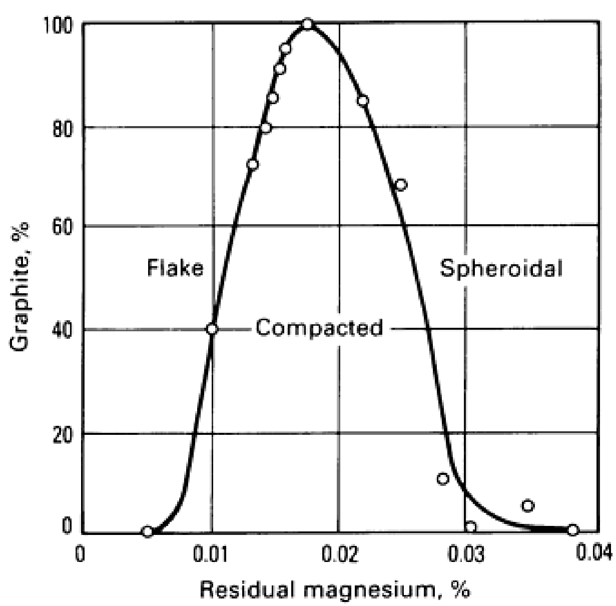


Figure 7.4: The influence of residual magnesium on graphite shape
(Source: ASM Handbook, Volume 15: Castings)

Compacted graphite structure can also be obtained by combining spheroidizing (magnesium, calcium, and/or rare earths) and antispheroidizing (titanium and/or aluminum) elements.

7.3 NON-FERROUS ALLOYS

7.3.1 Copper alloys

Pure copper shows low mechanical and casting properties and thus finds limited applications for cast parts. Hence it is often alloyed with Zn, Pb, Sn, Al, etc. Cast copper alloys are used as the shape in which they have been cast as it cannot be worked easily; however they can be machined and brazed.

The most important commercial copper alloys may be classified as;

i) Brasses and,
ii) Bronzes.

Brasses are essentially alloys of copper and zinc, with traces of lead, tin and aluminium added to improve their properties. Whereas, Bronzes are alloys containing copper and tin with traces of aluminium, silicon and beryllium.

Commonly used copper base alloys are

- Tin bronze
- Leaded tin bronze
- Aluminium bronze
- Red brass
- Yellow brass
- Gun metal

Table 7.2: Composition of typical copper base alloys and their applications

Copper base alloys	composition	Uses
Tin bronze	8-10% Sn, 2-4% Zn	Pressure castings, bushings, bearings
Leaded tin bronze	6-8.5%Sn, 0.5-1.5%Pb, 4%Zn	Electrical castings and pumps
Aluminium bronze	1-4%Fe, 9-11%Al	Marine equipments, gears, valves
Red brass	4-5%Sn, 5-6%Pb, 5-7%Zn	Plumbing goods, gears, pump impellers
Yellow brass	1%Sn, 1-3%Pb, 24-36%Zn	Valves, fittings, ornamental castings
Gun metal	5-10%Sn, 2-5%Zn	Bearings, valves, gears

Properties:

- Excellent resistance to corrosion
- Malleable and ductile
- High thermal and electrical conductivity
- Non-magnetic
- Moderate to high hardness and strength
- Resistance to fatigue, abrasion and corrosion
- It can be soldered, welded and brazed
- It has very good machinability

General applications:

- Electrodes of resistance welding machines
- Turbine runners
- Bearings
- Gears and corrosion resistant pumps
- Marine equipment
- Valves and fittings
- Steam pipe fittings
- Plumbing goods
- Water meter housing

7.3.2 Aluminium alloys

Aluminium is the most abundant metal in the earth crust. It is light weight and weighs about $1/3^{rd}$ that of steel. Most common alloying elements are Cu, Cr, Ni, Fe, Zn, Mn, Si and Mg. Aluminium alloys are broadly classified as cast alloys and wrought alloys. Cast alloys are cost effective, although they have lower tensile strength than wrought alloys. Aluminium and its alloys have good low temperature properties but they do not work well at high temperatures of the order 300 to 400 °C.

Table 7.3: Principal alloying additives and their effects

Elements	**Effects**
Copper	With 2 – 5 % results in optimum ductility Greater percentages of Cu add to strength and hardness
Silicon	Increasing Si content increases strength
Magnesium	Similar to that of Cu
Zinc	Enhanced mechanical properties in the as-cast condition

Properties:

- It is malleable and ductile
- Good electrical conductivity
- High thermal conductivity
- Resistance to corrosion
- Non-magnetic
- High tensile strength
- High coefficient of expansion
- High affinity for oxygen

General applications:

Aluminium alloys are widely used in engineering structures and components where light weight or corrosion resistance is required.

- *Transportation industry* – for structural framework, engine parts, fittings etc. of Trains, trucks, buses, cars and aeroplanes
- *Food industry* – food packaging, food preparation equipments, refrigeration, etc.
- *Architectural applications* – window frames, doors, railings, roofing lighting fixtures, etc.
- *Process industries* – to handle organic chemicals, petrochemicals and drugs
- Cryogenic applications, overhead cables and heat exchanger parts

7.3.2 (a) Aluminium – Copper alloys

They include cast and wrought alloys of aluminium containing from 2.5 to 15 % copper. In the cast alloys the basic structure consists of cored dendrites of aluminum solid solution, with a variety of constituents at the grain boundaries or interdendritic spaces, forming a brittle, more or less continuous network of eutectics. Wrought products consist of a matrix of aluminum solid solution with the other soluble and insoluble constituents dispersed within it. The following are a few commonly used wrought and cast Al-Cu alloys:

- Al-Cu alloy containing exactly 4% copper is known as Duralumin; the most well-known alloy for its excellent age hardenability.
- Cast alloys with 5% Cu, often with small amounts of silicon and magnesium.
- Cast alloys with 7-8% Cu, which often contain large amounts of iron and silicon and appreciable amounts of manganese, chromium, zinc, tin, etc.
- Cast alloys with 10-14% Cu. These alloys may contain small amounts of magnesium (0.10-0.30% Mg), iron up to 1.5%, up to 5% Si and smaller amounts of nickel, manganese, chromium.
- Wrought alloys with 5-6% Cu and often small amounts of manganese, silicon, cadmium, bismuth, tin, lithium, vanadium and zirconium. Alloys of this type containing lead, bismuth, and cadmium have superior machinability.

7.3.2(b) Aluminium – Silicon alloys

Aluminium – Silicon alloy, or commonly known as Silumin is the general term used for a group of casting alloys made up of a series of lightweight, high-strength aluminum alloys containing 3 to 50 % silicon content. Aluminium – Silicon alloy has a high resistance to corrosion, making it useful in humid environments, moreover the addition of silicon to aluminum also makes it less viscous making it a very good casting alloy.

In Al-Si alloy, silicon normally appears as coarse needles which mechanically weaken it. But when 0.01% Na is added, silicon separates in a finer, globular form which makes the alloy much stronger. This process of adding traces of impurities to enhance the properties is known as modification.

7.3.2(c) Aluminium – Zinc alloys

These are alloys with zinc and aluminium as main constituents; other alloying elements include magnesium and copper. Distinguishing features of Al-Zn alloys include high as-cast strength, excellent bearing properties, as well as low energy requirements. These alloys make good bearings because their final composition includes hard eutectic zinc-aluminium-copper particles embedded in a softer zinc-aluminium matrix.

7.3.3 Magnesium alloys

Magnesium is the lightest of all commercial metals; it is not strong enough in its pure form and hence is alloyed with elements such as Al, Mn, Zn, Zr, Th, etc. It has high strength to weight ratio and is superior as compared to aluminium alloys in this regard. They provide ease of casting; can be cast successfully in sand as well as in permanent molds

<u>Properties</u>**:**

- High strength to weight ratio
- Good fatigue strength
- Good damping capacity
- Good dimensional stability
- High thermal conductivity
- Relatively high electrical conductivity

Table 7.4: Properties of typical cast magnesium alloys

Magnesium casting alloys	**Properties**
General purpose alloy • Al 8 %, Zn 0.5 %, Mn 0.3 %	- Ductility - Strength - Castability - Shock resistance
High strength alloys • Zn 4 %, Zr 0.7%, RE 1.2 % • Zn 5.5 %, Zr 0.7%, Th 1.8 %	- strong, crack resistant and pressure tight parts
• RE 2.7%, Zn 2.2 %, Zr 0.6% • Th 3 %, Zn 2.2 %, Zr 0.7%	- Welding - Creep resistant
• Ag 2.5 %, RE 1.7 %, Zr 0.7 %	- High strength pressure tight castings - Can be welded also

Applications:

- For making airframes, engine, gear boxes, flooring, etc. for aeroplanes, helicopters, missiles and satellites
- Engines, transmission, floors and body parts of transportation vehicles
- For material handling equipments – hand trucks, shovels, etc.
- Storage tank, ladder, hopper, furniture, lawn movers, etc.
- Production of titanium, uranium, zirconium, etc.

7.3.4 Titanium alloys

Titanium has the highest strength to weight ratio among the structural metals. It is alloyed with Al, Sn, V, Mo, etc. Such alloys have very high tensile strength and toughness (even at extreme temperatures).

Titanium alloys are generally classified into three main categories:

- *Alpha alloys*, which contain neutral alloying elements (such as Sn) and/or alpha stabilizers (such as Al, O) only and are not heat treatable;
- *Alpha + beta alloys*, which generally contain a combination of alpha and beta stabilizers and are heat treatable to various degrees; and
- *Beta alloys*, which are metastable and contain sufficient beta stabilizers (such as Mo, V) to completely retain the beta phase upon quenching, and can be solution treated and aged to achieve significant increases in strength.

Properties:

- High strength to weight ratio
- Excellent room temperature corrosion resistance
- Retains strength at elevated temperature
- Offers ease of forging and machining

Applications:

The high cost of extraction and processing of titanium limit their use to high performance and specific applications.

- *military applications* - it is used in missiles and rockets where strength, low weight and resistance to high temperatures are important.
- *aircraft and spacecraft* - it has strength to weight ratio and hence it is the most suitable as structural material for aerospace applications.
- *marine applications* - titanium has excellent corrosion resistance to sea water, and thus is used in propeller shafts, rigging and other parts of boats that are exposed to sea water.
- *medical implants* - titanium does not react within the human body hence it is used to create artificial hips, pins for setting bones, and for other biological implants.
- *automotive applications* - highly stressed components such as connecting rods on expensive sports cars
- premium sports equipment and consumer electronics.

References:

1. ASM Handbook Volume 1 & 2
2. A text book of Foundry Technology – O.P. Khanna
3. Material Science and Metallurgy – K.R.Phaneesh
4. Material Science and Metallurgy – Kesthoor Praveen