

Material Science

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Chapter 9. Applications and Processing of Metals and Alloys

In the materials world we are living in, when making a new device/component, most often we come across a very familiar problem. This is nothing but select the right material. As learnt in earlier chapter, selection of material can play very important role preventing failures. Selection of material for a specific purpose depends on many factors. Some of the important ones are: strength, ease of forming, resistance to environmental degradation, etc. Another dimension an engineer should be aware of it is how to tailor the required properties of materials.

As introduced in one of the earlier chapters, materials can be broadly classified as metals, ceramics and plastics. This chapter introduces different classes of metallic materials, common fabrication methods, and means to alter their properties on purpose. Following chapters deal with ceramic materials and plastic materials.

9.1 Types of metals and alloys

Metallic materials are broadly of two kinds – *ferrous* and *non-ferrous* materials. This classification is primarily based on tonnage of materials used all around the world. Ferrous materials are those in which iron (*Fe*) is the principle constituent. All other materials are categorized as non-ferrous materials. Another classification is made based on their formability. If materials are hard to form, components with these materials are fabricated by casting, thus they are called cast alloys. If material can be deformed, they are known as wrought alloys. Materials are usually strengthened by two methods – cold work and heat treatment. Strengthening by heat treatment involves either precipitation hardening or martensitic transformation, both of which constitute specific heat treating procedure. When a material can not be strengthened by heat treatment, it is referred as non-heat-treatable alloys.

9.1.1 Ferrous materials

Ferrous materials are produced in larger quantities than any other metallic material. Three factors account for it: (a) availability of abundant raw materials combined with

economical extraction, (b) ease of forming and (c) their versatile mechanical and physical properties. One main drawback of ferrous alloys is their environmental degradation i.e. poor corrosion resistance. Other disadvantages include: relatively high density and comparatively low electrical and thermal conductivities. In ferrous materials the main alloying element is carbon (C). Depending on the amount of carbon present, these alloys will have different properties, especially when the carbon content is either less/higher than 2.14%. This amount of carbon is specific as below this amount of carbon, material undergoes eutectoid transformation, while above that limit ferrous materials undergo eutectic transformation. Thus the ferrous alloys with less than 2.14% C are termed as *steels*, and the ferrous alloys with higher than 2.14% C are termed as *cast irons*.

9.1.1.a Steels

Steels are alloys of iron and carbon plus other alloying elements. In steels, carbon present in atomic form, and occupies interstitial sites of Fe microstructure. Alloying additions are necessary for many reasons including: improving properties, improving corrosion resistance, etc. Arguably steels are well known and most used materials than any other materials.

Mechanical properties of steels are very sensitive to carbon content. Hence, it is practical to classify steels based on their carbon content. Thus steels are basically three kinds: low-carbon steels (% wt of C < 0.3), medium carbon steels (0.3 < % wt of C < 0.6) and high-carbon steels (% wt of C > 0.6). The other parameter available for classification of steels is amount of alloying additions, and based on this steels are two kinds: (plain) carbon steels and alloy-steels.

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

A special group of ferrous alloys with noticeable amount of alloying additions are known as HSLA (high-strength low-alloy) steels. Common alloying elements are: Cu, V, Ni, W, Cr, Mo, etc. These alloys can be strengthened by heat treatment, and yet the same time they are ductile, formable. Typical applications of these HSLA steels include: support columns, bridges, pressure vessels.

Medium carbon steels: These are stronger than low carbon steels. However these are of less ductile than low carbon steels. These alloys can be heat treated to improve their strength. Usual heat treatment cycle consists of austenitizing, quenching, and tempering at suitable conditions to acquire required hardness. They are often used in tempered condition. As hardenability of these alloys is low, only thin sections can be heat treated using very high quench rates. Ni, Cr and Mo alloying additions improve their

hardenability. Typical applications include: railway tracks & wheels, gears, other machine parts which may require good combination of strength and toughness.

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

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

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

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

By alloying additions, for martensitic steels M_s is made to be above the room temperature. These alloys are heat treatable. Major alloying elements are: Cr, Mn and Mo.

Ferritic and austenitic steels are hardened and strengthened by cold work because they are not heat treatable. On the other hand martensitic steels are heat treatable. Austenitic steels are most corrosion resistant, and they are produced in large quantities. Austenitic steels are non-magnetic as against ferritic and martensitic steels, which are magnetic.

9.1.1.b Cast irons

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

Hard and brittle constituent presented in these alloys, cementite is a meta-stable phase, and can readily decompose to form α -ferrite and graphite. In this way disadvantages of

brittle phase can easily be overcome. Tendency of cast irons to form graphite is usually controlled by their composition and cooling rate. Based on the form of carbon present, cast irons are categorized as gray, white, nodular and malleable cast irons.

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

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

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

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

9.1.2 Non-ferrous materials

Non-ferrous materials have specific advantages over ferrous materials. They can be fabricated with ease, high relative low density, and high electrical and thermal conductivities. However, different materials have distinct characteristics, and are used for specific purposes. This section introduces some typical non-ferrous metals and their alloys of commercial importance.

Aluminium alloys: These are characterized by low density, high thermal & electrical conductivities, and good corrosion-resistant characteristics. As Al has FCC crystal structure, these alloys are ductile even at low temperatures and can be formed easily. However, the great limitation of these alloys is their low melting point (660 °C), which

restricts their use at elevated temperatures. Strength of these alloys can be increased by both cold and heat treatment – based on these alloys are designated in to two groups, cast and wrought. Chief alloying elements include: Cu, Si, Mn, Mg, Zn. Recently, alloys of Al and other low-density metals like Li, Mg, Ti gained much attention as there is much concern about vehicle weight reduction. Al-Li alloys enjoy much more attention especially as they are very useful in aircraft and aerospace industries. Common applications of Al alloys include: beverage cans, automotive parts, bus bodies, aircraft structures, etc. Some of the Al alloys are capable of strengthening by precipitation, while others have to be strengthened by cold work or solid solution methods.

Copper alloys: As history goes by, bronze has been used for thousands of years. It is actually an alloy of Cu and Sn. Unalloyed Cu is soft, ductile thus hard to machine, and has virtually unlimited capacity for cold work. One special feature of most of these alloys is their corrosion resistant in diverse atmospheres. Most of these alloys are strengthened by either cold work or solid solution method. Common most Cu alloys: Brass, alloys of Cu and Zn where Zn is substitutional addition (e.g.: yellow brass, cartridge brass, muntz metal, gilding metal); Bronze, alloys of Cu and other alloying additions like Sn, Al, Si and Ni. Bronzes are stronger and more corrosion resistant than brasses. Mention has to be made about Beryllium coppers who possess combination of relatively high strength, excellent electrical and corrosion properties, wear resistance, can be cast, hot worked and cold worked. Applications of Cu alloys include: costume jewelry, coins, musical instruments, electronics, springs, bushes, surgical and dental instruments, radiators, etc.

Magnesium alloys: The most sticking property of Mg is its low density among all structural metals. Mg has HCP structure, thus Mg alloys are difficult to form at room temperatures. Hence Mg alloys are usually fabricated by casting or hot working. As in case of Al, alloys are cast or wrought type, and some of them are heat treatable. Major alloying additions are: Al, Zn, Mn and rare earths. Common applications of Mg alloys include: hand-held devices like saws, tools, automotive parts like steering wheels, seat frames, electronics like casing for laptops, camcoders, cell phones etc.

Titanium alloys: Ti and its alloys are of relatively low density, high strength and have very high melting point. At the same time they are easy to machine and forge. However the major limitation is Ti's chemical reactivity at high temperatures, which necessitated special techniques to extract. Thus these alloys are expensive. They also possess excellent corrosion resistance in diverse atmospheres, and wear properties. Common applications include: space vehicles, airplane structures, surgical implants, and petroleum & chemical industries.

Refractory metals: These are metals of very high melting points. For example: Nb, Mo, W and Ta. They also possess high strength and high elastic modulus. Common applications include: space vehicles, x-ray tubes, welding electrodes, and where there is a need for corrosion resistance.

Noble metals: These are eight all together: Ag, Au, Pt, Pa, Rh, Ru, Ir and Os. All these possess some common properties such as: expensive, soft and ductile, oxidation resistant.

Ag, Au and Pt are used extensively in jewelry, alloys of Ag and Au are employed as dental restoration materials; Pt is used in chemical reactions as a catalyst and in thermo couples.

9.2 Fabrication of metals

Metals are fabricated by different means to achieve metals and alloys of desired characteristics. There have been many kinds of fabrication techniques, and for a particular metal use of these depends on properties of metal, product shape-size-properties, cost, etc. Metal fabrication techniques are mainly four kinds: Casting - to give a shape by pouring in liquid metal into a mold that holds the required shape, and letting harden the metal without external pressure; Forming – to give shape in solid state by applying pressure; Machining – in which material is removed in order to give it the required shape; and Joining – where different parts are joined by various means. One of the most important miscellaneous techniques is powder metallurgy.

9.2.1 Metal casting

This technique is employed when (a) product is large and/or complicated shape (b) particular material is low in ductility. This is also employed as it is usually economical compared with other techniques. Different casting techniques include: sand, die, investment, continuous casting

Sand casting: The common casting method where sand is used as casting material. A two piece mold (cope and drag) is formed by compact packing of sand around a pattern of required shape. An additional gating is provided for proper distribution of liquid metal.

Die casting: Here metal is forced into mold by external pressure at high velocities. Usually a permanent two-piece mold made of steel is used. In this technique rapid cooling rates are achieved, thus inexpensive.

Investment casting: In this pattern is made of wax. Then fluid slurry of casting material is poured over which eventually hardens and holds the required shape. Subsequently, pattern material is heated to leave behind the cavity. This technique is employed when high dimensional accuracy, reproduction of fine details, and an excellent finish are required. For example: jewelry, dental crowns, and gas turbine blades jet engine impellers.

Continuous casting: After refining metals are usually in molten state, which are later solidified into ingots for further processing like forming. In continuous casting, solidification and primary forming process are combined, where refined metal is cast directly into a continuous strand which is cooled by water jets. This technique is highly automated and more efficient. Uniform composition through-out the casting is achievable when compared with ingot-cast products.

9.2.2 Metal forming

In these techniques, a metallic piece is subjected to external pressures (in excess of yield strength of the material) to induce deformation, thus material acquires a desired shape. These are basically two types – one that performed at relatively low temperatures, cold working; and the other performed at high temperatures, hot working. Hot working is responsible mainly for substantial change in cross section without material getting strengthened, while during cold working, fine details are achieved along with material getting strengthened. Most common forming techniques are: forging, rolling, extrusion, and drawing. *Figure-9.1* illustrates different forming processes.

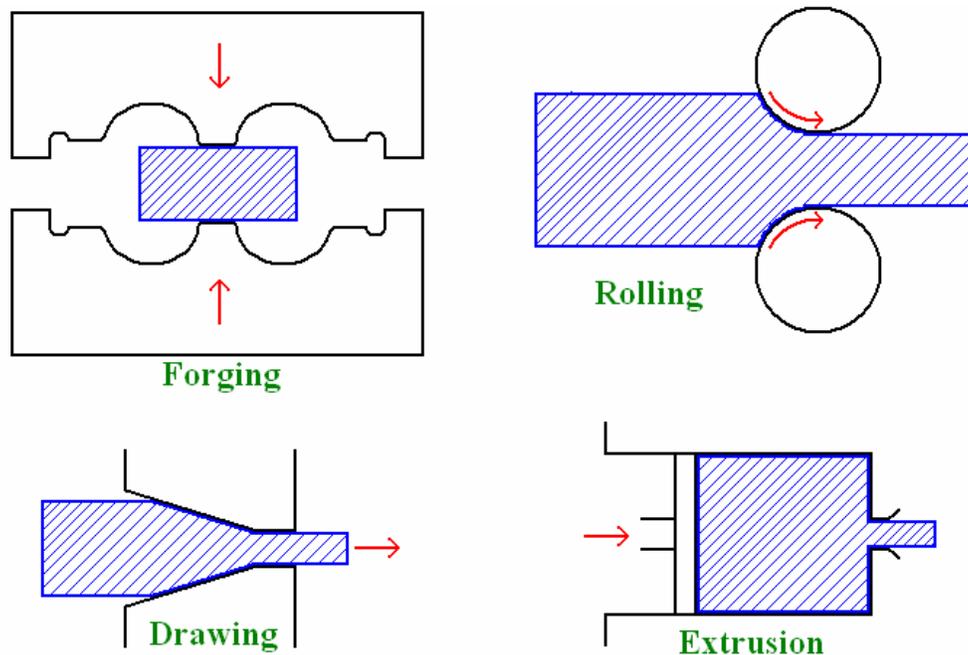


Figure-9.1: *Different forming processes.*

Forging: This involves deforming a single piece of metal, usually, by successive blows or continuous squeezing. In open die forging, two dies having same shape is employed, usually, over large work-pieces; while in closed die forging, there may be more than two pieces of die put together having finished shape. Forged products have outstanding grain structures and very good mechanical properties. Typical products include: crane hooks, wrenches, crank shafts, connecting rods.

Rolling: Most widely used forming technique because of high production rate and close dimensional control of final product. It involves passing a piece of metal between two rotating rolls. Deformation is terms of reduction in thickness resulting from applied compressive forces. This technique is typically employed to produce sheets, strips, foil, I-beams, rails, etc.

Extrusion: In this technique a piece of material is forced though a die orifice by a compressive force. Final product emerging from die will have the desired shape and reduced cross sectional area, and will constant cross-section over very long lengths. Two

varieties of extrusion are direct extrusion and indirect extrusion, where distinction limits to movement of tool and final product and consequent changes in required force. Typical extrusion products are: rods, (seamless) tubes, complicated shapes for domestic purpose.

Drawing: It is pulling of material through die orifice using tensile forces. Again a reduction in cross-section results with corresponding change in length. Drawing die entrance is at angle against to extrusion die which is usually rectangular. Typical drawing strand includes number of dies in a series sequence. Rods, wire, and tubes are commonly produced using drawing technique.

9.2.3 Machining

This technique employs removal of metal from selected areas of the workpiece to give final shape to the product. This is in direct contrast with metal forming where metal is moved and volume is conserved. Machining usually is employed to produce shapes with high dimensional tolerance, good surface finish, and often with complex geometry. And another important note is that when number of product pieces required is small, machining is preferred over forming as special tool cost will be less.

9.2.4 Joining

There been many joining techniques, especially for metallic materials. These include: welding, brazing, soldering, and riveting. In these techniques, two pieces are joined together either by adhesive/cohesive bonding and/or mechanical locking. Welding, brazing, and soldering involve melting of either parent metal or external metallic liquid (filler material) which upon cooling provides cohesive bonds. In riveting, pieces are put together by mechanical locking. These techniques are employed to join two pieces of same metal with complicated shapes, or of different metals because of difficulty in fabricating them using one of the previous methods. This may be employed when on-part fabrication is expensive or inconvenient.

9.2.5 Powder metallurgy

In this technique, metal powders or mixture of metal powders at desired relative amounts are compacted into the desired shape, followed by sintering in controlled atmosphere to produce a denser product. It makes it possible to produce a virtually non-porous product where diffusional processes control the efficiency of the process. It is suitable, especially, for metals with low ductility/high melting points. Other advantages include: close dimensional tolerance of complicated shapes. Usually products are less dense than wrought products because of porosity. However, it is advantageous as pores can retain oil for self-lubrication of bushes, and high damping capacity.

9.3 Thermal processing of metals and alloys

Apart from mechanical processing, metals are very often subjected to thermal processing for various reasons, like: to refine grain structure/size, to minimize residual stresses, to

impart phase changes, to develop special phases over external surfaces, etc. Metals and alloys develop requisite properties by thermal processing either through grain refinement of phase changes. Thermal processing is also known as heat treatment. Heat treatment originated as an ancient art in man's attempts to improve the performance of materials in their practical applications. In present day metallurgical practice, heat treatment has become very important for obvious reasons. There has been tremendous progress over centuries in the systematic understanding of materials structure and structure-property relationships that eliminated the empiricism in thermal processing. Properly designed and implemented thermal processing can result in optimum modifications in the composition and distribution of phases, corresponding changes in physical, chemical and mechanical properties at substantial levels. However, most of the thermal processes are aimed to improving mechanical characteristics of materials. Thus it is possible to extend the service performance of materials considerably within constraints of available resources.

All metals can be subjected to thermal processing. But the effect of it may differ from one metal to another. Metals are subjected to heat treatment for one or more of the following purposes: improvement in ductility; relieving internal stresses; grain size refinement; increase of strength; improvement in machinability, toughness; etc.

Heat treatment of materials involves number of factors – temperature up to which material is heated, length of time that the material is held at the elevated temperature, rate of cooling, and the surrounding atmosphere under the thermal treatment. All these factors depend on material, pre-processing of the material's chemical composition, size and shape of the object, final properties desired, material's melting point/liquidus, etc.

Thermal processes may be broadly classified into two categories based on cooling rates from elevated temperatures – annealing and quenching & tempering. Annealing involved cooling the material from elevated temperatures slowly, while quenching means very fast cooling of the material using cooling medium like water/oil bath. Quenching is done to retain the phases of elevated temperatures at room temperature.

9.3.1 Annealing processes

The term annealing was used by craftsmen who discovered the beneficial effects of heating the material at elevated temperatures followed by slow cooling of it to room temperature. *Annealing* can be defined as a heat treatment process in which the material is taken to a high temperature, kept there for some time and then cooled. High temperatures allow diffusion processes to occur fast. The time at the high temperature (soaking time) must be long enough to allow the desired transformation to occur. Cooling is done slowly to avoid the distortion (warping) of the metal piece, or even cracking, caused by stresses induced by differential contraction due to thermal inhomogeneities. Benefits of annealing are:

- relieve stresses
- increase softness, ductility and toughness
- produce a specific microstructure

Depending on the specific purpose, annealing is classified into various types: process annealing, stress relief, full annealing and normalizing.

Process annealing is primarily applied to cold worked metals to negate the effects of cold work. During this heat treatment, material becomes soft and thus its ductility will be increased considerably. It is commonly sandwiched between two cold work operations. During this, recovery and recrystallization are allowed whereas grain growth was restricted.

Stress relief operation removes the stresses that might have been generated during plastic deformation, non-uniform cooling, or phase transformation. Unless removed, these stresses may cause distortion of components. Temperature used is normally low such that effects resulting from cold working are not affected.

Full annealing is normally used for products that are to be machined subsequently, such as transmission gear blanks. After heating and keeping at an elevated temperature, components are cooled in furnace to effect very slow cooling rates. Typically, the product receives additional heat treatments after machining to restore hardness and strength.

Normalizing is used to refine the grains and produce a more uniform and desirable size distribution. It involves heating the component to attain single phase (e.g.: austenite in steels), then cooling in open air atmosphere.

9.3.2 Quenching and Tempering processes

Quenching is heat treatment process where material is cooled at a rapid rate from elevated temperature to produce Martensite phase. This process is also known as *hardening*. Rapid cooling rates are accomplished by immersing the components in a quench bath that usually contains quench media in form of either water or oil, accompanied by stirring mechanism.

Quenching process is almost always followed by tempering heat treatment. *Tempering* is the process of heating martensitic steel at a temperature below the eutectoid transformation temperature to make it softer and more ductile. During the tempering process, Martensite transforms to a structure containing iron carbide particles in a matrix of ferrite.

Martempering is a modified quenching procedure used to minimize distortion and cracking that may develop during uneven cooling of the heat-treated material. It involves cooling the austenized steel to temperature just above M_s temperature, holding it there until temperature is uniform, followed by cooling at a moderate rate to room temperature before austenite-to-bainite transformation begins. The final structure of martempered steel is tempered Martensite.

Austempering is different from martempering in the sense that it involves austenite-to-bainite transformation. Thus, the structure of austempered steel is bainite. Advantages of

austempering are – improved ductility; decreased distortion and disadvantages are – need for special molten bath; process can be applied to limited number of steels.

9.4 Case Hardening

In case hardening, the surface of the steel is made hard and wear resistant, but the core remains soft and tough. Such a combination of properties is desired in applications such as gears.

9.4.1. Induction hardening

Here, an alternating current of high frequency passes through an induction coil enclosing the steel part to be heat treated. The induced *emf* heats the steel. The depth up to which the heat penetrates and raises the temperature above the elevated temperature is inversely proportional to the square root of the *ac* frequency. In induction hardening, the heating time is usually a few seconds. Immediately after heating, water jets are activated to quench the surface. Martensite is produced at the surface, making it hard and wear resistant. The microstructure of the core remains unaltered. Induction hardening is suitable for mass production of articles of uniform cross-section.

9.4.2. Flame hardening

For large work pieces and complicated cross-sections induction heating is not easy to apply. In such cases, flame hardening is done by means of an oxyacetylene torch. Heating should be done rapidly by the torch and the surface quenched, before appreciable heat transfer to the core occurs

9.4.3. Laser hardening

In this case, a laser beam can be used for surface hardening. As laser beams are of high intensity, a lens is used to reduce the intensity by producing a defocused spot of size ranging from 0.5 to 25 mm. Proper control of energy input is necessary to avoid melting. Laser hardening has the advantage of precise control over the area to be hardened, an ability to harden reentrant surfaces, very high speed of hardening and no separate quenching step. The disadvantage is that the hardening is shallower than in induction and flame hardening

9.4.4. Carburizing

Carburizing is the most widely used method of surface hardening. Here, the surface layers of low carbon steel are enriched with carbon up to 0.8-1.0%. The source of carbon may be a solid medium, a liquid or a gas. In all cases, the carbon enters the steel at the surface and diffuses into the steel as a function of time at an elevated temperature. Carburizing is done at 920-950° C. This fully austenitic state is essential. If carburizing is done in the ferritic region, the carbon, with very limited solubility in ferrite, tends to form massive cementite particles near the surface, making the subsequent heat treatment

difficult. For this reason, carburizing is always done in the austenitic state, even though longer times are required due to the diffusion rate of carbon in austenite being less than in ferrite at such temperatures.

9.4.5. Cyaniding

Cyaniding is done in a liquid bath of NaCN, with the concentration varying between 30 and 97%. The temperature used for cyaniding is lower than that for carburizing and is in the range of 800-870° C. The time of cyaniding is 1-3 hr to produce a case depth of 0.25 mm or less

9.4.5. Nitriding

Nitriding is carried out in the ferritic region. No phase change occurs after nitriding. The part to be nitrided should possess the required core properties prior to nitriding. During nitriding, pure ammonia decomposes to yield nitrogen which enters the steel. The solubility of nitrogen in ferrite is small. Most of the nitrogen, that enters the steel, forms hard nitrides (e.g., Fe₃N). The temperature of nitriding is 500-590° C. The time for a case depth of 0.02 mm is about 2 hr. In addition to providing outstanding wear resistance, the nitride layer increases the resistance of carbon steel to corrosion in moist atmospheres.

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