

**Ministry of Education and Science of Ukraine
Ternopil Ivan Puluj National Technical University**

Department of building mechanics

Notes on the course

“Building Material Science”

Part 1 “Material Science”

for students of “Civil Engineering” *field of study 6.060101*

Student _____

Faculty _____

Course _____ Group _____

**Ternopil
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INTRODUCTION

“Building Material Science” for students of “Civil Engineering” consists of two parts – Part 1 “Material science” and Part 2 “ Modern building materials” and studying in 1 semesters. Part 1 “Material science” include 16 hours of lectures, 16 hours of labs and 54 hours of individual work. Part 2 “ Modern building materials” has 18 hours of lectures, 18 hours of labs and 54 hours of individual work.

“Building Material Science” is one of the basic technical disciplines in the curriculum for “Civil Engineering” field of study.

The study of materials that are used in construction, alloy’s properties dependence on the chemical composition, structure, methods of treatment and external environments is of great importance for the Civil Engineering bachelors training. The study of the theory and practice of different methods of materials strengthening is to provide a high reliability and longevity of the building construction, machine’s details, devices, tools etc.

Selecting the most appropriate material of construction for an application involves the making of numerous important decisions. This is true whether it be for the construction of a bridge, a household appliance, a piece of chemical processing equipment, or the decorative facing of a building. Factors such as physical and mechanical properties, corrosion resistance, workability, and cost must all be taken into consideration.

With the introduction of new metallic alloys and advances in the production of the so-called exotic metals, what was the best choice several years ago may no longer be so. Over the years, improvements have been made to specific properties of various alloys. These improvements include methods to increase mechanical, physical, and corrosion resistance properties. Alternatives in composition have also been formulated to improve the workability of many alloys.

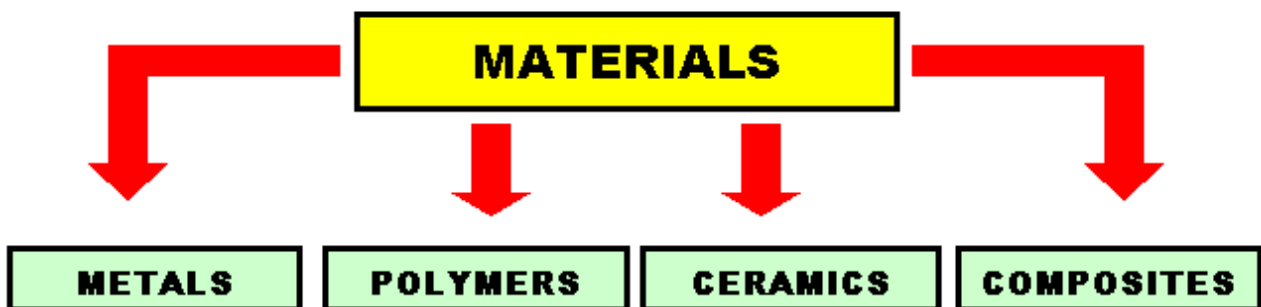
In order to conduct a meaningful evaluation of a design, all the data needed to select the most appropriate material must be available. It is the purpose of this book to supply as much of this information as possible for commercially available metallic materials.

Topic 1. *TYPES OF MATERIALS*

1. Materials that are used in the construction.
2. Some applications of metals.
3. Future trends.

1. Materials, that are used in the construction.

There are four types of materials that are used in the construction.



Metals

Metals are metallically bonded compounds made from most of the elements on the periodic table. Metals can be monatomic such as copper, or an alloy such as steel. Metals can be easily bent, machined, cast or extruded into shape. The use of Metals is in large part due to this ease of manufacturing.

Metals are elements that generally have good electrical and thermal conductivity, ductile, malleable. Many metals have high strength, high stiffness, and have good ductility. Some metals, such as iron, cobalt and nickel are magnetic.

All of these properties come from the way metallic atoms bond together.

Pure metals:

Pure metals are elements of the periodic table. Examples of pure metals include copper in wire and water pipes, electrical wires; aluminum in cooking foil and beverage cans etc.

Metal Alloys:

Metal Alloys contain more than one metallic element. Their properties can be changed by changing the elements present in the alloy. Examples of metal alloys include stainless steel which is an alloy of iron, nickel, and chromium; gold jewelry which contains an alloy of gold and nickel.

The most important properties of metals include density, toughness, strength and plastic deformation. The atomic bonding of metals also affects their properties. In metals, the outer valence electrons are shared among all atoms, and are free to travel

everywhere. Since electrons conduct heat and electricity, metals make good cooking pans and electrical wires.

Many metals and alloys have high densities and are used in applications which require a high mass-to-volume ratio.

Some metal alloys, such as those based on Aluminum, have low densities and are used in aerospace applications. Aluminium was available at a reasonable cost and in sufficient quantities until the beginning of XX century. He then gradually began to enter into the architecture, though initially only as a material for decorative items. The first loud In construction alloys based aluminum use on riveted bearing structures also are producing moldings, sheets, strip, wire, casing wall and roof panels, fittings.

Many metal alloys also have high toughness, which means they can withstand impact and are durable.

Polymers

Polymer have one type of repeating unit of many different types of repeating units.

Polymers are light-weight, ductile, usually non-conductive and melt at low temperatures. A polymer has a repeating structure, usually based on a carbon. The repeating structure results in large molecules.

Polymers are useful because they are lightweight, are corrosion resistant, are easy to process at low temperatures, and are generally inexpensive.

Some important characteristics of polymers include their size (or molecular weight), softening and melting points, crystallinity, and structure. The mechanical properties of polymers generally include low strength and high toughness.

One of the distinct properties of polymers is that they are poor conductors of electricity and heat, which makes them good insulators.

Disadvantages and limitations:

- Properties are very sensitive to mixing and proportioning procedures;
- Strong Allergenic, toxical;
- non bio-degradable;
- easily breakable;
- flame retardancy is low;
- a long time to decompose etc.

Polymers are used for a large kinds of goods: bags, wire insulation, computer chips, packing materials etc.

In construction polymers are used for manufacturing of pipe, window and door profiles PVC, mouldings, production of finishing materials, production of various products needed in engineering and technical areas of operation (plumbing etc.), production of protective, paint, etc.

Polymers can be made into goods by injection molding, extrusion, pressing, stamping or machining.

Ceramics

Ceramics are defined as inorganic non-metallic materials. Ceramics are covalently or ionically bonded (or a mixture of the two).

Examples of such materials can be NaCl (salt), clay (a complex silicate).

Ceramics are brittle, strong and non-conducting materials. Ceramics are compounds consisting of metals covalently bonded to oxygen, nitrogen or carbon. Ceramics are used for high temperature applications, abrasives, transparent windows and pottery. Ceramic goods are generally made through extrusion, slip casting, or compression molding.

Some of the useful properties of ceramics and glasses include high melting temperature, low density, high strength, stiffness, hardness, wear resistance, and corrosion resistance. Many ceramics are good electrical and thermal insulators.

Some ceramics have special properties: some ceramics are magnetic materials; some are piezoelectric materials; and a few special ceramics are superconductors at very low temperatures.

A glass is an inorganic nonmetallic material that does not have a crystalline structure. Such materials are amorphous.

Ceramics and glasses have one major disadvantage: they are brittle. Slow to process. Temperature to melt for repairs is very high in some cases. This could cause serious problems for *in-situ* repairs to primary or secondary structures, especially if being done near fuel tanks or hydraulic systems. Can be health hazards. Slow to repair.

Composites

A composite material is made up of a matrix and a reinforcement phase. Composites take advantage of directional properties of the reinforcement phase and gluing properties of the matrix. The reinforcement phase may be any material in fiber, platelet, or aggregate form. The matrix phase must be able to flow around the reinforcement and later hardened. Metals, ceramics, cement, and polymers are all regularly used for composites. Composites are very difficult to manufacture. New techniques has made it easier to make sporting equipment, space shuttle parts, and car parts out of composites.

Composites are formed from two or more types of materials. Examples include polymer/ceramic and metal/ceramic composites.

Composites are used because their properties are better to those of the individual components. For example: polymer/ceramic composites have a greater modulus than the polymer component, but aren't as brittle as ceramics.

Composite construction is a generic term to describe any building construction involving multiple dissimilar materials. Composite construction is often used in building aircraft, watercraft, and building construction. There are several reasons to

use composite materials including increased strength, aesthetics, and environmental sustainability.

1. *Some applications of metals.*

Metals and metal alloys are used in:

Construction – rolling profiles, roofing sheets, fittings, columns, supporting pillars, pipes, arches, form of large span bridges, public and industrial buildings.

Transportation—cars, buses, trucks, trains, ships, and airplanes.

Aerospace— rockets and the space shuttle.

Computers and other electronic devices that require conductors (TV, radio, stereo, calculators, security devices, etc.)

Communications including satellites that depend on a tough but light metal shell.

Food processing —Microwave and conventional ovens and refrigerators and freezers.

Biomedical applications—As artificial limb.

Electrical power production — Boilers, turbines, generators, transformers, power lines, nuclear reactors and pipelines.

Farming—Tractors, combines etc.

Mode goods —Ovens, dish and clothes washers, vacuum cleaners, blenders, pumps, etc.

3. Future Trends

In the future, we will continue to depend heavily on metals. Lightweight aluminum alloys will be utilized more in automobiles to increase fuel efficiency. New, heat resistant superalloys will be developed so that engines can operate at higher, more efficient temperatures. Similarly, ceramic coatings will be used more to protect metals from high temperatures, and to increase the lifetime of tools. New, radiation-resistant alloys will allow nuclear power plants to operate longer, and thus lower the cost of nuclear energy.

Steel will continue to be the most commonly used metal for many years to come, due to its very low cost (approximately 20 cents/pound) and the ability to customize its properties by adding different alloying elements.

As easily-mined, high grade ores are depleted, recycling will become more important. Already, half of all aluminum, copper, and steels are being recycled.

Topic 2. ***STRUCTURE OF METALS***

1. Metallic bonds and lattice structure of metals
2. Crystal defects.

1. Metallic bond and lattice structure of metals

The **metallic bond** is bond between the metallic ions and the negative electron cloud. This is illustrated schematically in Fig. 2.1.

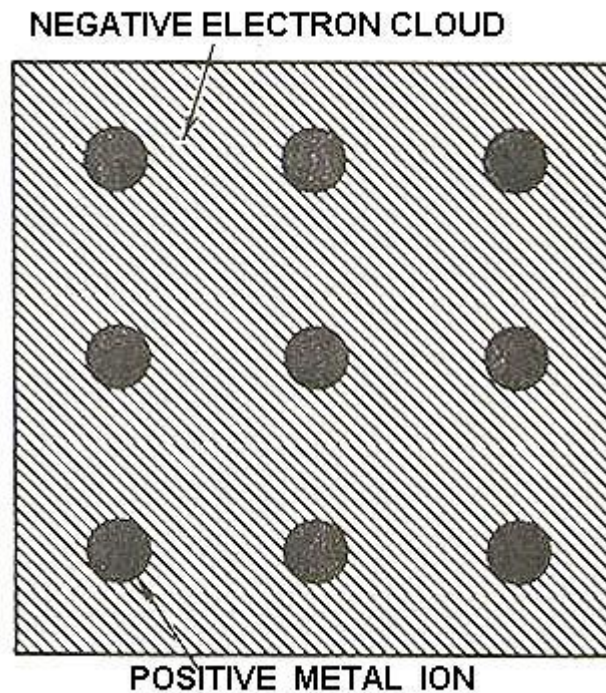


Fig.2.1. Metallic bond and electron cloud

Metals are widely used because they have high properties: strength, ductility, high melting point, thermal and electrical conductivity, toughness that depend on the structure of metals. Metals are composed of atoms, which are held together by strong bonds.

Above their melting point, metals are liquids, and their atoms are randomly arranged and relatively free to move. However, when cooled below their melting point, metals rearrange to form ordered, crystalline structures.

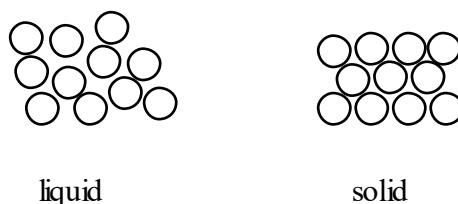


Fig.2.2. Arrangement of atoms in a liquid and a solid states

Atoms are the building blocks of all materials. In a liquid state the atoms of metal having short-range order. However, this is a probability event. Since the forces are weak and there is much activity taking place, they soon separate and re-form again. This phenomenon of random grouping, scattering, and regrouping for short periods of time is characteristic of the liquid state.

The random movement of the unlike atoms becomes less frequent, the bonding becomes stronger, and ordered arrays of atoms form lattices.

A crystal is a repeating array. In describing this structure we must distinguish between the pattern of repetition (the lattice type) and what is repeated (the unit cell). The most fundamental property of a crystal lattice is its symmetry. In three-dimensions, unit cells stack like boxes, filling the space, making the crystal. The different colors are just to show the separate boxes - each unit cell is identical.

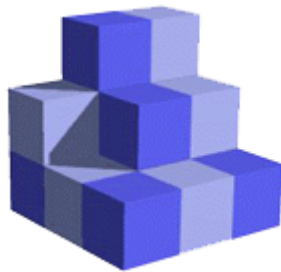


Fig.2.3. Cubic Lattice Structure

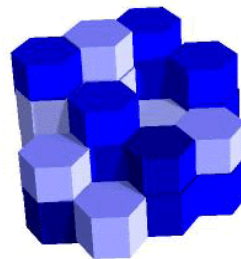


Fig.2.4. Hexagonal Lattice Structure

If we take a unit cell and stack it, we produce a lattice. Once the orientation of a unit cell is determined, all unit cells within that lattice have the same orientation.

Unit Cell: When a solid has a crystalline structure, the atoms are arranged in repeating structures called unit cells, which are the smallest units that show the full symmetry of a crystal. The smallest repeating array of atoms in a crystal is called a **unit cell**.

Lattice: The three dimensional array formed by the unit cells of a crystal is called **lattice**.

The majority of metals have one of **three well-packed crystal structures**:

- Face-centered cubic (F.C.C.): Aluminum, γ -Iron, Nickel, Copper, Lead, Gold, Platinum
- Body-centered cubic (B.C.C.) Chromium, α -Iron, Niobium, Vanadium, Silver
- Hexagonal-close-packed (H.C.P.): Cadmium, Cobalt, Titanium, Zinc, Zirconium, Magnesium.

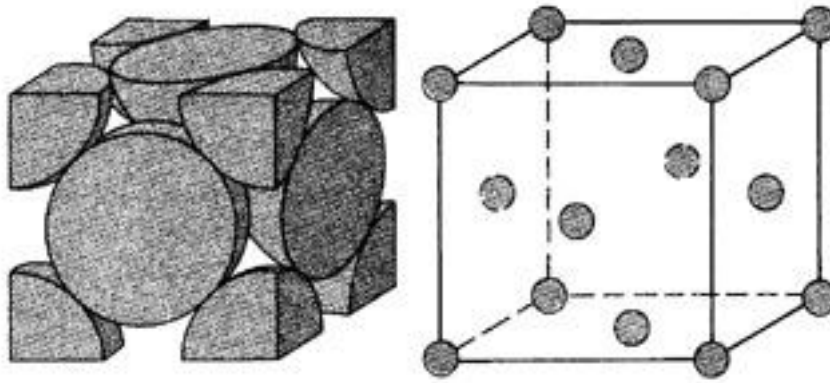


Fig.2.5. Face Centered Cubic (F.C.C) Lattice Structure

In the FCC arrangement, again there are eight atoms at corners of the unit cell and one atom centered in each of the faces. FCC unit cells consist of four atoms, eight eighths at the corners and six halves in the faces.

The body-centered cubic (BCC) unit cell has atoms at each of the eight corners of a cube plus one atom in the center of the cube. The BCC unit cell consists of a net total of two atoms, the one in the center and eight eighths from the corners.

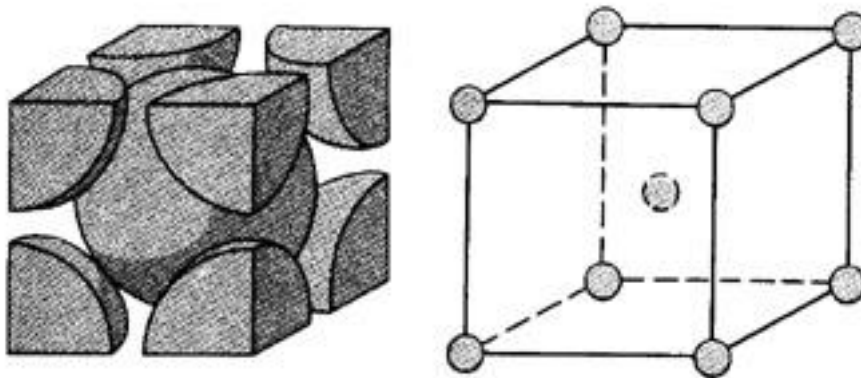


Fig.2.7. Body Centered Cubic (B.C.C) Lattice Structure

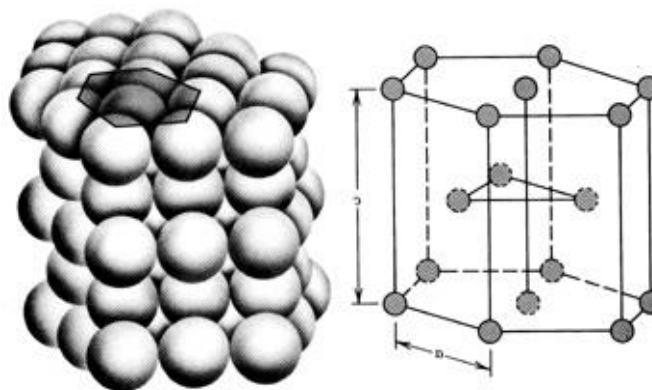


Fig.2.8. Closed Packed Hexagonal (C.P.H) Lattice Structure

Unit cell structures determine some of the properties of metals. For example, FCC structures are more likely to be ductile than BCC, (body centered cubic) or HCP (hexagonal close packed

Basic descriptions of unit cell are:

Lattice parameter, or period, – it is distance between neighbouring atoms;

closeness of packing – amount of atoms, that is on an elementary unit cell.

3. Crystal defects

The most important crystal defects are:

- Vacancies
- Interstitials
- Dislocations

Vacancies:

Vacancies are simply empty atom sites as shown in Fig.5.9. By successive jumps of atoms, it is possible for a vacancy to move in the lattice structure and therefore play an important part in diffusion of atoms through the lattice.

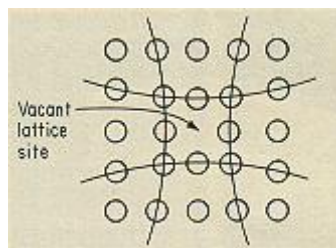


Fig.2.9. Vacancy crystal defect

Interstitials:

It is possible that some atoms may fall into interstitial positions or in the spaces of the lattice structure which may not be used by the atoms of a specific unit cell as shown in Fig.5.10. Interstitials tend to push the surrounding atoms farther apart and also produce distortion of the lattice planes.

Interstitial atoms may be produced by the severe local distortion during plastic deformation.

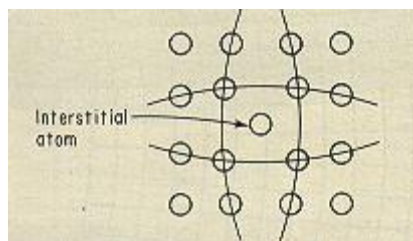


Fig.2.10. Interstitial crystal defect

Dislocations:

A **dislocation may be defined** as a disturbed region between two substantially perfect parts of a crystal. A dislocation is a linear defect around which some of the atoms are misaligned. Two simple types of dislocation are :

- Edge dislocation
- Screw dislocation

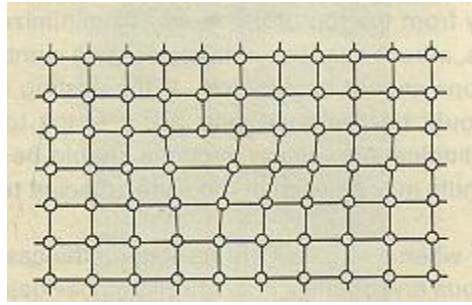


Fig.2.11. Edge dislocation

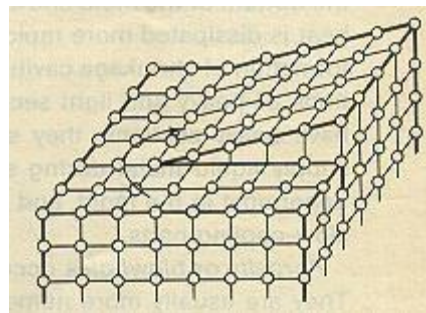


Fig. 2.12. Screw dislocation

Dislocations can be observed in crystalline materials using electron-microscopic techniques. Virtually all crystalline materials contain some dislocations that were introduced during solidification, during plastic deformation, and as consequence of thermal stresses that result from rapid cooling.

The importance of dislocations to the metal user is that dislocation interactions within a metal are a primary means by which metals are deformed and strengthened. When metals deform by dislocation motion, the more barriers the dislocations meet, the stronger the metal.

Deformation by dislocation motion is one of the characteristics of metals that make them the most useful engineering materials. The metallic bond is such that strains to the crystal lattice are accommodated by dislocation motion. Many metals can tolerate significant plastic deformation before failing.

Topic 3. CRYSTALLIZATION PROCESS

1. *Conditions of the crystallization process.*
2. *Stages of crystallization.*
3. *Phenomenon of anisotropy and polymorphism.*

1. Conditions of the crystallization process.

The crystallization process is a basic part of the technological process of obtaining goods by casting.

A primary crystallization process is the transition from the liquid to the solid state with forming of crystalline lattice.

Crystallization begins after some overcooling of liquid metal below than equilibrium temperature of crystallization (or theoretical temperature of crystallization) T_s (fig.3.1). At a temperature the T_s both phases (liquid and solid) are found in equilibrium and the process of crystallization or process of melting does not take place.

Thus, the process of crystallization can pass only at overcooling of metal below than equilibrium temperature T_s . Difference between theoretical temperature T_s and real temperatures of crystallization T_r is called the overcooling degree:

$$\Delta T = T_s - T_r \quad (6.1)$$

The degree of overcooling is not a permanent size (fig.3.2). It depends on speed of cooling, nature and purity of metal.

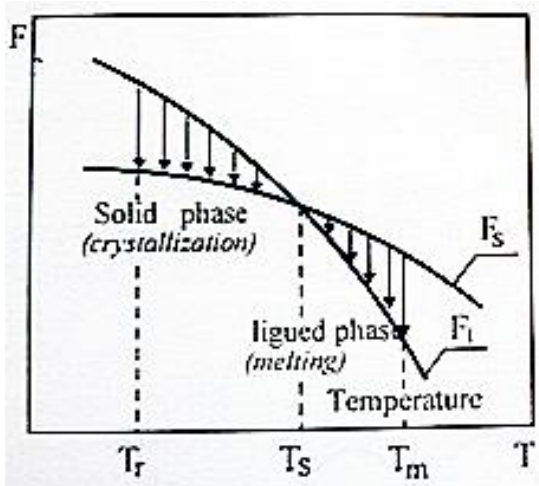


Fig.3.1. Change of free energy of the state liquid and crystalline depending on a temperature.

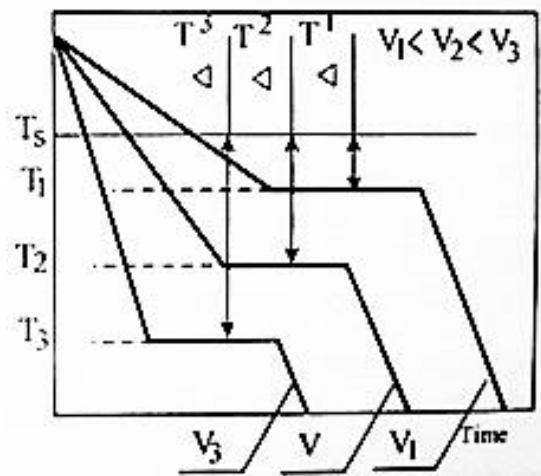


Fig.3.2. Curve cooling during crystallization.

2. Stages of crystallization process

The crystallization process occurs in two stages:

1. Nucleus formation.
2. Crystal growth.

Atomic motion in the liquid state of a metal is almost completely disordered. Atoms in the liquid state of a metal do not have any definite arrangement. It is possible that some atoms at any given instant are in positions exactly corresponding to the space lattice they assume when solidified. As the energy in the liquid system decreases, the movement of the atoms decreases and the probability increases for the arrangement of a number of atoms into a characteristic lattice for that material.



Fig.3.3. Stages of solidification (square grids represent the unit cells).

(a) Nucleus formation; (b), (c) Growth of the crystallites; (d) Grain boundaries.

Now consider a pure metal at its theoretical temperature of crystallization where both the liquid and solid states are at the same temperature. When the temperature of the liquid metal has overcooling below its temperature, stable aggregates or nuclei appear spontaneously at various points in the liquid. These nuclei, which have now solidified, act as centers for further crystallization. Each nucleus grows by the attraction of atoms from the liquid into its space lattice. Crystal growth continues in three dimensions, the atoms attaching themselves in certain preferred directions, usually along the axes of a crystal. This gives rise to a characteristic treelike structure which is called dendrite (fig.3.4).

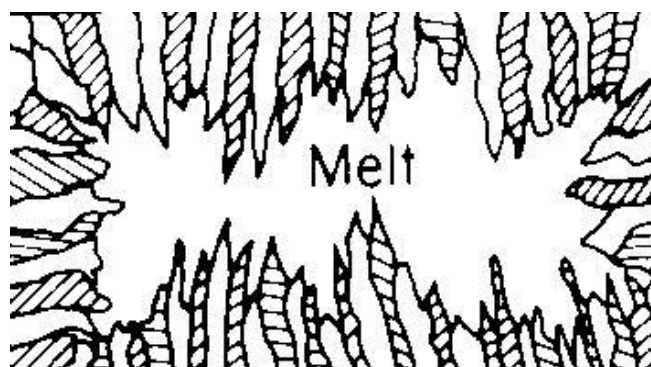


Fig.3.4. Formation of dendrites in a molten metal.



Fig.3.5. Dendrites observed at a magnification of x 250.

Since each nucleus is formed by chance, the crystal axes are pointed at random and the dendrites will grow in different directions in each crystal. Finally, as the amount of liquid decreases, the gaps between the arms of the dendrite will be filled and the growth of the dendrite will be mutually obstructed by that of its neighbors.

As atoms of melted metal begin to pack together to form a crystal lattice, groups of these atoms form small crystals. These small crystals increase in size by the progressive addition of atoms. The resulting solid is not one crystal but actually many smaller crystals, called **grains**. The interface formed between them is called a **grain boundary** (fig.3.6). The boundaries are formed by materials that are not part of a lattice, such as impurities, which do not show a specific grain pattern. Since the last liquid to solidify is generally along the grain boundaries, there tends to be a higher concentration of impurity atoms in that area.

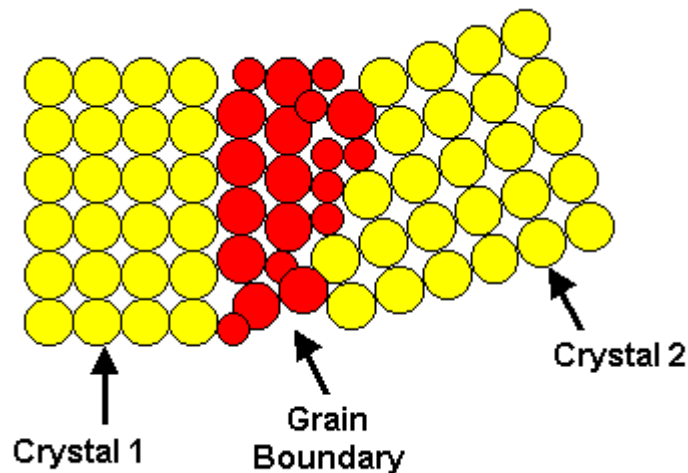


Fig.3.6. Grain boundary .

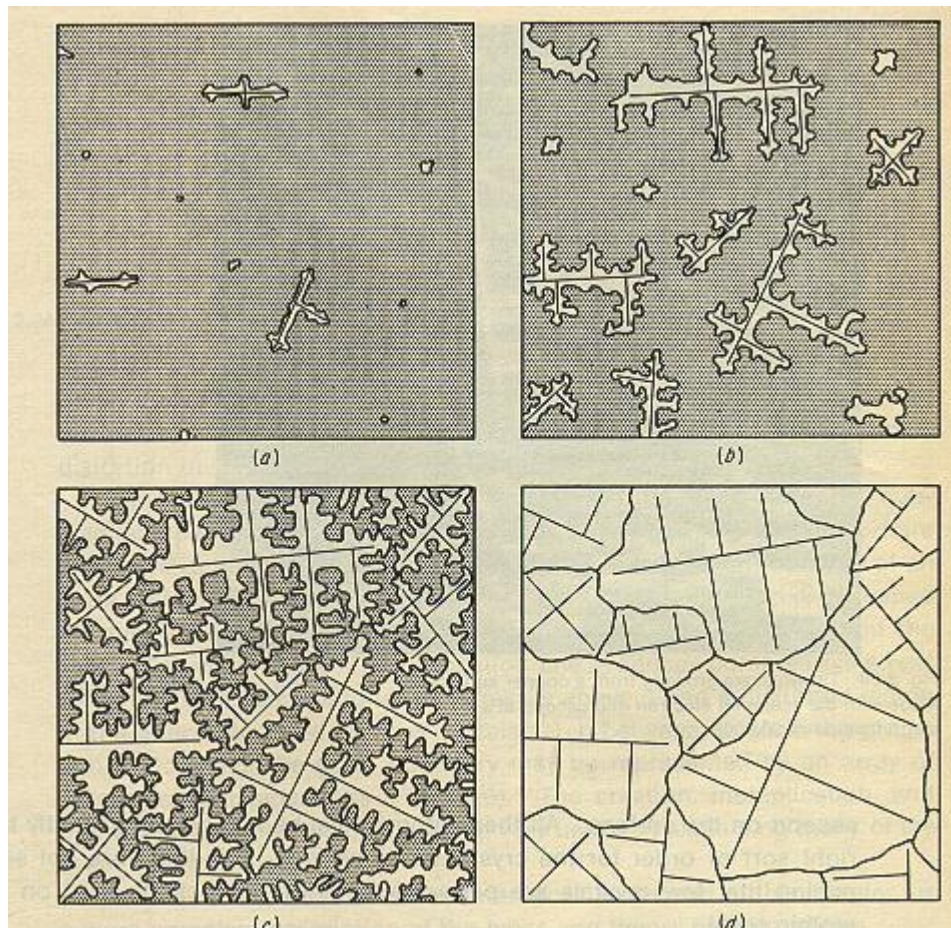


Fig. 3.7. Process of crystallization by nucleation and dendritic growth.

Grains are sometimes large enough to be visible under an ordinary light microscope or even to the unaided eye. Fig.3.8 shows a typical view of a metal surface with many grains, or crystals.

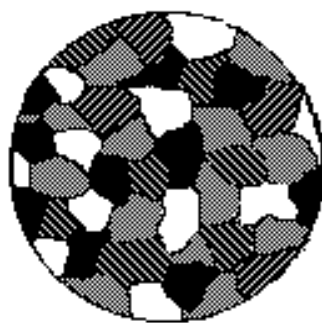


Fig.3.8. Grains and Grain Boundaries for a Metal.

The amount of nucleus (A.N.) formed in a metal, and speed of crystals growth (S.G.) depends on the degree of system's overcooling which in the turn depends on cooling speed (fig.3.9).

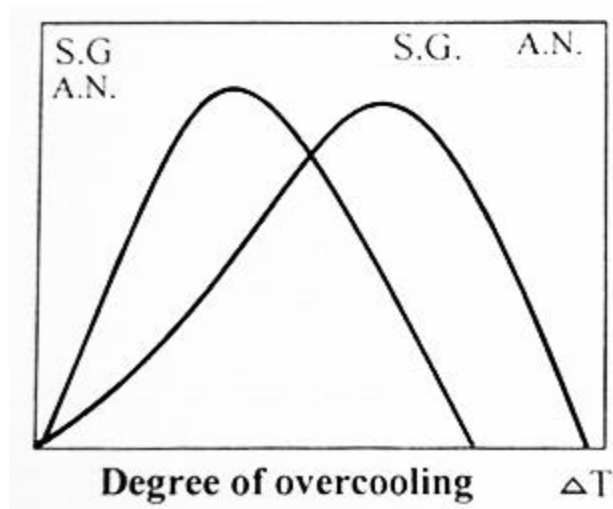


Fig.3.9. Speed of growth and amount of nucleus depending on the degree of overcooling.

3. Phenomenon of anisotropy and polymorphism

Anisotropy is difference of crystalline bodies' properties in various directions. It is due to the different distances and, consequently, by different values of communication forces between ions in different directions in a crystal.

Polymorphism is a physical phenomenon where a material may have more than one unit cell. A material that shows polymorphism exists in more than one type of space lattice in the solid phase. If the change in structure is reversible, then the polymorphic change is known as **allotropy**. Different crystalline structures of the same element are called its polymorphic **modifications** and marked by the initial letters of the Greek alphabet, beginning from low temperatures (Fe_α , Fe_γ ; Co_α , Co_β ; Mn_α , Mn_β , Mn_γ , Mn_δ and etc.).

Topic 4. **PROCESS OF PLASTIC DEFORMATION**

1. Process of elastic and plastic deformation of metal.
2. Processes of cold working and annealing.

1. Process of elastic and plastic deformation of metal.

In industry, molten metal is cooled to form the solid. The solid metal is then mechanically shaped to form a particular product. These steps are very important because heat and plastic deformation can strongly affect the mechanical properties of a metal.

When small loads (stresses) are applied to metals they deform, and they return to their original shape when the load is released. Bending a sheet of steel is an example where the bonds are bent or stretched only a small percentage. This is called elastic deformation and involves temporary stretching or bending of bonds between atoms (fig.4.1).

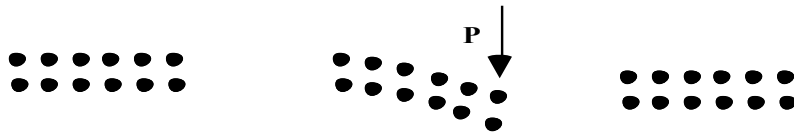


Fig.4.1. Elastic deformation in a bar of metal

When higher stresses are applied plastic deformation take place. This plastic deformation involves the breaking of bonds, often by the motion of dislocations. Dislocations move easily in metals, due to the delocalized bonding (fig.4.2), but do not move easily in ceramics. This largely explains why metals are ductile, while ceramics are brittle.

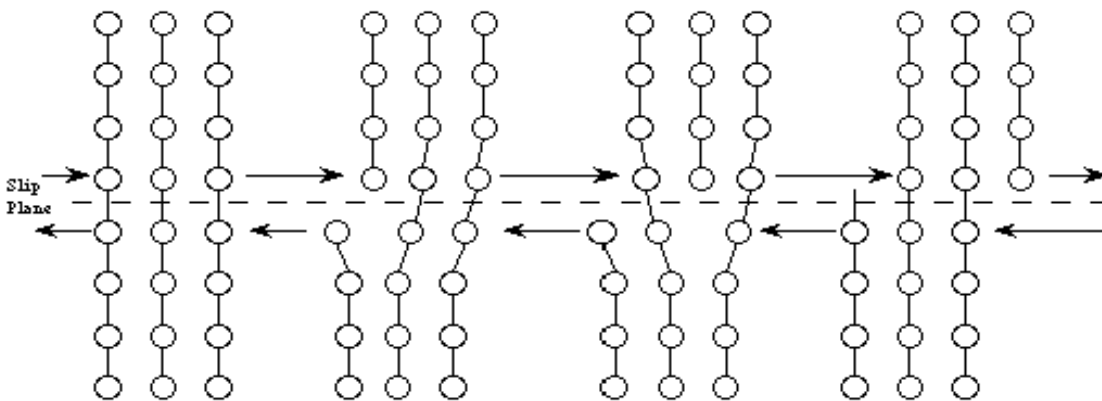


Fig.4.2. Dislocation movement in a crystal

If placed under large of a stress, metals will mechanically fracture. This can also result over time from many small stresses. The most common reason (about 80%) for metal failure is fatigue. Through the application and release of small stresses as the metal is used, small cracks in the metal are formed and grow slowly. Then the metal is permanently deformed or it breaks (fractures).

When a material is stressed below its elastic limit, the resulting deformation or strain is temporary. When a material is stressed beyond its elastic limit, plastic or permanent deformation takes place, and it will not return to its original shape by the application of force alone. The ability of a metal to undergo plastic deformation is most important outstanding characteristic in comparison with other materials.

All shaping operations such as stamping, pressing, spinning, rolling, forging, drawing, and extruding involve plastic deformation of metals. Various machining operations such as milling, turning, sawing, and punching also involve plastic deformation.

Plastic deformation may take place by :

- Slip
- Twinning
- Combination of slip and twinning

Deformation by Slip:

If a single crystal of a metal is stressed in tension beyond its elastic limit, it elongates slightly, a step appears on the surface indicating relative displacement of one part of the crystal with respect to the rest, and the elongation stops. Increasing the load will cause another step. It is as if neighboring thin sections of the crystal had slipped past one another like a sliding cards on a deck. Each successive elongation requires a higher stress and results in the appearance of another step, which is actually the intersection of a slip plane with the surface of the crystal. Progressive increase of the load causes the material to fracture.

Slip occurs in directions in which the atoms are most closely packed.

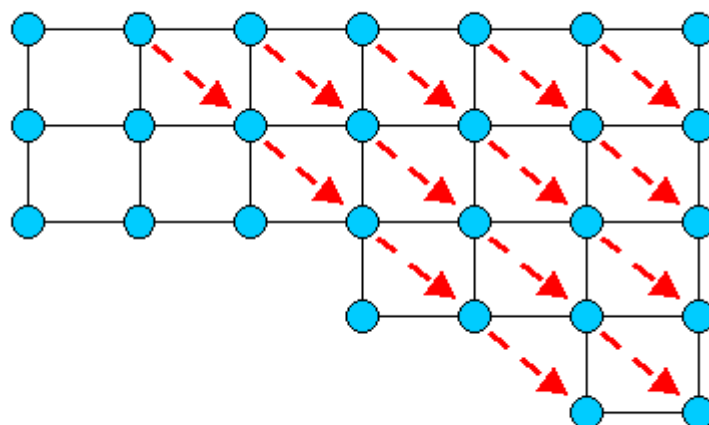


Fig.4.3. The effect of slip on the lattice structure

Fig.4.3. shows that when the plastic deformation is due to slip, the atoms move a whole interatomic space (moving from one corner to another corner of the unit cell). This means that overall lattice structure remains the same. Slip is observed as thin lines under the microscopes and these lines can be removed by polishing (fig.4.4, 4.5).

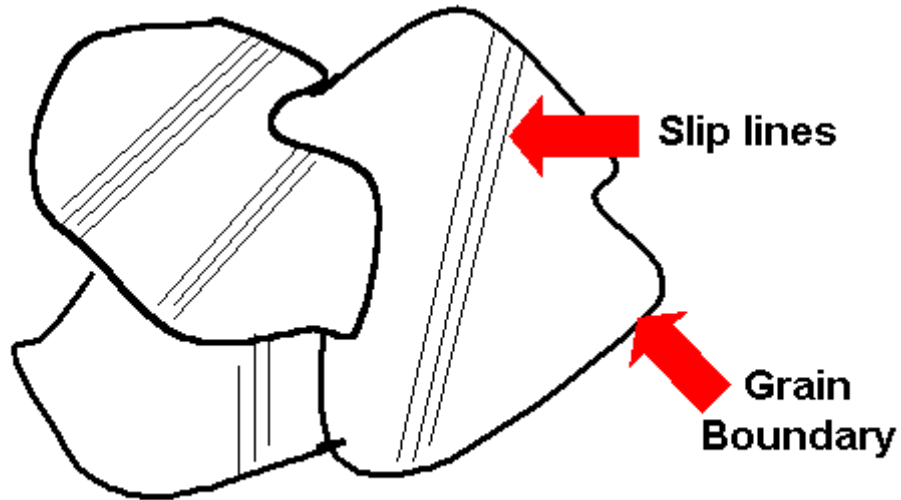


Fig.4.4. Slip appears as thin lines under the microscope



Fig.4.5. Slip lines in copper

Deformation by Twinning:

When mechanical deformation is created by twinning, the lattice structure changes. The atoms move only a fraction of an interatomic space and this leads to a rearrangement of the lattice structure. Twinning is observed as wide bands under the microscope fig.4.6. These wide bands can not be removed by polishing.

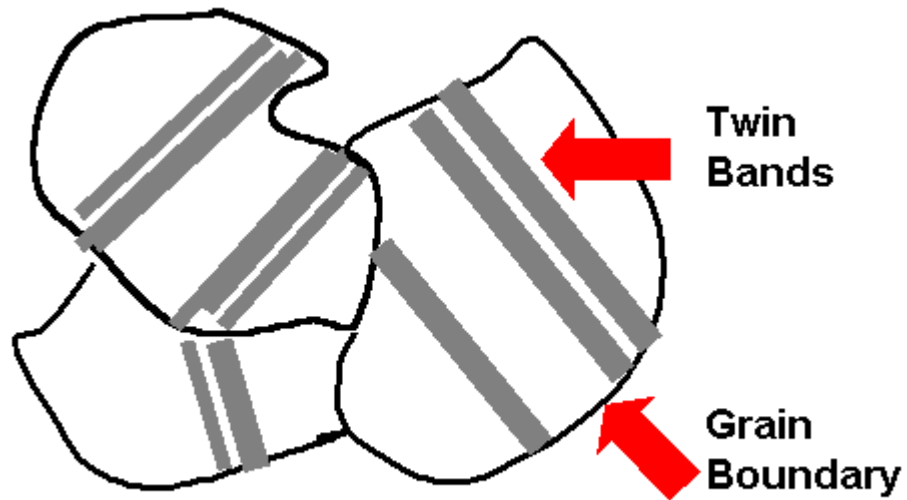


Fig.4.6. Twin bands

There are two kinds of twins:

1. Deformation or mechanical twins, most prevalent in close packed hexagonal metals (magnesium, zinc (fig.4.7)).
2. Annealing twins, most prevalent in F.C.C. (Face centered cubic) metals (aluminum, copper, brass, γ -iron). These metals have been previously worked and heat treated. The twins are formed because of a change in the normal growth mechanism.



Fig. 4.7. Twin bands in zinc

3. Processes of cold working and annealing:

Because plastic deformation results from the movement of dislocations, metals can be strengthened by preventing this motion. When a metal is bent or shaped, dislocations are generated and move. As the number of dislocations in the crystal increases, they will get tangled or pinned and will not be able to move. This will strengthen the metal, making it harder to deform. This process is known as **cold working**. At higher temperatures the dislocations can rearrange, so little strengthening occurs.

Heating removes the effects of cold-working. When cold worked metals are heated, recrystallization occurs. New grains form and grow to consume the cold worked portion. The new grains have fewer dislocations and the original properties are restored.

Annealing is a process in which metals are heated and then allowed to cool slowly.

As a result of cold working, the hardness, tensile strength, and electrical resistance increase, while ductility decreases. There is also a large increase in the number of dislocations, and certain planes in the crystal structure are severely distorted. Most of the energy used to cold work the metal is dissipated in heat, and a finite amount of energy is stored in the crystal structure as internal energy associated with the lattice defects created by the deformation.

Full annealing is the process by which the distorted cold worked lattice structure is changed back to one which is strain free through the application of heat. This process is carried out entirely in the solid state and is usually followed by slow cooling in the furnace from the desired temperature.

The **annealing process** may be divided into three stages:

- Recovery
- Recrystallization
- Grain growth.

Recovery:

This is primarily a low temperature process, and the property changes produced do not cause appreciable change in microstructure or the properties, such as tensile strength, yield strength, hardness and ductility. The principal effect of recovery is the relief of internal stresses due to cold working.

When the load which causes plastic deformation is released, all the elastic deformation does not disappear. This is due to the different orientation of crystals, which will not allow some of them to move back when the load is released. As the temperature is increased, there is some spring back of these elastically displaced atoms which relieve most of the internal stresses. Electrical conductivity is also increased appreciably during the recovery stage.

Since the mechanical properties of the metal are essentially unchanged, the main purpose of heating in the recovery range is stress relieving cold worked alloys to prevent stress corrosion cracking or to minimize the distortion produced by

residual stresses. Commercially, this low temperature treatment in the recovery range is known as stress relief annealing or process annealing.

Recrystallization:

As the temperature of the recovery range is reached, minute new crystals appear in the microstructure. These new crystals have the same composition and lattice structure as the original undeformed grains and are not elongated but are uniform in dimensions. The new crystals generally appear at the most drastically deformed portions of the grain, usually the grain boundaries and slip planes. The cluster of atoms from which the new grains are formed is called a nucleus. Recrystallization takes place by a combination of nucleation of strain free grains and the growth of these nuclei to absorb the entire cold worked material.

The term recrystallization temperature does not refer to a definite temperature below which recrystallization will not occur, but refers to the approximate temperature at which a highly cold worked material completely recrystallizes in one hour.

Pure metals have low recrystallization temperatures as compared with alloys. Zinc, tin and lead have recrystallization temperatures below room temperature. This means that these metals cannot be cold worked at room temperature since they crystallize spontaneously, reforming a strain free structure.

The greater the prior deformation, the lower the temperature for the start of recrystallization.

Increasing the annealing time decreases the recrystallization temperature for the start of recrystallization.

During recrystallization stage, there is a significant drop in tensile strength, hardness and a large increase in the ductility of the material (See Figure 1).

Grain Growth:

In this stage the tensile strength and hardness continue to decrease but at a much less rate than the recrystallization stage. The major change observed during this stage is the growth of the grain boundaries and reaching the original grain size (See Fig.4.8).

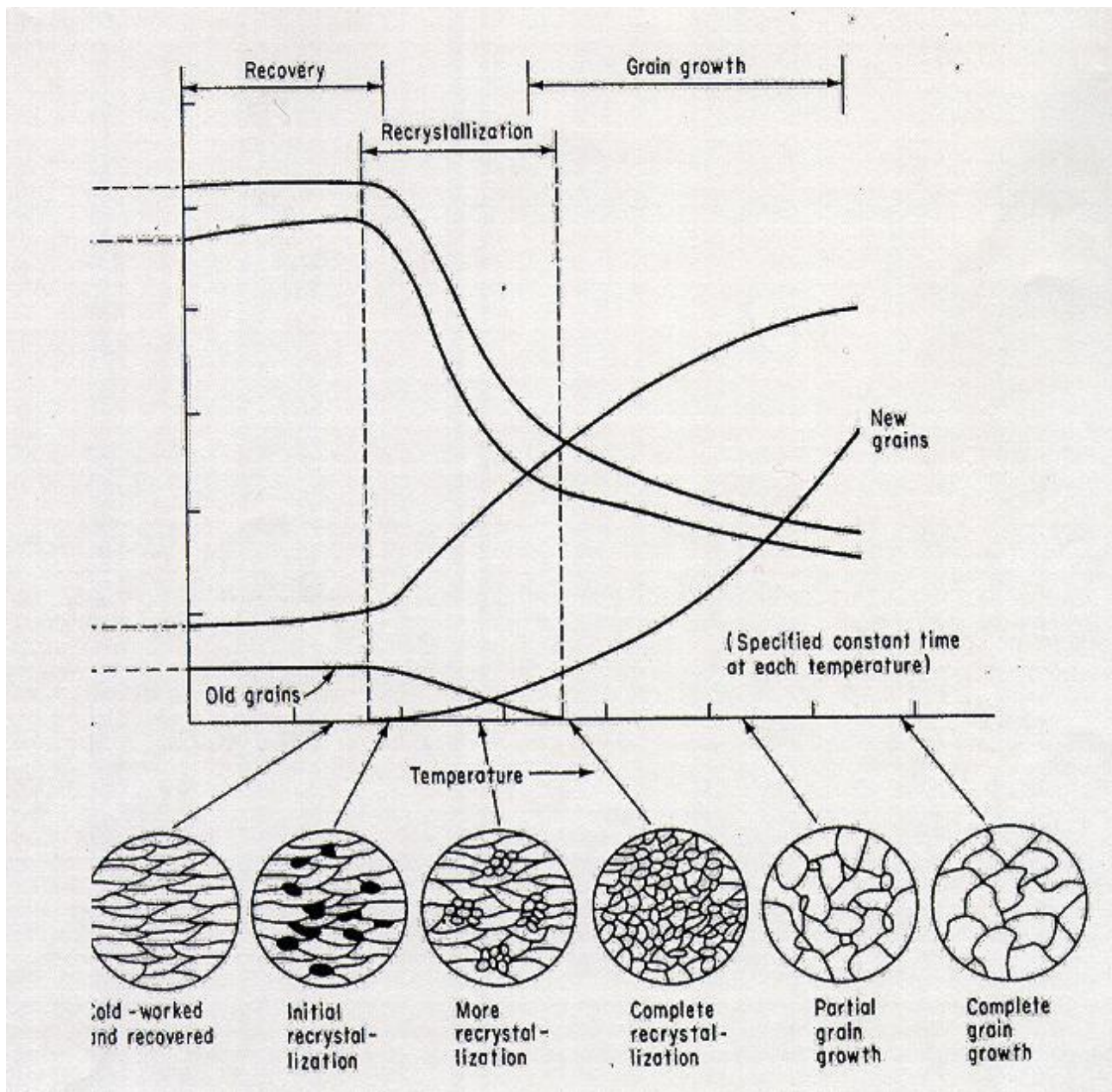


Fig.4.8. Effect of annealing on tensile strength, hardness, ductility and grain size

Topic 5. PHASE DIAGRAMS ANALYSIS

1. Methods of phase diagrams analysis.
2. Construction of the phase diagrams.
3. Inverse Lever Rule
4. Eutectic and eutectoid systems

1. Methods of phase diagrams analysis

The properties of a material depend on the type, number, amount, and form of the phases present, and can be changed by altering these quantities. In order to make these changes, it is essential to know the conditions under which these quantities exist and the conditions under which a change in phase will occur.

The best method to record the data of phase changes in many alloy systems is in the form of **phase diagrams**, also known as equilibrium diagrams.

In order to specify completely the state of a system in equilibrium, it is necessary to specify three independent variables: temperature, pressure and composition. When pressure is constant and equal at atmospheric value, the equilibrium diagram indicates the structural changes due to variation of temperature and composition.

Phase diagrams show the phase relationships under equilibrium conditions, that is, under conditions in which there will be no change with time. Equilibrium conditions may be approached by extremely slow heating and cooling, so that if a phase change is to occur, sufficient time is allowed.

Phase diagrams are usually plotted with temperature as the ordinate, and the alloy composition as the abscissa as shown in Fig.5.1.

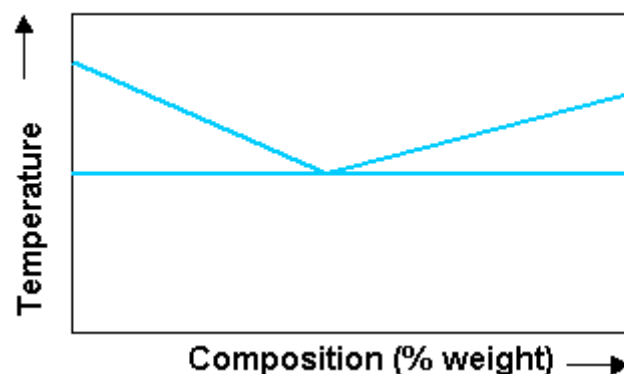


Fig.5.1. Sample Phase Diagram (A+B)

Experimental Methods:

The data for the construction of equilibrium diagrams are determined experimentally by a variety of methods, the most common methods are:

- Metallographic Methods

- X-ray Diffraction Technique
- Thermal Analysis

Metallographic Methods:

This method is applied by heating samples of an alloy to different temperatures, waiting for equilibrium to be established, and then quickly cooling to retain their high-temperature structure. The samples then examined microscopically. This method is difficult to apply to metals at high temperatures because the rapidly cooled samples do not always retain their high-temperature structure, and considerable skill is then required to interpret the observed microstructure correctly.

X-ray Diffraction Technique:

This method is applied by measuring the lattice dimensions and indicating the appearance of a new phase either by the change in lattice dimension or by the appearance of a new crystal structure. This method is very precise and very useful in determining the changes in solid solubility with temperature.

Thermal Analysis:

This is the most widely used experimental method. ***It relies*** on the information obtained from the cooling diagrams. In this method, alloys mixed at different compositions are melted and then the temperature of the mixture is measured at a certain time interval while cooling back to room temperature.

A cooling diagram for each mixture is constructed and the initial and final phase change temperatures are determined. Then these temperatures are used for the construction of the phase diagrams.

2. Construction of the phase diagrams

Cooling Curve of a Pure Metal:

Under equilibrium conditions, all metals exhibit a definite melting or crystallization point. If a cooling curve is plotted for a pure metal. It will show a horizontal line at the melting or freezing temperature.

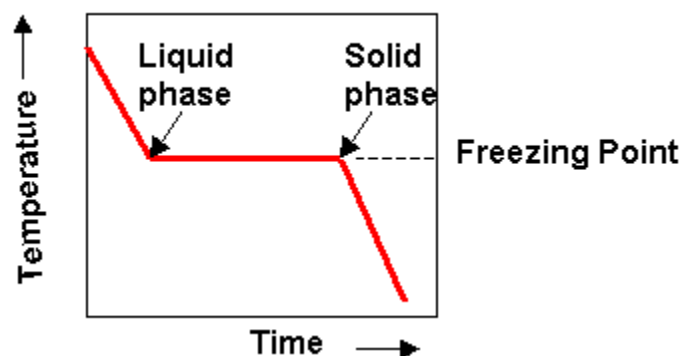


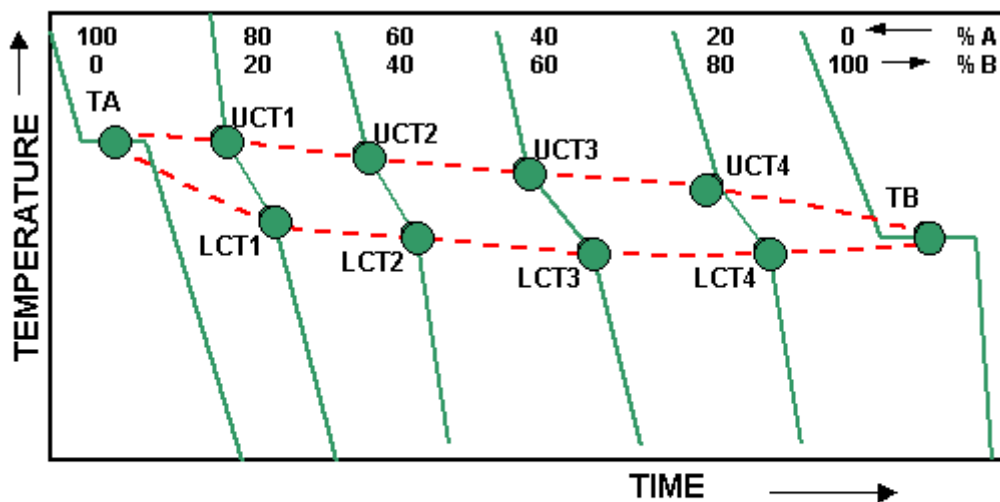
Fig5.2. Cooling curve for the solidification of a pure metal.

There are three kinds of initial elements (or components) interaction:

1. Solid solution (complete and partial solubility). It is marked as $\alpha \Rightarrow A(B)$,
 $\beta \Rightarrow B(A)$.
2. Mechanically mixture. It is marked as $A + B$.
3. Chemical composition. It is marked as A_nB_m .

Cooling Curve of a Solid Solution:

A solid solution is a solution in the solid state and consists of two kinds of atoms combined in one type of space lattice. A solution is composed of two parts: a solute and a solvent. The solute is the minor part of the solution or the material which is dissolved, while the solvent constitutes the major portion of the solution. When solidification of the solution starts, the temperature may be higher or lower than the freezing point of the pure solvent. Most solid solutions solidify over a range in temperature. Fig.5.3 shows the cooling curve for the solidification of a solid solution.



LCT=Lower Critical Temperature

UCT=Upper Critical Temperature

TA=Melting Temperature of Alloy A

TB=Melting Temperature of Alloy B

Fig.5.3. Cooling curve for a solid solution $\alpha \Rightarrow A(B)$.

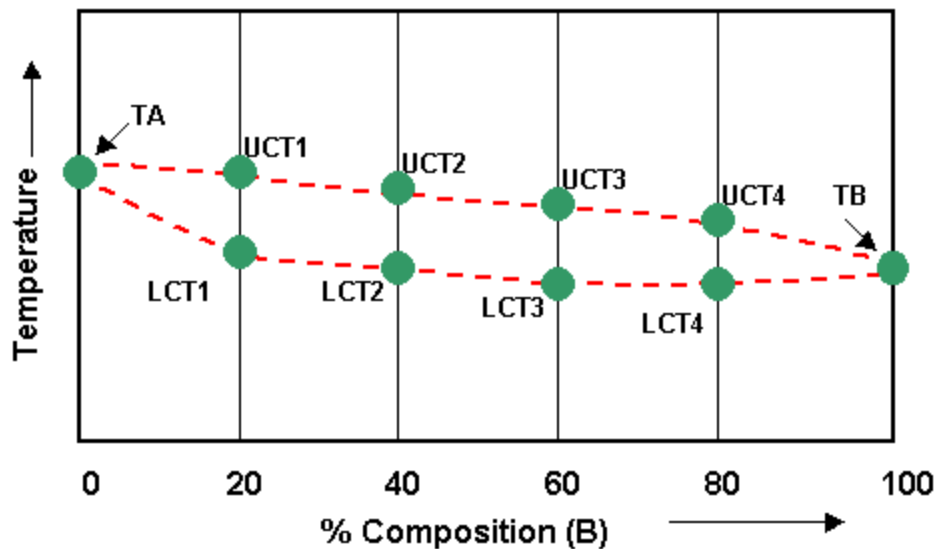


Fig.5.4. Series of cooling curves for different alloys in a completely soluble system. The dotted lines indicate the form of the phase diagram.

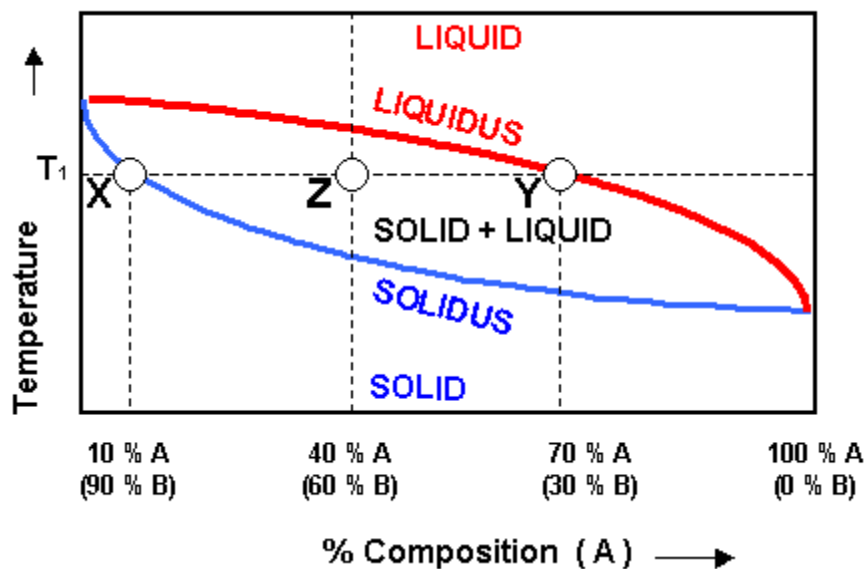


Fig.5.5. Phase Diagram of alloy $\alpha \Rightarrow A(B)$.

3. Inverse Lever Rule

Inverse Lever Rule:

Inverse lever rule is used to determine the percentage of each phase that is present at various temperatures.

The length of line XY represents the sum of the two phases as 100 percent. The inverse lever rule states that liquid phase can be calculated by taking the length of the line XZ and dividing this by XY.

The solid phase can be calculated by taking the length of the line ZY and dividing it by XY. To get the percentages, the values are multiplied by 100.

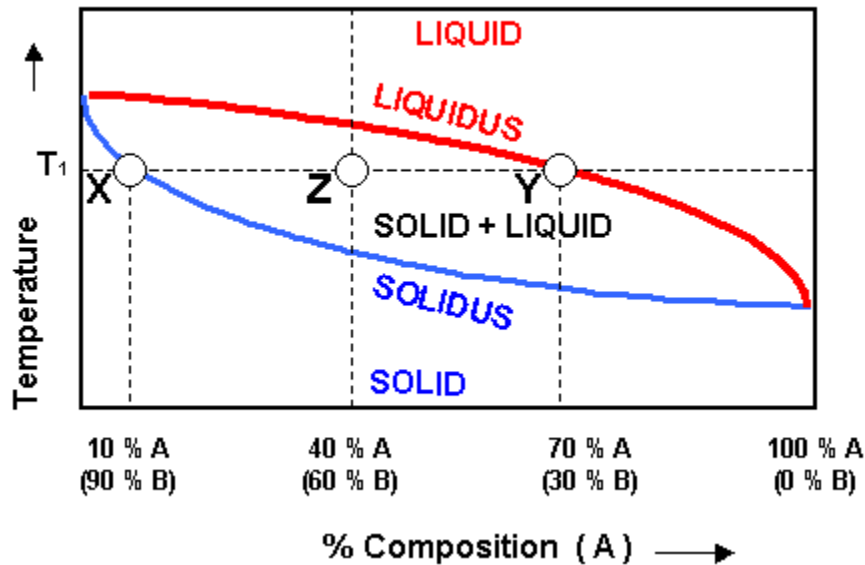


Fig.5.6. Phase diagram with complete solubility in liquid and solid states

Sample Calculation :

Alloy with 40 % A and 60 % B at room temperature is heated to a temperature T_1 . Calculate the liquid and solid phase and indicate the composition of each phase.

Liquid Phase = $(XZ / XY) \times 100 = [(40-10) / (70-10)] \times 100 = 50\%$

Solid Phase = $(ZY / XY) \times 100 = [(70-40) / (70-10)] \times 100 = 50\%$

At temperature T_1 , the solid composition is found by the intersection (point X) of isothermal line T_1 and the solidus curve.

Solid composition: 10 % A and 90 % B

The liquid composition at temperature T_1 is found by the intersection (point Y) of isothermal line T_1 and the liquidus curve.

Liquid composition: 70% A and 30 % B

4. Eutectic and eutectoid systems

Eutectic System:

Eutectic system is a phase transformation that takes place when a single-phase liquid transforms directly to a two-phase solid.

$L \rightarrow S_1 + S_2$

Liquid \rightarrow Solid 1 + Solid 2

(This is a reversible phase transformation)

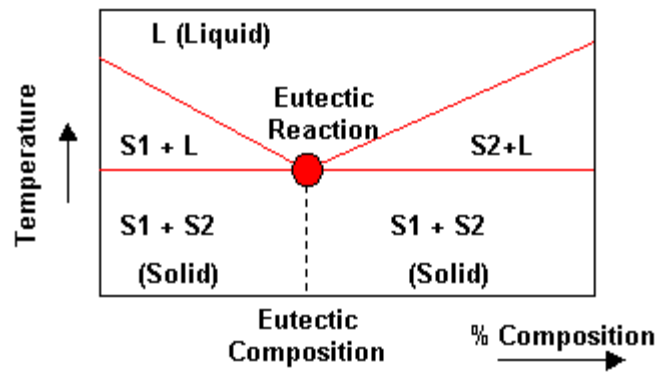


Fig.5.7. Eutectic phase transformation

Eutectoid System:

The eutectoid phase transformation occurs when a single-phase solid transforms directly to two-phase solid.



Solid 1 \rightarrow Solid 2 + Solid 3

(This is a reversible phase transformation)

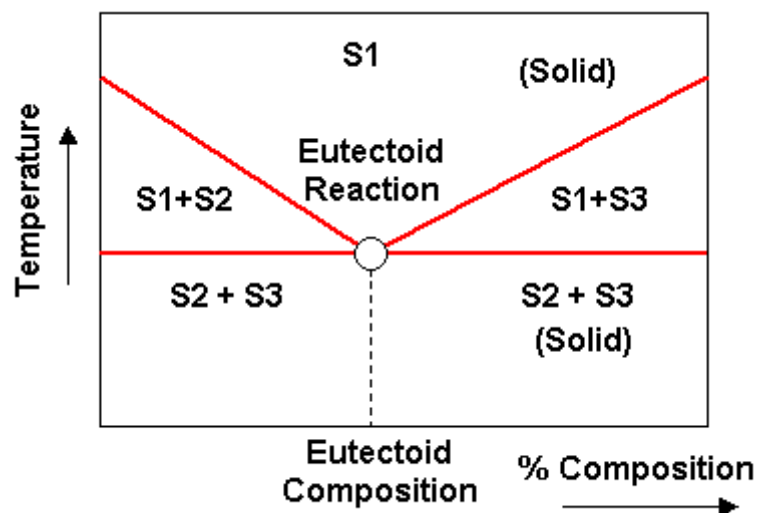


Fig.5.8. Eutectoid phase transformation

Topic 6. CARBON AND ALLOY STEELS

1. Features and structure of the Fe - Fe₃C diagram. Iron-Iron Carbide Diagram.
2. Effect of Carbon on the Properties of Steel.
3. Classification of Steels.

1. Features and structure of the Fe - Fe₃C diagram. Iron-Iron Carbide Diagram

Main components of Fe - Fe₃C diagram are: Fe and C.

Fe has polymorphic modifications and marked by the initial letters of the Greek alphabet, beginning from low temperatures (Fe_α, Fe_γ, Fe_δ).

When iron crystallizes at 1539 °C it is B.C.C. (δ -iron), at 1392 °C the structure changes to F.C.C. (γ -iron or austenite), and at 911 °C it again becomes B.C.C. (α - iron or ferrite).

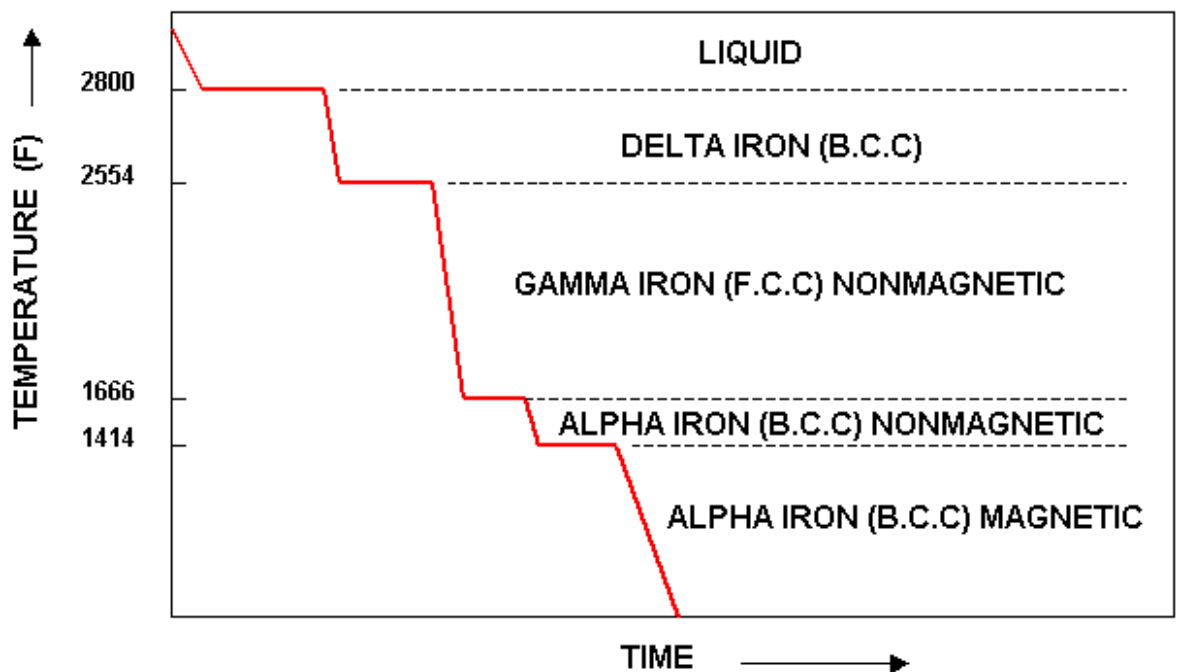


Fig.6.1. Cooling curve for pure iron. (Allotropic behavior of pure iron)

There are following features and structure:

CEMENTITE (Fe₃C):

Cementite is iron carbide which has a chemical formula, Fe₃C. It contains 6.67 % Carbon by weight. It is a typical hard and brittle interstitial compound of low tensile strength but high compressive strength. Its crystal structure is orthorhombic.

AUSTENITE (γ - iron):

It is also known as (γ -) gamma-iron, which is an interstitial solid solution of carbon dissolved in iron with a face centered cubic crystal (F.C.C) structure. Average properties of austenite are:

Table 6.1. Properties of Austenite

Elongation	10 %
Hardness	Rockwell R _C 40
Toughness	High



Fig.6.2. Austenite (gamma iron) crystal structure

Austenite is normally unstable at room temperature. Under certain conditions it is possible to obtain austenite at room temperature.

FERRITE (α - iron):

It is (α -) alpha -iron, which is an interstitial solid solution of a small amount of carbon dissolved in iron with a Body Centered Cubic (B.C.C.) crystal structure. It is the softest structure on the iron-iron carbide diagram. Average properties are:

Table 6.2. Properties of Ferrite

Elongation	40 %
Hardness	Less than Rockwell R _C 10
Toughness	Low

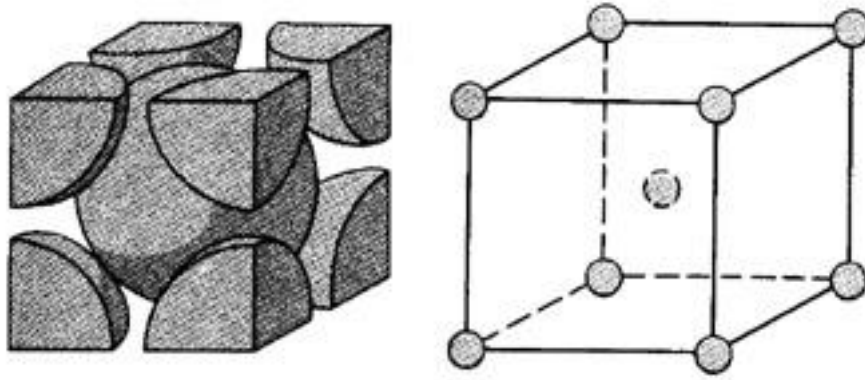
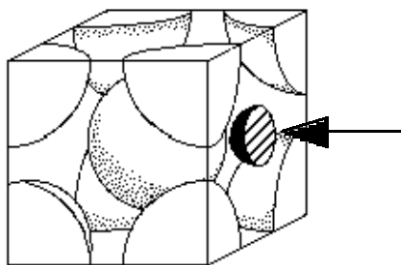


Fig.6.3. Ferrite (alpha iron) crystal structure



Interstitial Carbon in Iron
 Since the interstitial sites are so small, the maximum solubility in BCC iron is only one carbon atom for 5000 iron atoms.

Fig.6.4. BCC iron showing the location of interstitial carbon atoms

PEARLITE (α - Fe + Fe₃C)

It is the eutectoid mixture containing 0.8 % Carbon and is formed at 727°C on very slow cooling. It is very fine platelike or lamellar mixture of ferrite and cementite. The structure of pearlite includes a white matrix (ferritic background) which includes thin plates of cementite.

Average properties are:

Table 6.3. Properties of pearlite.

Elongation	20 %
Hardness	Rockwell R _C 20 or BHN 250-300

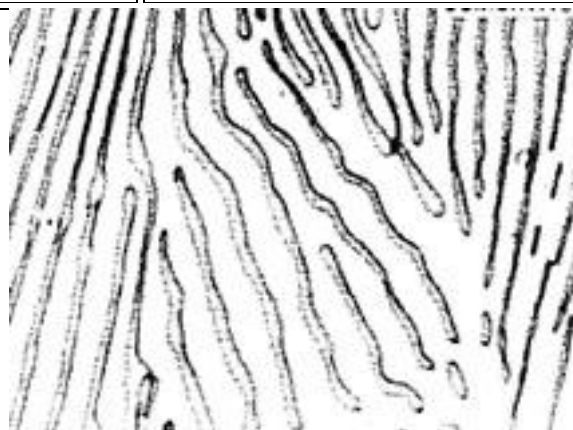


Fig.6.5. Pearlite microstructure (Light background is the ferrite matrix, dark lines are the cementite network)

A fixed amount of carbon and a fixed amount of iron are needed to form cementite (Fe_3C). Also, pearlite needs fixed amounts of cementite and ferrite.

LEDEBURITE ($\gamma - \text{Fe} + \text{Fe}_3\text{C}$)

It is the eutectic mixture of austenite and cementite. It contains 4.3 % Carbon and represents the eutectic of cast iron. Ledeburite exists when the carbon content is greater than 2.14%, which represents the dividing line on the equilibrium diagram between steel and cast iron.

(δ -) DELTA IRON:

Delta iron exists between 1392 and 1539 °C. It may exist in combination with the melt to about 0.50 % Carbon, in combination with austenite to about 0.18 % Carbon and in a single phase state out to about 0.10 % carbon. Delta iron has the Body Centered Cubic (B.C.C) crystal structure and is magnetic.

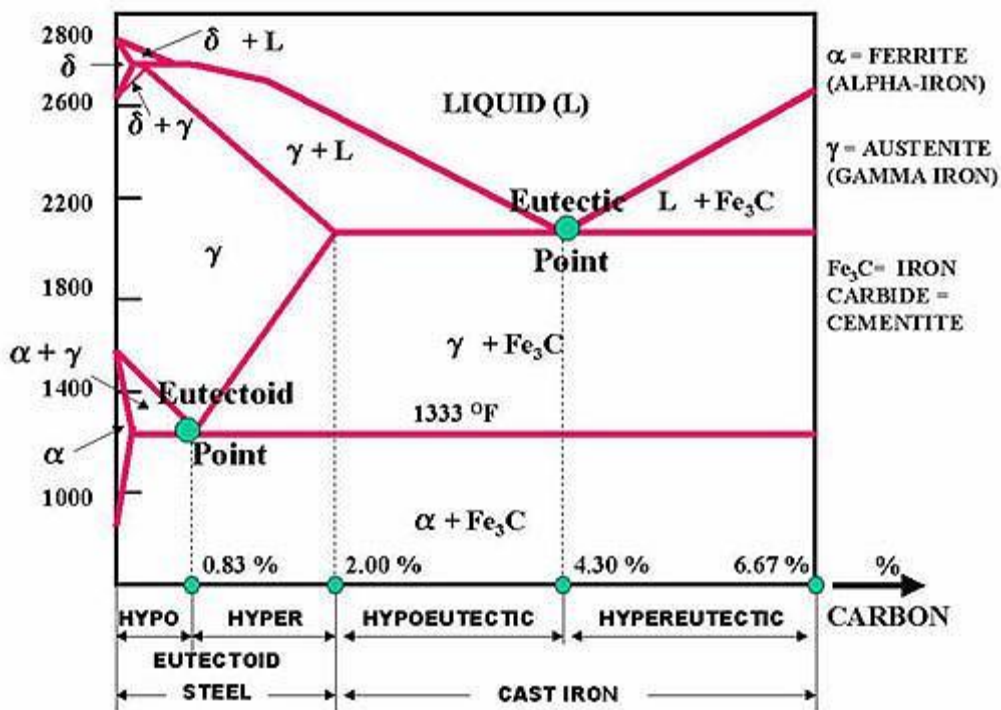


Fig.6.6. Iron-ironcarbide diagram.

2. Effect of Carbon on the Properties of Steel

In general, as the carbon content increases the hardness of the steel also increases. The tensile strength and the yield strength also increase to about 0.8 % carbon. Thereafter, they level out. This is shown in Figure 6.7.

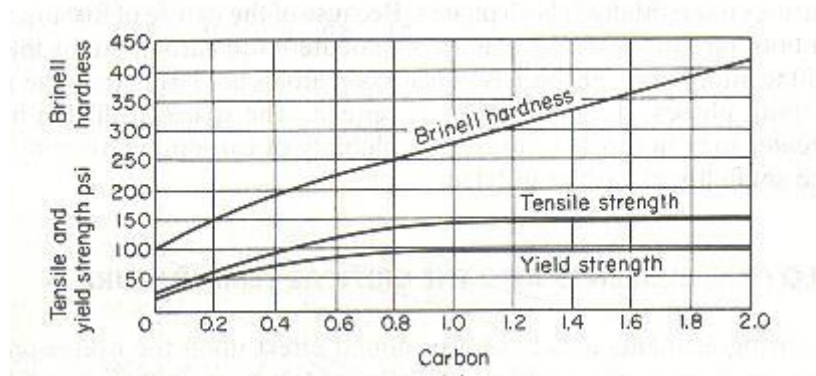


Fig.6.7. Effect of carbon on hardness, tensile strength and yield strength of steels.

The tensile strength and hardness are affected as the ratio of ferrite to cementite in the structure of steel changes. As the percentage of pearlite increases in the hypoeutectoid steels, the tensile strength increases. The hardness does not increase dramatically. The hypereutectoid steels show only a slight increase in strength as the cementite-to-ferrite ratio increases.

The elongation and the reduction in area represent how ductile or brittle a material is. Fig. 9.8 indicates the effect of carbon on the ductility and impact resistance (toughness) of steels. The elongation and the reduction in area drop sharply with increase in carbon content, going almost to zero at about 1.5 % carbon. This indicates that the carbon content of 1.5 % or more will cause high brittleness. The impact resistance also decreases very sharply up to about 0.83 % carbon and then levels out.

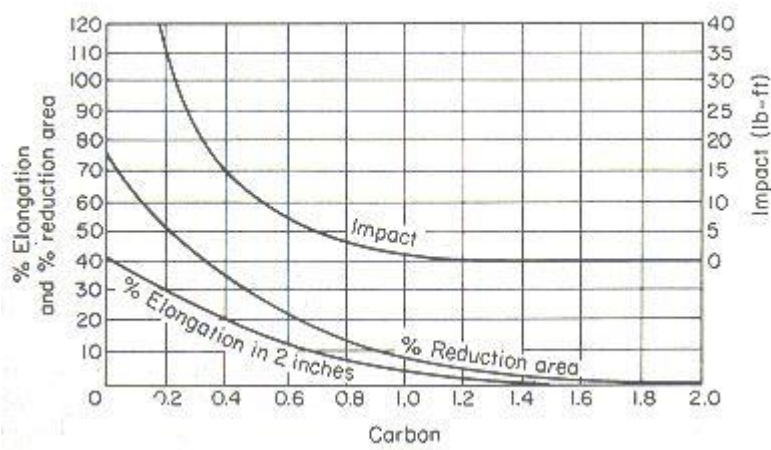


Fig. 6.8. Effect of carbon on the impact resistance and ductility of steels.

3. Classification of Steels

The Society of Automotive Engineers (SAE) has established standards for specific analysis of steels. In the 10XX series, the first digit indicates a plain carbon steel. The second digit indicates a modification in the alloys. 10XX means that it is a plain carbon steel where the second digit (zero) indicates that there is no

modification in the alloys. The last two digits denote the carbon content in points. For example SAE 1040 is a carbon steel where 40 points represent 0.40 % Carbon content. Alloy steels are indicated by 2XXX, 3XXX, 4XXX, etc.. The American Iron and Steel Institute (AISI) in cooperation with the Society of Automotive Engineers (SAE) revised the percentages of the alloys to be used in the making of steel, retained the numbering system, and added letter prefixes to indicate the method used in steel making. The letter prefixes are:

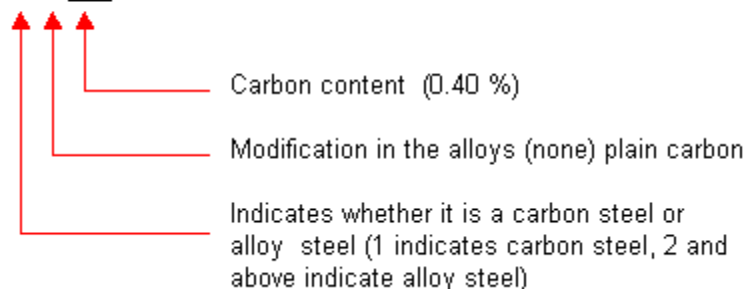
A = alloy, basic open hearth
B = carbon, acid Bessemer
C = carbon, basic open hearth
D = carbon, acid open hearth
E = electric furnace

If the prefix is omitted, the steel is assumed to be open hearth. Example: AISI C1050 indicates a plain carbon, basic-open hearth steel that has 0.50 % Carbon content.

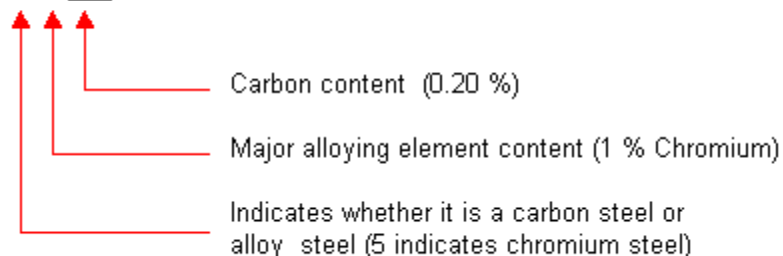
Another letter is the hardenability or H-value. Example: 4340H

General representation of steels:

SAE 1 0 40



SAE 5 1 20



SAE 25 15

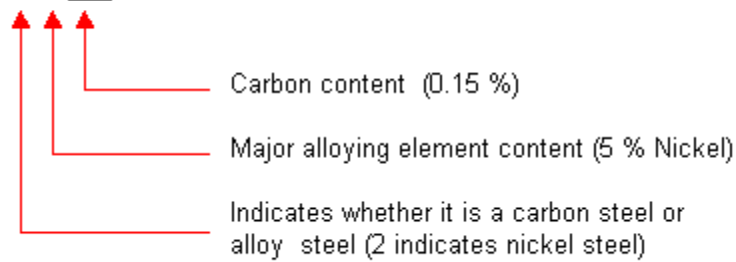


Table 6.4. Classification of steels

SAE - AISI Number	Classification
1XXX	Carbon steels Low carbon steels: 0 to 0.25 % C Medium carbon steels: 0.25 to 0.55 % C High carbon steels: Above 0.55 % Carbon
2XXX	Nickel steels 5 % Nickel increases the tensile strength without reducing ductility. 8 to 12 % Nickel increases the resistance to low temperature impact 15 to 25 % Nickel (along with Al, Cu and Co) develop high magnetic properties. (Alnicometals) 25 to 35 % Nickel create resistance to corrosion at elevated temperatures.
3XXX	Nickel-chromium steels These steels are tough and ductile and exhibit high wear resistance , hardenability and high resistance to corrosion.
4XXX	Molybdenum steels Molybdenum is a strong carbide former. It has a strong effect on hardenability and high temperature hardness. Molybdenum also increases the tensile strength of low carbon steels.
5XXX	Chromium steels Chromium is a ferrite strengthener in low carbon steels. It increases the core toughness and the wear resistnace of the case in carburized steels.
86XX 87XX 93XX 94XX 97XX 98XX	Triple Alloy steels which include Nickel (Ni), Chromium (Cr), and Molybdenum (Mo). These steels exhibit high strength and also high strength to weight ratio, good corrosion resistance.

The properties of steel can be tailored for special uses by the addition of other metals to the alloy. Titanium, vanadium, molybdenum and manganese are among the metals added to these specialty steels. Stainless steel contains a minimum of 12% chromium, which stops further **oxidation** by forming a protective **oxide** on the surface.

Table 6.5. The effect of alloying elements on the properties of steel

Element	Effect
Aluminum	Ferrite hardener Graphite former Deoxidizer
Chromium	Mild ferrite hardener Moderate effect on hardenability Graphite former Resists corrosion Resists abrasion
Cobalt	High effect on ferrite as a hardener High red hardness
Molybdenum	Strong effect on hardenability Strong carbide former High red hardness Increases abrasion resistance
Manganese	Strong ferrite hardener
Nickel	Ferrite strengthener Increases toughness of the hypoeutectoid steel With chromium, retains austenite Graphite former
Copper	Austenite stabilizer Improves resistance to corrosion
Silicon	Ferrite hardener Increases magnetic properties in steel
Phosphorus	Ferrite hardener Improves machinability Increases hardenability

Red Hardness: This property , also called hot-hardness, is related to the resistance of the steel to the softening effect of heat. It is reflected to some extent in the resistance of the material to tempering.

Hardenability: This property determines the depth and distribution of hardness induced by quenching.

Hot-shortness: Brittleness at high temperatures is called hot-shortness which is usually caused by sulfur. When sulfur is present, iron and sulfur form iron sulfide (FeS) that is usually concentrated at the grain boundaries and melts at temperatures below the melting point of steel. Due to the melting of iron sulfide, the cohesion between the grains is destroyed, allowing cracks to develop. This occurs when the steel is forged or rolled at elevated temperatures. In the presence of manganese, sulfur tends to form manganese sulfide (MnS) which prevents hot-shortness.

Cold-shortness: Large quantities of phosphorus (in excess of 0.12%P) reduce the ductility, thereby increasing the tendency of the steel to crack when cold worked. This brittle condition at temperatures below the recrystallization temperature is called cold-shortness.

Topic 7. **CAST IRON**

1. Types of cast iron.
2. Gray cast iron and low alloy gray cast iron.
3. White cast iron.
4. Ductile Cast iron (nodular cast).
5. Malleable cast iron.

1. Types of cast iron

Cast irons may often be used in place of steel at considerable cost savings. The design and production **advantages** of cast iron include:

- Low tooling and production cost
- Good machinability without burring
- Ability to cast into complex shapes
- Excellent wear resistance and high hardness (particularly white cast irons)
- High inherent damping capabilities

The properties of the cast iron are affected by the following factors:

Chemical composition of the iron

Rate of cooling of the casting in the mold (which depends on the section thickness in the casting)

Type of graphite formed (if any)

Major types of cast iron are shown in Figure 7.1.

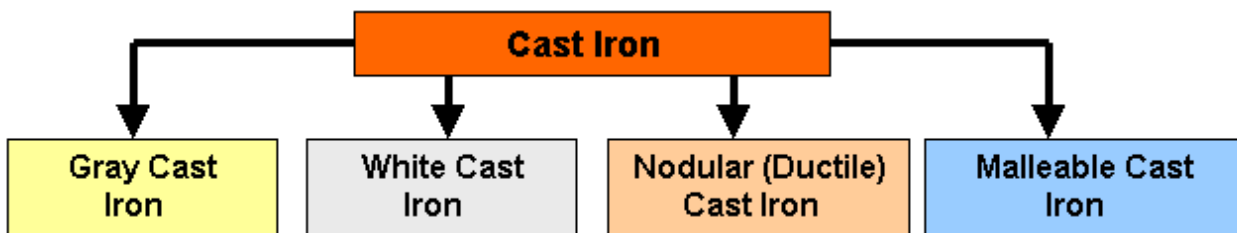


Fig.7 1. Types of Cast Iron

2. Gray cast iron and low alloy gray cast iron

Gray Cast Iron:

Gray cast iron is by far the oldest and most common form of cast iron. Gray iron, named so because of its fracture has a gray appearance. It contains carbon in the form of **flake graphite** in a matrix which consists of ferrite, pearlite or a mixture of the two. The fluidity of liquid gray iron, and its expansion during solidification due to the formation of graphite, has made this metal ideal for the economical production of shrinkage-free, intricate castings such as motor blocks.

The flake-like shape of graphite in Gray iron, see Fig.7.2 and 7.3, exerts a dominant influence on its mechanical properties. The graphite flakes act as stress raisers which may prematurely cause localized plastic flow at low stresses, and initiate fracture in the matrix at higher stresses. As a result, Gray iron exhibits no elastic behavior but excellent damping characteristics, and fails in tension without significant plastic deformation. The presence of graphite flakes also gives Gray Iron excellent machinability and self-lubricating properties.

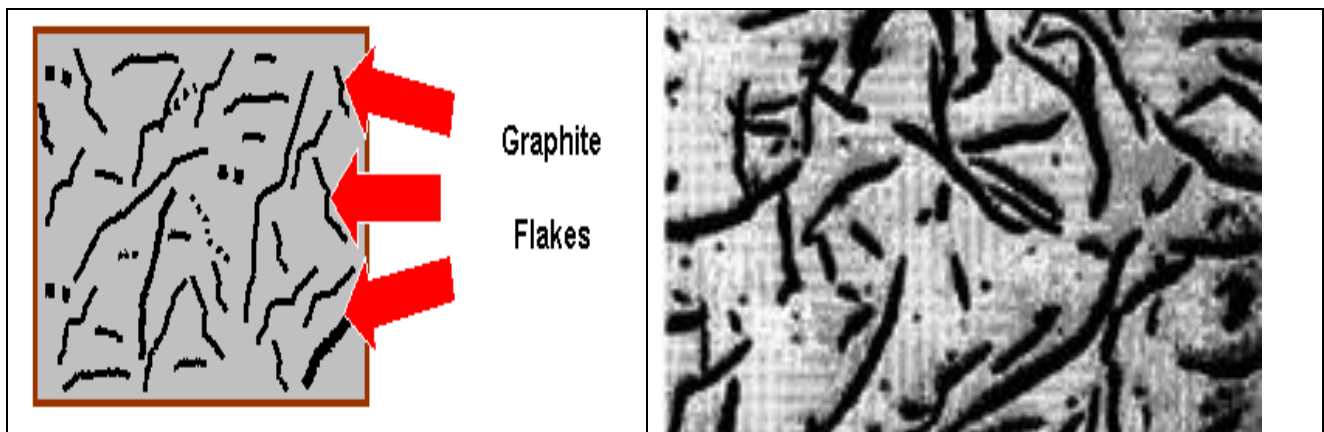


Fig.7. 2. Graphite Flakes in Gray Cast iron

Fig.7.3. Photomicrograph of Gray Cast iron

Advantages of Gray Cast Iron:

- Graphite acts as a chip breaker and a tool lubricant.
- Very high damping capacity.
- Good dry bearing qualities due to graphite.
- After formation of protective scales, it resists corrosion in many common engineering environments.

Disadvantages:

- Brittle (low impact strength) which severely limits use for critical applications.

- Graphite acts as a void and reduces strength. Maximum recommended design stress is 1/4 of the ultimate tensile strength. Maximum fatigue loading limit is 1/3 of fatigue strength.
- Changes in section size will cause variations in machining characteristics due to variation in microstructure.
- Higher strength gray cast irons are more expensive to produce.

Low Alloy Gray Cast Iron:

Enables gray cast iron to be used in higher duty applications without redesign or need for costly materials.

Advantages:

- Reduction in section sensitivity.
- Improvement in strength, corrosion resistance, heat and wear resistance or combination of these properties.

Disadvantages:

- Higher cost.
- Alloy additions can cause foundry problems with reuse of scrap (runners, risers, etc) and interrupt normal production.
- Increase in strength does not bring corresponding increase in fatigue strength.
- Cr, Mo and V are carbide stabilizers which improve strength and heat resistance but impair machinability.

4. White cast iron

White cast iron is unique in that it is the only member of the cast iron family in which **carbon is present only as carbide**. Due to the absence of graphite, it has a light appearance. The presence of different carbides, depending on the alloy content, makes white cast irons extremely hard and abrasion resistant but very brittle. An improved form of white cast iron is the chilled cast iron.

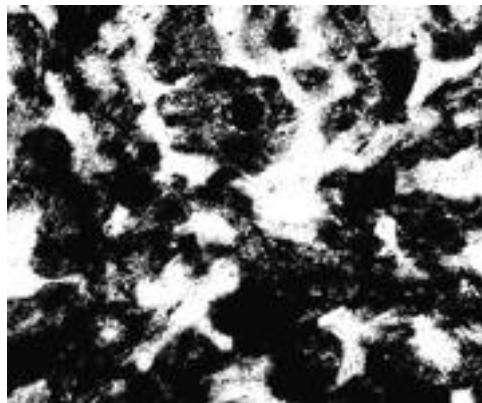


Fig.7.4a. Photomicrograph of White Cast Iron

Chilled Cast Iron:

When localized area of a gray cast iron is cooled very rapidly from the melt, cast iron is formed at the place that has been cooled. This type of white cast iron is called **chilled iron**. A chilled iron casting can be produced by adjusting the carbon composition of the white cast iron so that the normal cooling rate at the surface is just fast enough to produce white cast iron while the slower cooling rate below the surface will produce gray iron. The depth of chill decreases and the hardness of the chilled zone increases with increasing carbon content.

Chromium is used in small amounts to control chill depth. Because of the formation of chromium carbides, chromium is used in amount of 1 to 4 percent in chilled iron to increase hardness and improve abrasion resistance. It also stabilizes carbide and suppresses the formation of graphite in heavy sections. When added in amounts of 12 to 35 percent, chromium will impart resistance to corrosion and oxidation at elevated temperatures.

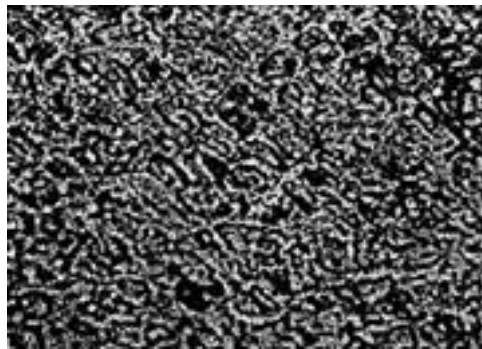


Fig.7.4b. Photomicrograph of Chilled Cast Iron

Fast cooling prevents graphite and pearlite formation. If alloys such as nickel, chromium, or molybdenum are added, much of the austenite transforms to martensite instead of pearlite. The hardness of chilled cast iron is generally due to the formation of martensite. Chilled cast iron is used for railway-car wheels, crushing rolls, stamp shoes and dies, and many heavy-duty machinery parts.

4. Ductile Cast iron (nodular cast)

This structure is developed from the melt. The carbon forms into spheres when cerium, magnesium, sodium, or other elements are added to a melt of iron with very low sulfur content that will inhibit carbon from forming. The control of the heat-treating process can yield pearlitic, ferritic, martensitic matrices into which the carbon spheres are embedded.

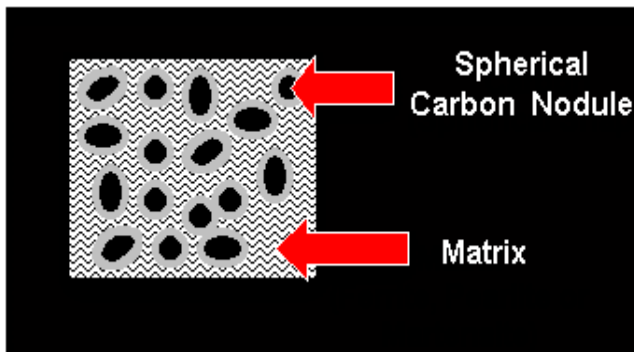


Fig.7. 5. Nodular (Ductile) Cast Iron and the spherical carbon embedded into the matrix.

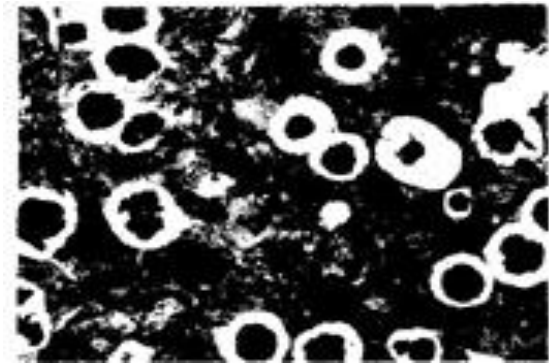


Fig.7. 6. Photomicrograph of Nodular Cast iron

The advantages of ductile cast iron which have led to its success are numerous, but they can be summarized easily- versatility and high performance at low cost. Other members of the ferrous casting family may have superior individual properties which might make them the material of choice in some applications, but none have the versatility of ductile cast iron, which often provides the designer with the best combination of overall properties. This is especially evident in the area of mechanical properties where ductile cast iron offers the designer the option of selecting high ductility, with grades guaranteeing more than 18% elongation (as high as 25 %), or high strength, with tensile strengths exceeding 1200 MPa. Austempered ductile irons offers even greater mechanical and wear resistance, providing tensile strengths exceeding 230 Ksi.

In addition to cost advantages offered by all castings, ductile cast iron, when compared to steel and malleable cast iron, also offers further cost savings. Like most commercial cast metal, steel and malleable cast iron decrease in volume during solidification, and as a result, require feeders and risers to offset the shrinkage and prevent the formation of internal or external shrinkage defects. Ductile cast iron offers significantly low shrinkage during casting. In the case of large castings produced in rigid molds, it does not require feeders. In other cases, it requires feeders that are much smaller than those used for malleable cast iron and steel. This reduced requirement for feed metal increases the productivity of ductile cast iron and reduces its material and energy requirements, resulting in substantial cost savings.

Ductile cast iron is used for many structural applications, particularly those requiring strength and toughness combined with good machinability and low cost. The automotive and agricultural industries are the major users of ductile iron castings. Because of economic advantage and high reliability, ductile iron is used for such critical automotive parts as crankshafts, engine connecting rods, idler arms, wheel hubs, truck axles, front wheel spindle supports, disk brake calipers, suspension system parts, power transmission yokes, high temperature applications for turbo housing and manifolds, and high security valves for many applications. The cast iron pipe industry is another major user of ductile iron.

5. Malleable Cast Iron

If cast iron is cooled rapidly, the graphite flakes needed for gray cast iron do not get a chance to form. Instead, white cast iron forms. This white cast iron is reheated to about 950°C for long periods of time and at the elevated temperatures cementite (Fe_3C) decomposes into ferrite and free carbon. Upon cooling, the combined carbon further decomposes to small compact particles of graphite (instead of flake-like graphite seen in gray cast iron). If the cooling is very slow, more free carbon is released. This free carbon is referred to as temper carbon, and the process is called malleableizing.

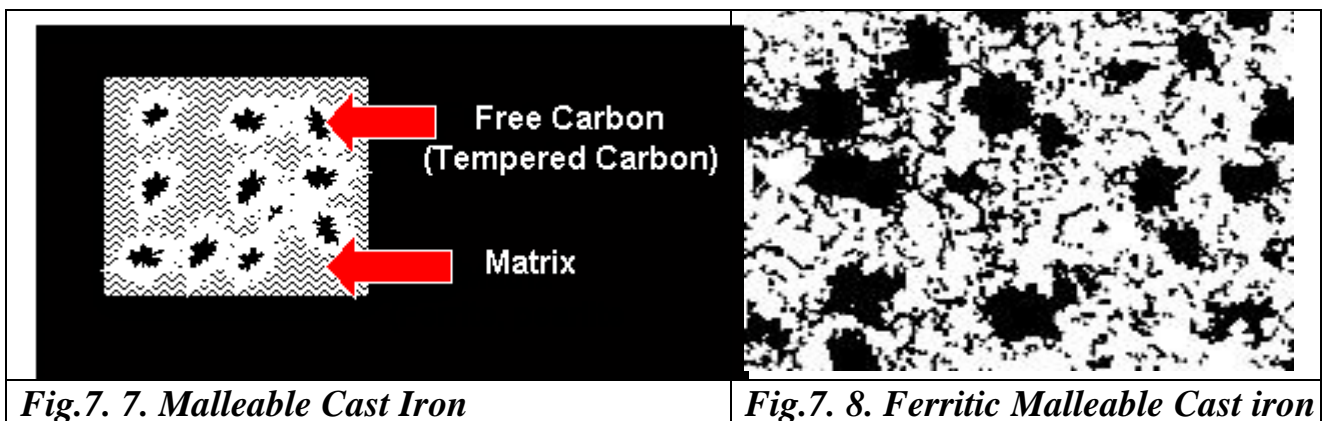


Fig.7.8 shows ferritic malleable cast iron, which has a ferrite matrix and the tempered carbon particles are embedded into the matrix. Fig.7.9 shows pearlite malleable cast iron, which has a pearlite matrix. By adding manganese to the structure, carbon is retained in the form of cementite.

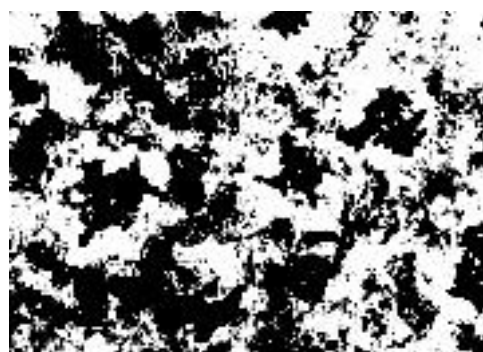


Fig.7. 9. Pearlitic Malleable Cast Iron

A wide variety of physical properties can be obtained by heating and cooling through the eutectoid temperature or by adding alloying elements. Slow cooling will cause the cementite to decompose and release more free carbon (temper carbon). Fast cooling will retain some of the cementite. The amount retained, will depend on the rapidity of cooling.

Malleable cast iron is used for connecting rods and universal joint yokes, transmission gears, differential cases and certain gears, compressor crankshafts and hubs, flanges, pipe fittings and valve parts for railroad, marine and other heavy-duty applications.

Advantages:

- Excellent machinability
- Significant ductility
- Good shock resistance properties

Disadvantages:

The major disadvantage is shrinkage. Malleable cast iron decreases in volume during solidification, and as a result, requires attached reservoirs (feeders and risers) of liquid metal to offset the shrinkage and prevent the formation of internal or external shrinkage defects.

Topic 8. ***HEAT TREATMENT OF STEEL***

1. Types of heat treatment processes.
2. Time-Temperature-Transformation (TTT)Diagram.
3. Processes of annealing and spheroidizing.
4. Process of normalizing.
5. Processes of Hardening and Tempering.

1. Types of heat treatment processes

Various types of heat treatment processes are used to change the following properties or conditions of the steel:

- Improve the toughness
- Increase the hardness
- Increase the ductility
- Improve the machinability
- Refine the grain structure
- Remove the residual stresses
- Improve the wear resistance

The following are the general reasons for heat treatment:

Hardening (Steels can be heat treated to high hardness and strength levels. The reasons for doing this are obvious. Structural components subjected to high operating stress need the high strength of a hardened structure. Similarly, tools such as dies, knives, cutting devices, and forming devices need a hardened structure to resist wear and deformation.)

Tempering (As-quenched hardened steels are so brittle that even slight impacts may cause fracture. Tempering is a heat treatment that reduces the brittleness of steel without significantly lowering its hardness and strength. All hardened steels must be tempered before use.)

Softening a Hardened Structure (Hardening is reversible. If a hardened tool needs to be remachined, it may be softened by heat treatment to return it to its machinable condition. Most steels weld better in their soft state than in their hardened state; softening may be used to aid weldability.)

Recrystallization (If a metal is cold worked, grains or crystals deform, become elongated, and in doing so harden and strengthen a metal. There is a limiting amount of cold work that a particular metal can be subjected to. In rolling of steel into thin sheets, you can only reduce the cross-sectional area so much before it gets too hard to roll. At this point it would be desirable to return the grains to their original shape. Heat treatment can accomplish this. The transformation of cold-worked grains to an

undistorted shape is called **recrystallization**. Very large coarse grains can also be refined by recrystallization. This type of heat treatment is essential if steel is to be subjected to severe cold working in rolling, drawing, etc.)

Stress Relief (One of the most frequent reasons for heat treatment is to remove internal stress from a metal that has been subjected to cold working or welding. Stress relieving is a heat treatment used to remove internal strains without significantly lowering the strength. It is used where close dimensional control is needed on welding, forgings, castings, etc.)

Hot-Working Operations (Most metal shapes produced by steel mills are at least rough shaped at elevated temperatures. Heat treating is required to bring the rough metal shapes to the proper temperature for hot-forming operations. Forging, hot rolling, roll welding, and the like are all performed at temperatures of sufficient magnitude as to prevent the formation of distorted grains that will harden the metals. Hot-working operations require dynamic recrystallization which is achieved by working at the proper hot-work temperatures.)

Diffusion of Alloying Elements (One of the criteria for hardening a steel is that it have sufficient carbon content. Low carbon steels can be hardened, at least on the surface, by heat treating at an elevated temperature in an atmosphere containing an alloying element that will diffuse into the steel and allow surface hardening on quenching. Carbon is frequently diffused into the surface of soft steels for surface hardening. Using this same principle, elements such as chromium, boron, nitrogen, and silicon can be diffused in the surface of steel for special purposes.)

There are two types of Critical Temperature according to the diagram iron-ironcarbide: **LCT (Lower Critical Temperature)** - line **PSK** (constant temperature 727 °C for all steel);

UCT (Upper Critical Temperature) - line **GSE** (temperature depends of carbon contain).

Figure 8.1 shows major types of heat treatment processes.

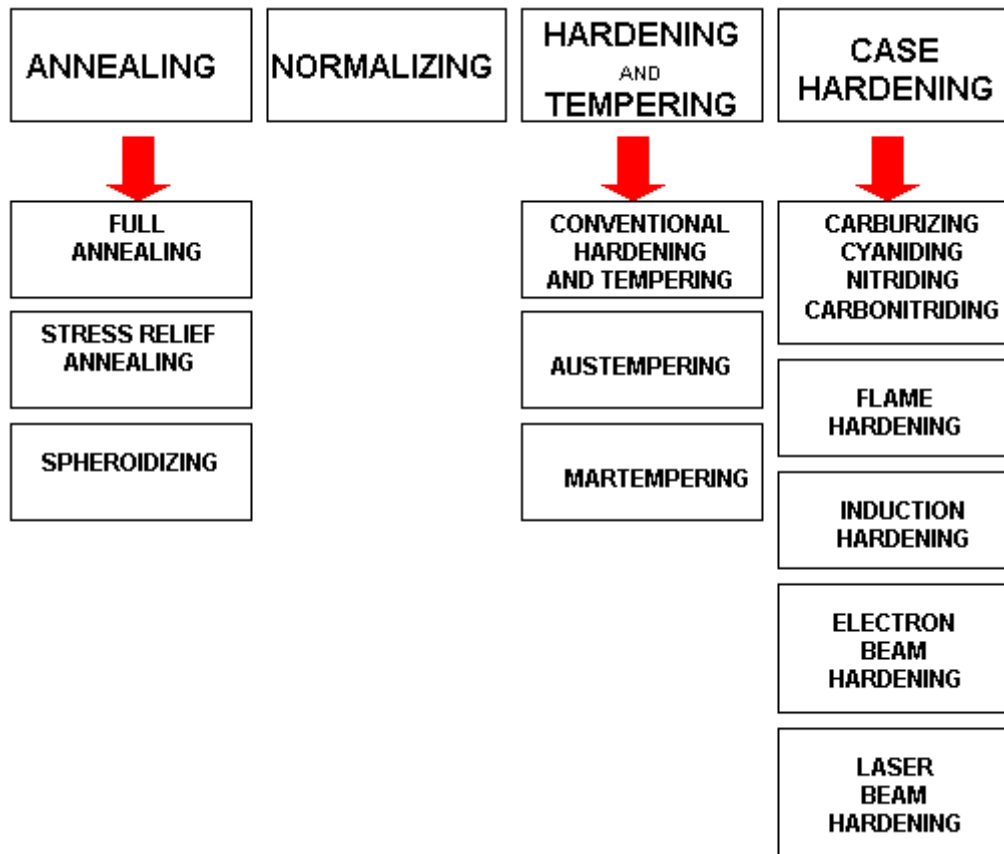


Fig.8.1. *Types of Heat Treatment Processes.*

2. Time-Temperature-Transformation (TTT) Diagram

T (Time) T(Temperature) T(Transformation) diagram is a plot of temperature versus the logarithm of time for a steel alloy of definite composition. It is used to determine when transformations begin and end for an isothermal (constant temperature) heat treatment of a previously austenitized alloy. When austenite is cooled slowly to a temperature below **LCT (Lower Critical Temperature)**, the structure that is formed is Pearlite. As the cooling rate increases, the pearlite transformation temperature gets lower. The microstructure of the material is significantly altered as the cooling rate increases. By heating and cooling a series of samples, the history of the austenite transformation may be recorded. **TTT diagram indicates** when a specific transformation starts and ends and it also shows what percentage of transformation of austenite at a particular temperature is achieved.

Cooling rates in the order of increasing severity are achieved by quenching from elevated temperatures as follows: furnace cooling, air cooling, oil quenching, liquid salts, water quenching, and brine. If these cooling curves are superimposed on the TTT diagram, the end product structure and the time required to complete the transformation may be found.

In Fig.8.2 the area on the left of the transformation curve represents the austenite region. Austenite is stable at temperatures above LCT but unstable below LCT. Left curve indicates the start of a transformation and right curve represents the finish of a transformation. The area between the two curves indicates the

transformation of austenite to different types of crystal structures. (Austenite to pearlite, austenite to martensite, austenite to bainite transformation.)

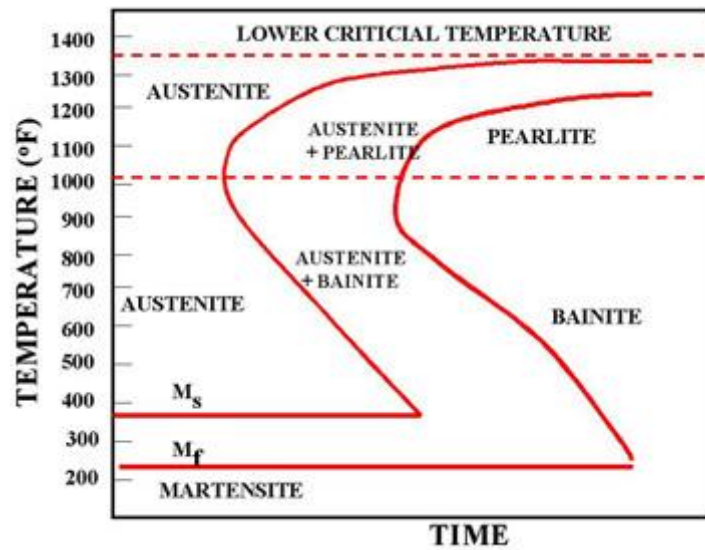


Fig.8.2. TTT Diagram

If the cooling rate is very slow such as annealing process, the cooling curve passes through the entire transformation area and the end product of this the cooling process becomes 100% Pearlite.

In Fig.8.3 the cooling rates A and B indicate two rapid cooling processes. In this case curve A will cause a higher distortion and a higher internal stresses than the cooling rate B. The end product of both cooling rates will be ***martensite***. Cooling rate B is also known as the ***Critical Cooling Rate***, which is represented by a cooling curve that is tangent to the nose of the TTT diagram. Critical Cooling Rate is defined as the lowest cooling rate which produces 100% Martensite while minimizing the internal stresses and distortions.

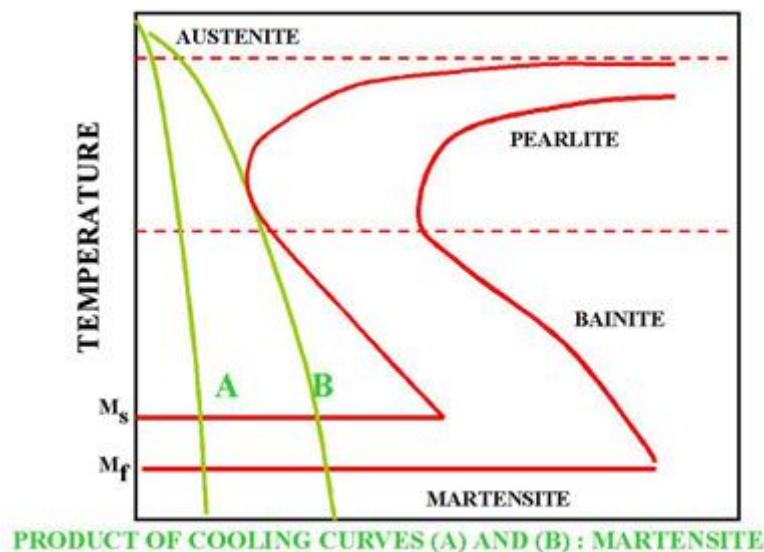


Fig.8.3. Rapid Quench

In Fig.8.4, a rapid quenching process is interrupted (horizontal line represents the interruption) by immersing the material in a molten salt bath and soaking at a constant temperature followed by another cooling process that passes through Bainite region of TTT diagram. The end product is Bainite, which is not as hard as Martensite. As a result of cooling rate D; more dimensional stability, less distortion and less internal stresses are created.

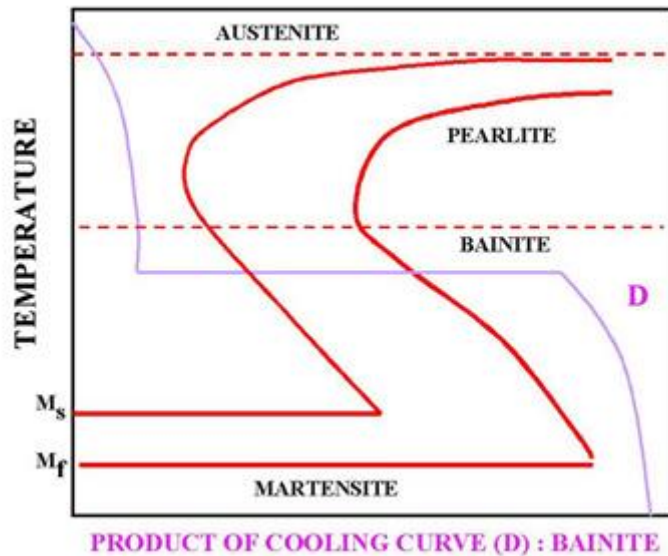


Fig. 8.4. Interrupted Quench

In Fig.8.5 cooling curve C represents a slow cooling process, such as furnace cooling. An example for this type of cooling is annealing process where all the Austenite is allowed to transform to Pearlite as a result of slow cooling.

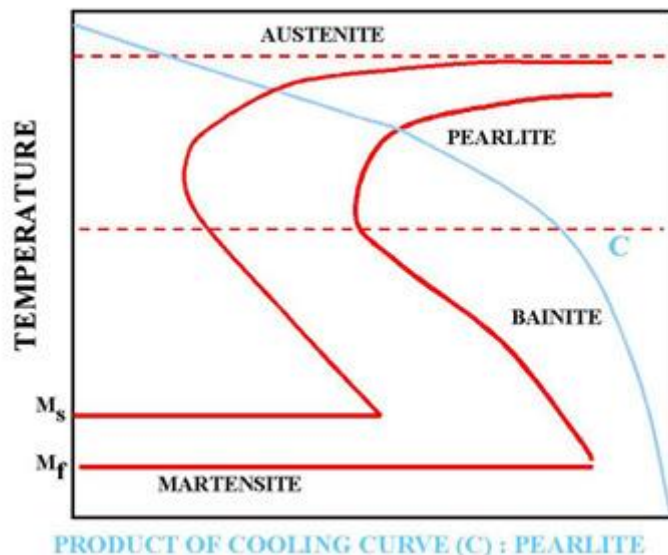


Fig.8.5. Slow cooling process (Annealing)

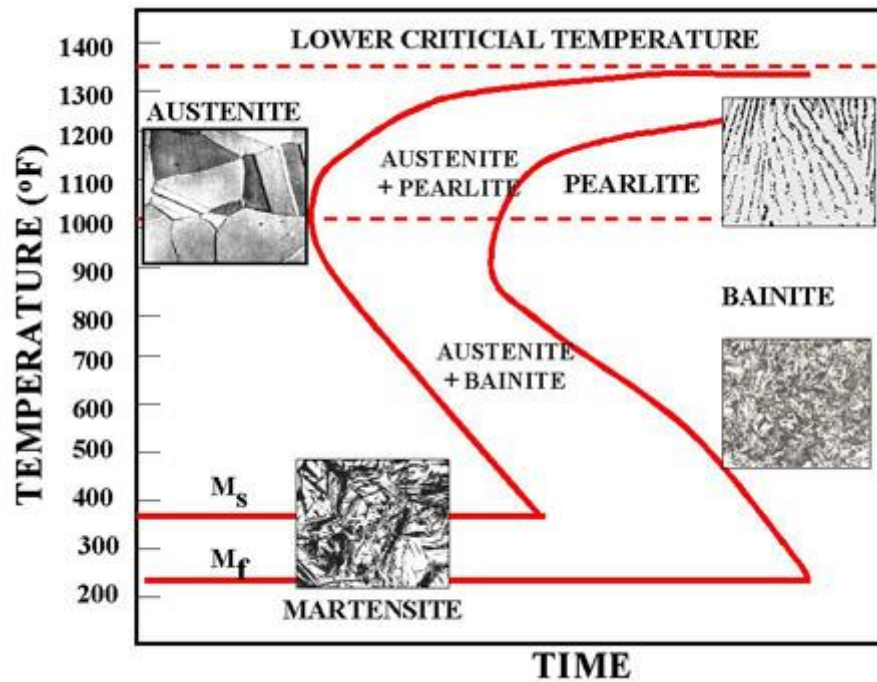


Fig.8.6. TTT Diagram and microstructures obtained by different types of cooling rates

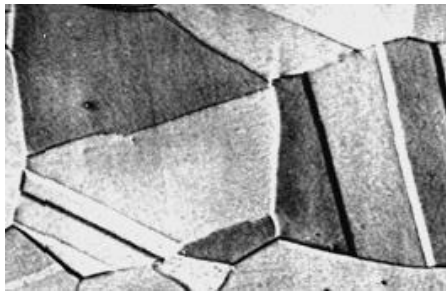


Fig.8.7. Austenite

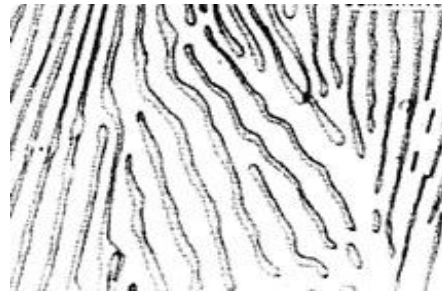


Fig.8.8. Pearlite



Fig.8.9. Martensite



Fig.8.10. Bainite

3. Processes of Annealing and Spheroidizing

Full annealing is accomplished by heating a hypoeutectoid steel to a temperature *above the UCT* (Upper Critical Temperature). In practice, the steel is heated to about 30-50 °C above the UCT. It is then cooled in the furnace very slowly

to room temperature. The formation of austenite destroys all structures that have existed before heating. Slow cooling yields the original phases of ferrite and pearlite.

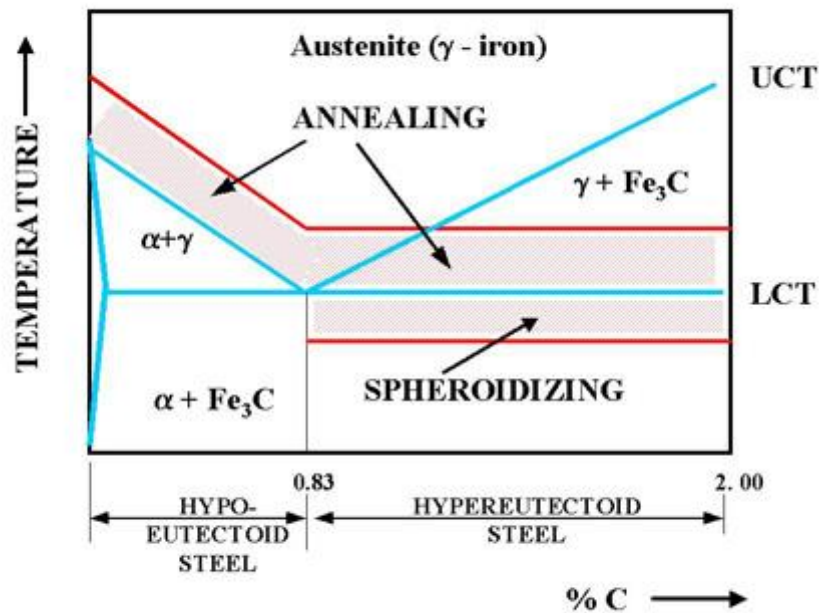


Fig. 8.11. Annealing and Spheroidizing Temperatures

Hypereutectoid steels consist of pearlite and cementite. The cementite forms a brittle network around the pearlite. This presents difficulty in machining the hypereutectoid steels. To improve the machinability of the annealed hypereutectoid steel spheroidize annealing is applied. This process will produce a spheroidal or globular form of a carbide in a ferritic matrix which makes the machining easy. Prolonged time at the elevated temperature will completely break up the pearlitic structure and cementite network. The structure is called spheroidite. This structure is desirable when minimum hardness, maximum ductility and maximum machinability are required.

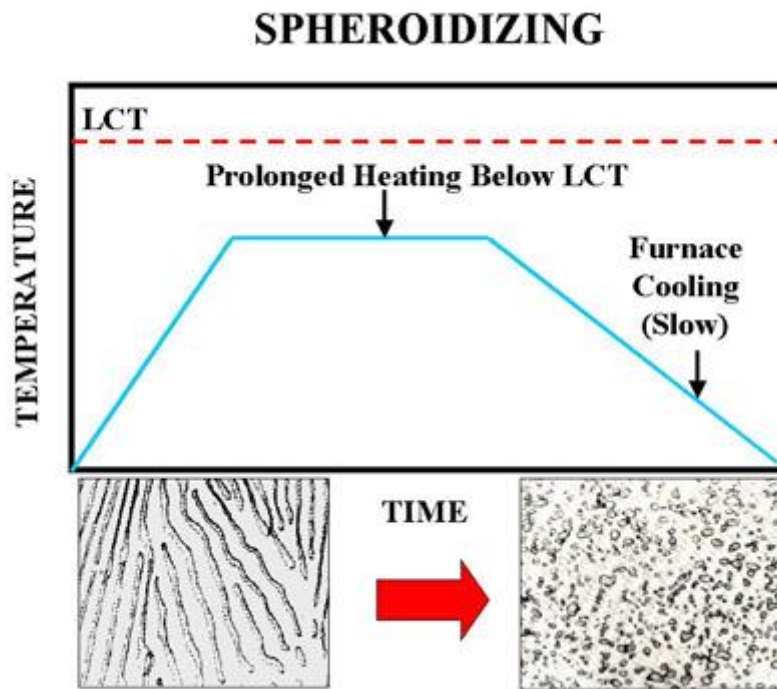


Fig.8.12. Spheroidizing process applied at a temperature below the LCT

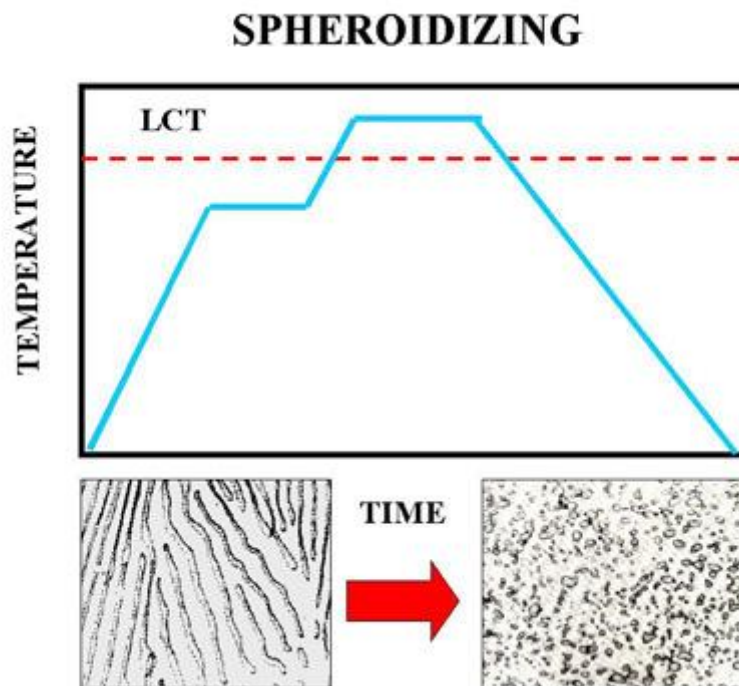


Fig.8.13. Spheroidizing process applied at a temperature below and above the LCT

Low carbon steels are seldom spheroidized for machining, because they are excessively soft and gummy in the spheroidized conditions. The cutting tool will tend to push the material rather than cut it, causing excessive heat and wear on the cutting tip.

Stress-Relief Annealing is sometimes called subcritical annealing, is useful in removing residual stresses due to heavy machining or other cold-working processes. It is usually carried out at temperatures below the LCT, which is usually selected around 1000oF.

The benefits of annealing are:

- Improved ductility
- Removal of residual stresses that result from cold-working or machining
- Improved machinability
- Grain refinement

Full annealing consists of (1) recovery (stress-relief), (2) recrystallization, (3) grain growth stages. Annealing reduces the hardness, yield strength and tensile strength of the steel.

4. Process of Normalizing

The normalizing of steel is carried out by heating approximately 30-50 °C above the UCT (Upper Critical Temperature) followed by cooling in air to room temperature. Normalizing can be applied above the UCT for both hypoeutectoid and hypereutectoid steels. Fig.8.14 shows the normalizing temperatures.

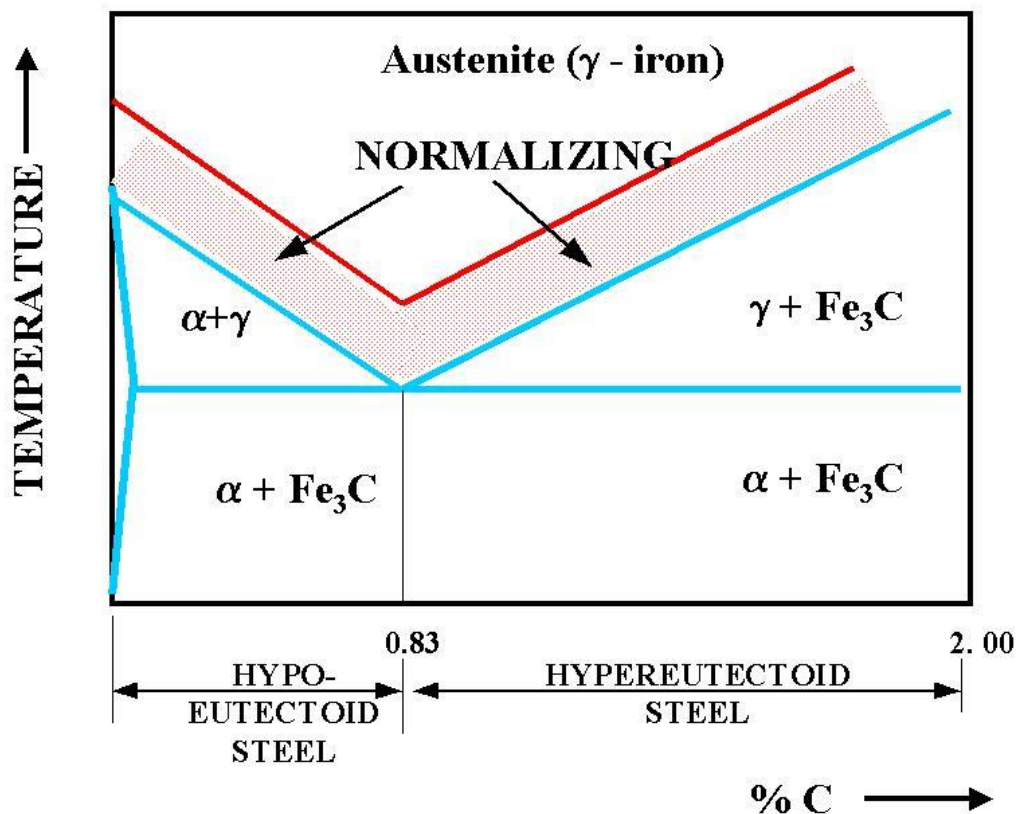


Fig.8.14. Normalizing temperatures for hypoeutectoid and hypereutectoid steels.

The following is the list of the reasons for normalizing the steel :

- To produce a harder and stronger steel than full annealing
- To improve the machinability
- To modify and refine the grain structure
- To obtain a relatively good ductility without reducing the hardness and strength

Figures 8.15, 8.16, 8.17, 8.18 show the effect of annealing and normalizing on the ductility, tensile strength, hardness and yield point of steels.

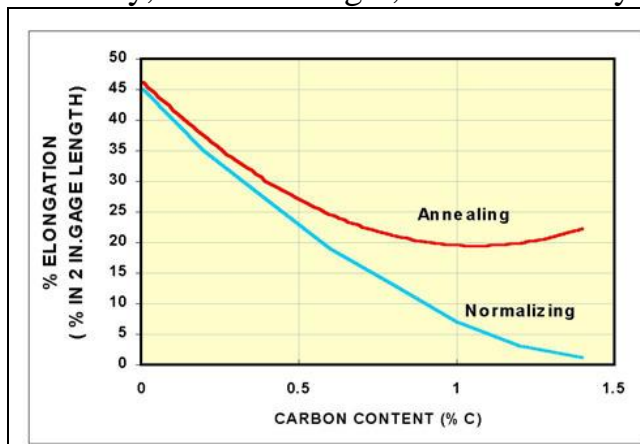


Fig.8.15. Ductility of annealed and normalized steels.

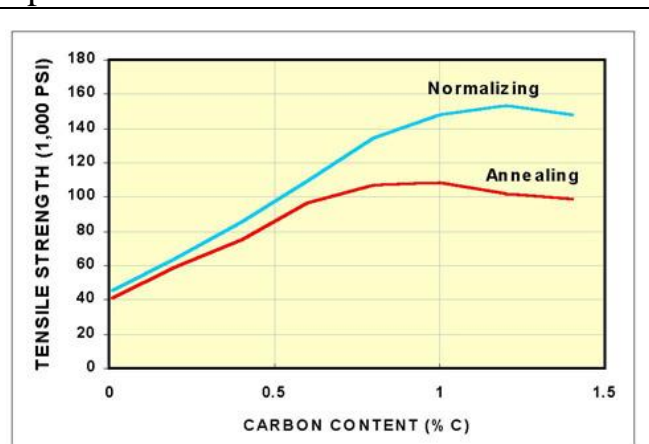


Fig.8.16. Tensile strength of normalized and annealed steels.

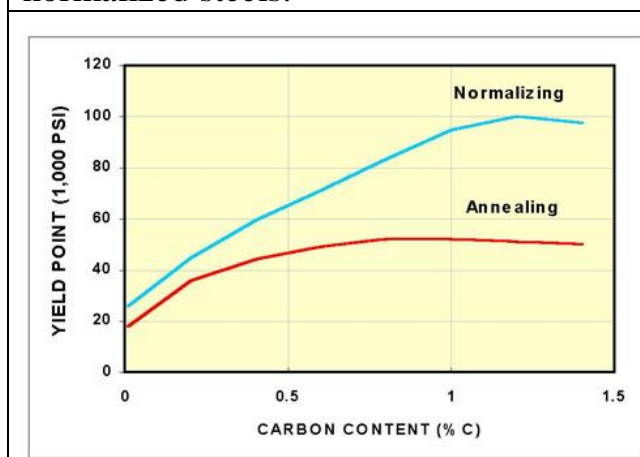


Fig.8.17. Yield point of annealed and normalized steels

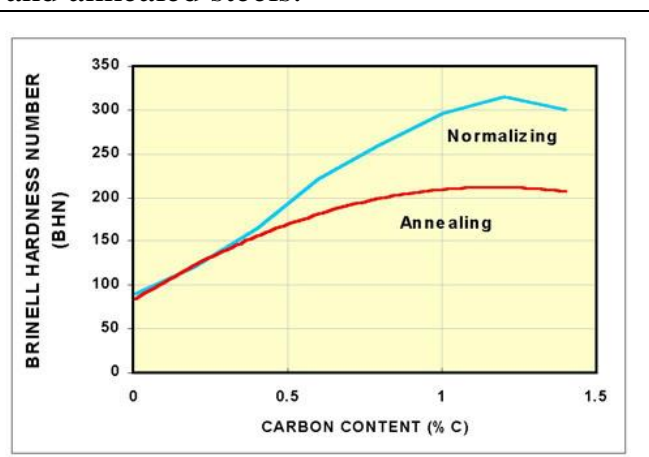


Fig.8.18. Hardness of normalized and annealed steels

As indicated in Fig.8.15, annealing and normalizing do not present a significant difference on the ductility of low carbon steels. As the carbon content increases, annealing maintains the % elongation around 20%. On the other hand, the ductility of the normalized high carbon steels drop to 1 to 2 % level.

Fig.8.16 and 8.17 show that the tensile strength and the yield point of the normalized steels are higher than the annealed steels. Normalizing and annealing do not show a significant difference on the tensile strength and yield point of the low carbon steels. However, normalized high carbon steels present much higher tensile strength and yield point than those that are annealed.

As seen from Fig.8.18, low and medium carbon steels can maintain similar hardness levels when normalized or annealed. However, when high carbon steels are normalized they maintain higher levels of hardness than those that are annealed.

5. Processes of Hardening and Tempering

Steels can be heat treated to high hardness and strength levels. The reasons for doing this are obvious. Structural components subjected to high operating stress need the high strength of a hardened structure. Similarly, tools such as dies, knives, cutting devices, and forming devices need a hardened structure to resist wear and deformation.

As-quenched hardened steels are so brittle that even slight impacts may cause fracture. **Tempering** is a heat treatment that reduces the brittleness of a steel without significantly lowering its hardness and strength. All hardened steels must be tempered before use.

QUENCH AND TEMPERING PROCESSES:

- (1) Conventional Heat, Quench and Temper process
- (2) Martempering
- (3) Austempering

Conventional Heat, Quench and Temper Process:

In this process, Austenite is transformed to Martensite as a result of rapid quench from furnace to room temperature. Then, martensite is heated to a temperature which gives the desired hardness. As the metal cools, it also contracts and its microstructure occupies less volume. Extreme variations in size of metal parts complicate the work of the heat treater and should be avoided in the designing of metal parts. This means there is a limit to the overall size of parts that can be subjected to such thermal processing. Figure 1 shows the conventional hardening, tempering process.

CONVENTIONAL QUENCHING AND TEMPERING

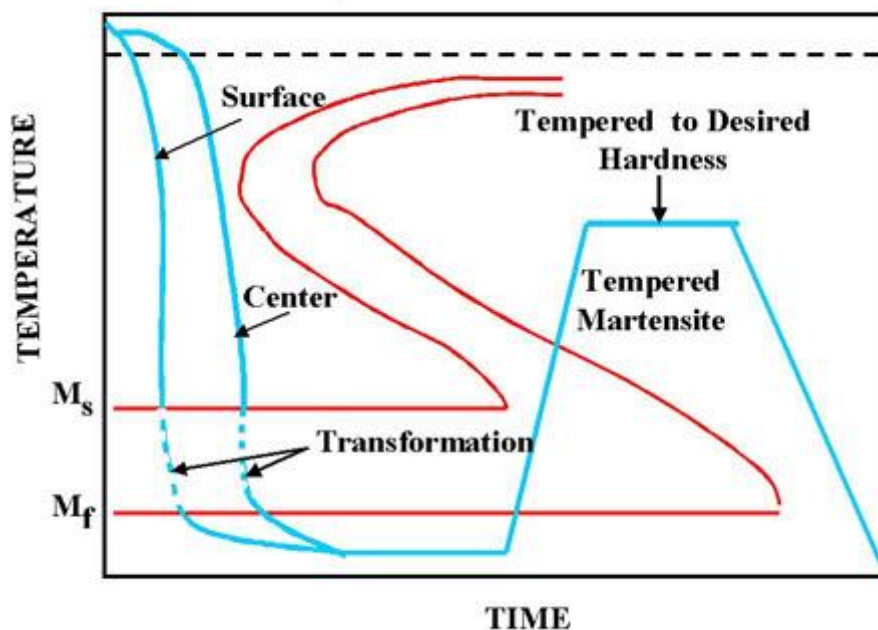


Fig.8.19. Conventional quenching and tempering process.

Martempering (Marquenching):

To overcome the restrictions of conventional quenching and tempering, Martempering process can be used. Martempering or marquenching permits the transformation of Austenite to Martensite to take place at the same time throughout the structure of the metal part. Then cooling is continued through the martensite region, followed by the usual tempering.

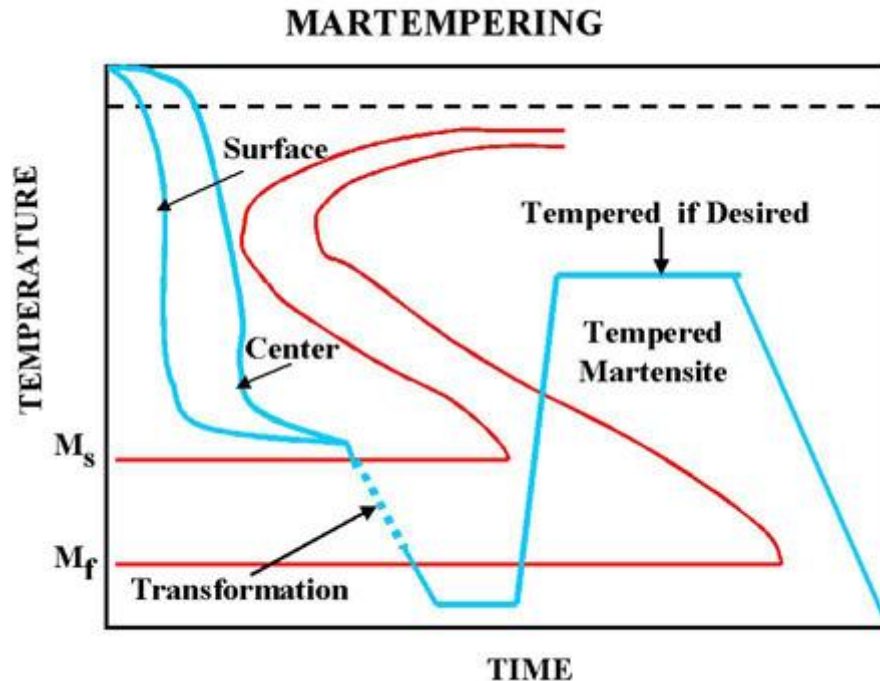


Fig.8.20. Martempering process

Austempering:

This is the second method that can be used to overcome the restrictions of conventional quench and tempering. The quench is interrupted at a higher temperature than for Martempering to allow the metal at the center of the part to reach the same temperature as the surface. By maintaining that temperature, both the center and the surface are allowed to transform to Bainite and are then cooled to room temperature.

Advantages of Austempering:

- (1) Less distortion and cracking than martempering,
- (2) No need for final tempering (less time consuming and more energy efficient)
- (3) Improvement of toughness (impact resistance is higher than the conventional quench and tempering)
- (4) Improved ductility

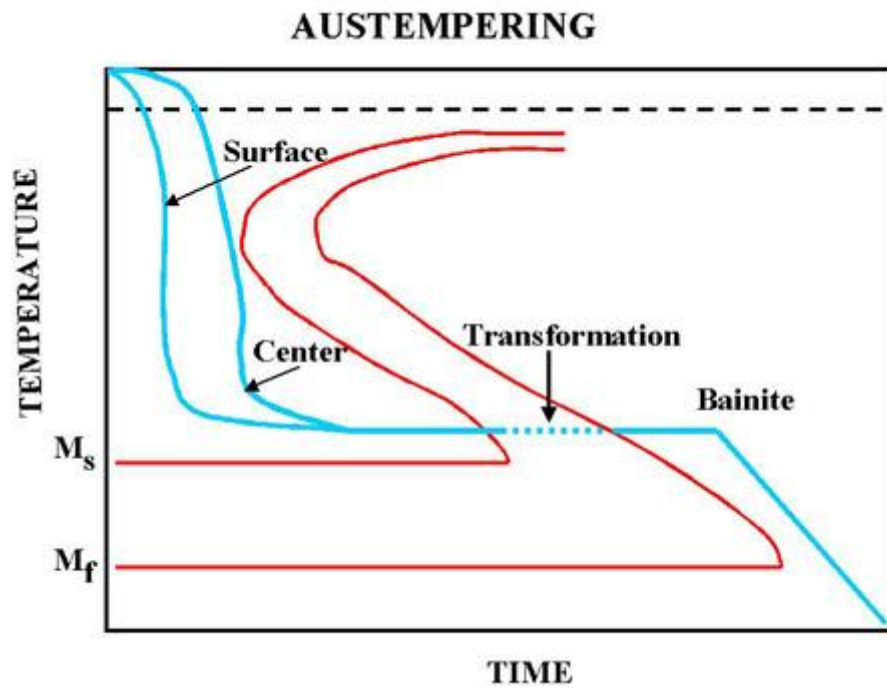


Figure 8.21. Austempering process.

In Austempering process, the end product is 100% bainite. It is accomplished by first heating the part to the proper austenitizing temperature followed by cooling rapidly in a salt bath which is maintained between 400 and 800 °F. The part is left in the bath until the transformation to bainite is complete. The steel is caused to go directly from austenite to bainite.

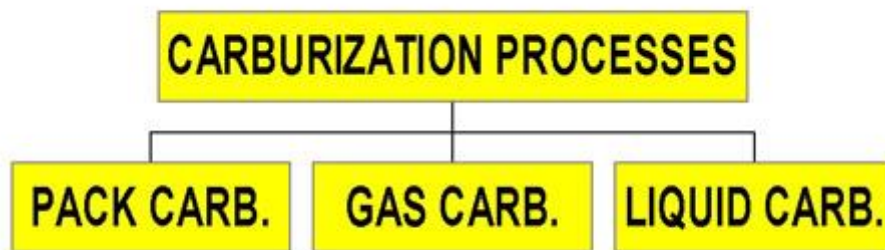
TOPIC 9. Chemical heat treatment process

1. Carburization process.
2. Nitriding process.
3. Carbonitriding and Cyaniding processes.

1. Carburization process

CARBURIZING

Purpose of Carburization: to provide a hard surface on normally unhardenable steels.



Technological parameters of carburization:

- Depth of Hardening:

there is no technical limit to the depth of hardening with carburizing techniques, but it is not common to carburize to depths in excess of 1.2 mm.

- Carburizing Time:

4 to 10 hours

- Carburizing Temperature:

950 °C (above the upper critical temperature-Austenite area)

Quenching:

All of the carburizing processes (pack, gas, liquid) require quenching from the carburizing temperature or a lower temperature or reheating and quenching. Parts are then tempered to the desired hardness.

Pack Carburizing:

In this process, the part that is to be carburized is packed in a steel container so that it is completely surrounded by granules of charcoal. The charcoal is treated with an activating chemical such as Barium Carbonate (BaCO_3) that promotes the formation of Carbon Dioxide (CO_2). This gas in turn reacts with the excess carbon in the charcoal to produce carbon monoxide; CO . Carbon Monoxide reacts with the low-carbon steel surface to form atomic carbon which diffuses into the steel. Carbon Monoxide supplies the carbon gradient that is necessary for diffusion. The carburizing process does not harden the steel. It only increases the carbon content to some predetermined depth below the surface to a sufficient level to allow subsequent quench hardening.

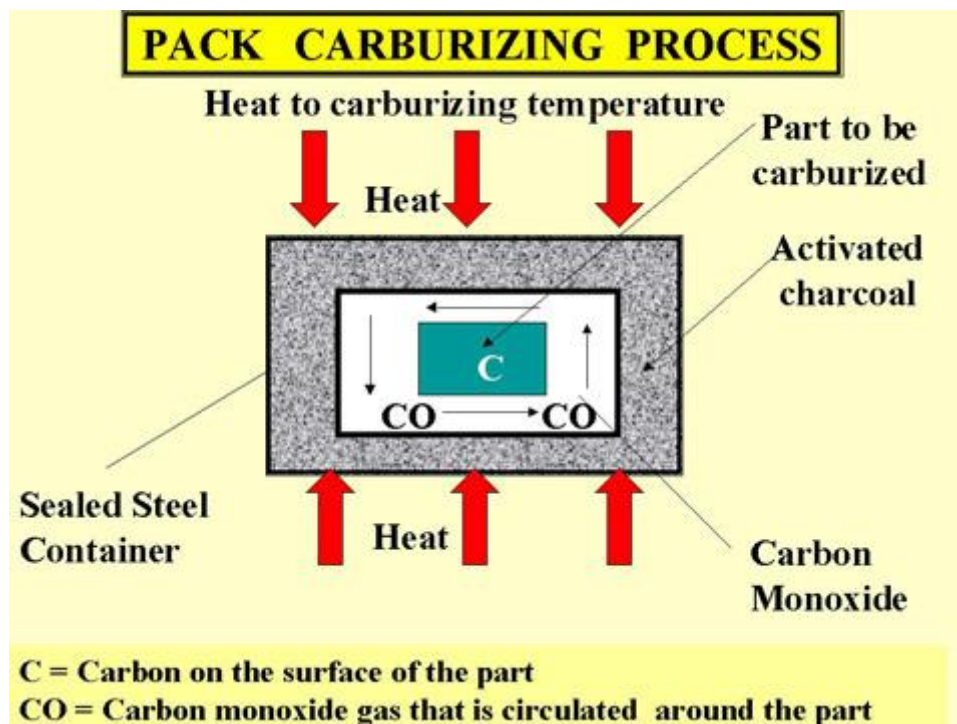


Fig.9.1. Pack carburizing process

Quenching Process:

It is difficult to quench the part immediately, as the sealed pack has to be opened and the part must be removed from the pack. One technique that is used often is to slow cool the entire pack and subsequently harden and temper the part after it is removed from the sealed pack.

Gas Carburizing:

Can be done with any carbonaceous gas, such as methane, ethane, propane, or natural gas. Most carburizing gases are flammable and controls are needed to keep carburizing gas at 930°C from contacting air (oxygen). The advantage of this process over pack carburizing is an improved ability to quench from the carburizing

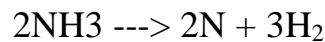
temperature. Conveyor hearth furnaces make quenching in a controlled atmosphere possible.

Liquid Carburizing:

Can be performed in internally or externally heated molten salt pots. Carburizing salt contains cyanide compounds such as sodium cyanide (NaCN). Cycle times for liquid cyaniding is much shorter (1 to 4 hours) than gas and pack carburizing processes. Disadvantage is the disposal of salt. (environmental problems) and cost (safe disposal is very expensive).

2. Nitriding Process:

In this process, nitrogen is diffused into the surface of the steel being treated. The reaction of nitrogen with the steel causes the formation of very hard iron and alloy nitrogen compounds. The resulting nitride case is harder than tool steels or carburized steels. The advantage of this process is that hardness is achieved without the oil, water or air quench. As an added advantage, hardening is accomplished in a nitrogen atmosphere that prevents scaling and discoloration. Nitriding temperature is below the lower critical temperature of the steel and it is set between 500°C and 600 °C. The nitrogen source is usually Ammonia (NH₃). At the nitriding temperature the ammonia dissociates into Nitrogen and Hydrogen.



The nitrogen diffuses into the steel and hydrogen is exhausted. A typical nitriding setup is illustrated in Fig.9.2.

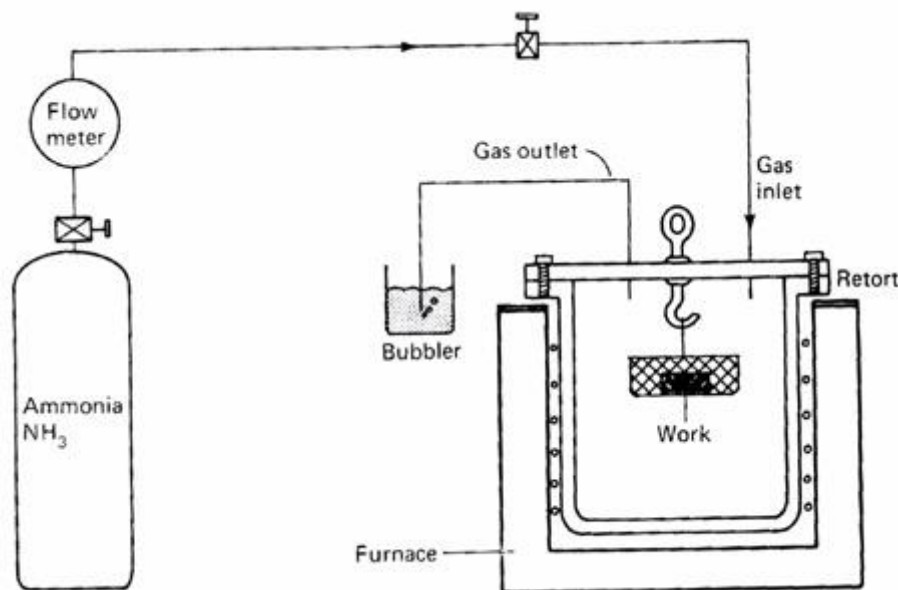


Fig.9.2. Nitriding process

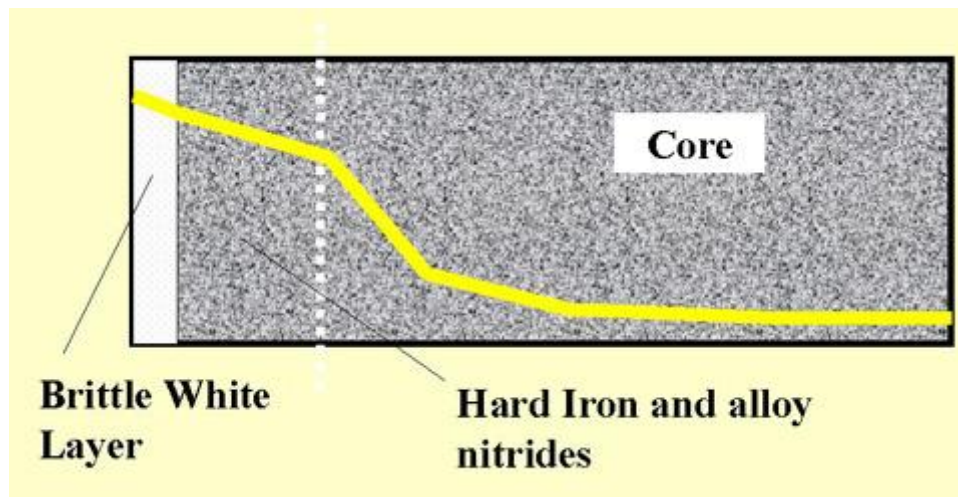


Fig.9.3. Nitriding microstructure.

The white layer shown in Fig.9.3 4 has a detrimental effect on the fatigue life of nitrided parts, and it is normally removed from parts subjected to severe service. Two stage gas-nitriding processes can be used to prevent the formation of white layer. White layer thickness may vary between 0.2 and 0.4 mm, which depends on nitriding time. The most commonly nitrided steels are chromium-molybdenum alloy steels and Nitralloys. Surface hardness of 55 HRC to 70 HRC can be achieved with case depths varying from 0.1 in to 0.5 mm. Nitrided steels are very hard and grinding operations should not be performed after nitriding. White layer is removed by lapping.

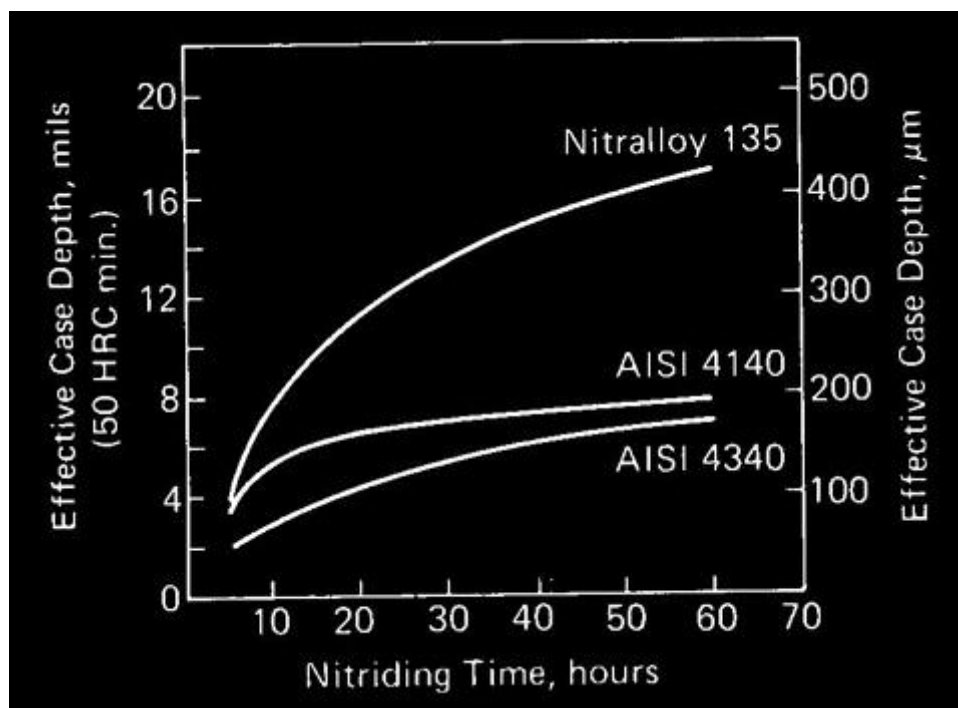
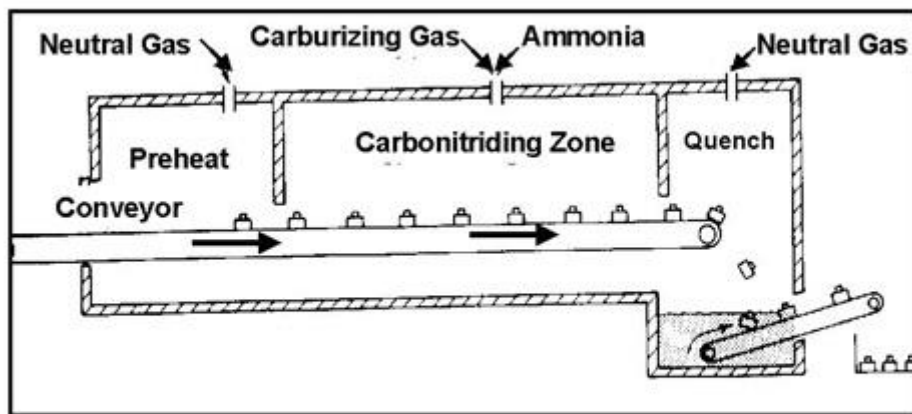


Fig.9.4. Nitriding time for various types of alloy steels

3. Carbonitriding and Cyaniding processes:

This process involves with the diffusion of both carbon and nitrogen into the steel surface. The process is performed in a gas atmosphere furnace using a carburizing gas such as propane or methane mixed with several percent (by volume) of ammonia. Methane or propane serve as the source of carbon, the ammonia serves as the source of nitrogen. Quenching is done in a gas which is not as severe as water quench. As a result of less severe quench, there is less distortion on the material to be treated. Case hardness of HRC 60 to 65 is achieved at the surface. (Not as high as nitrided surfaces.) Case depths of 0.5 to 0.7 mm can be accomplished by carbonitriding. One of the advantages of this process is that it can be applied to plain carbon steels which give significant case depths. Carbonitriding gives less distortion than carburizing. Carbonitriding is performed at temperatures above the transformation temperature of the steels (840 to 860°C).



Conveyor Hearth Carbonitriding

Fig.9.5. Carbonitriding process.

Cyaniding

It is similar to carbonitriding, and involves the diffusion of both carbon and nitrogen into the surface of the steel. The source of the diffusing element in this method is a molten cyanide salt such as sodium cyanide. It is a supercritical treatment involving temperatures in the range of 840 to 860°C. Case depths are between 0.2 and 0.6 mm. Diffusion times are less than one hour. Water or oil quench is required. This type of cases presents a significant distortion. Advantage of this method is the short time it requires to complete the diffusion, otherwise it should be avoided because of high distortion.

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