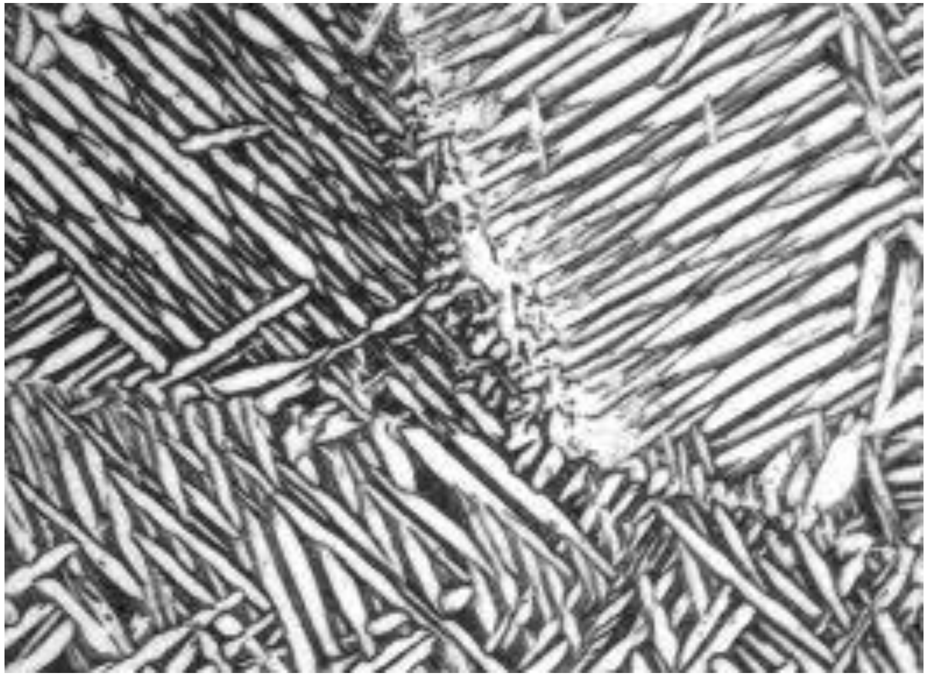
Part 1. Solid Body structure

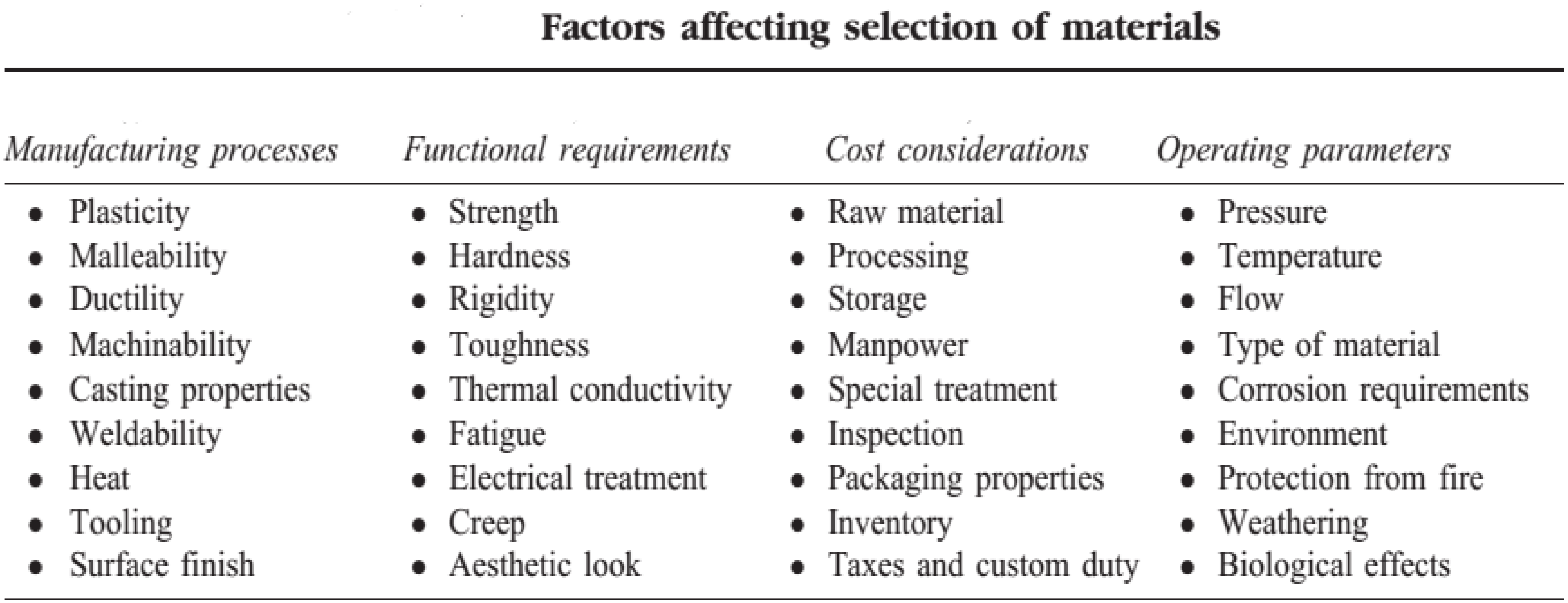


1. INTRODUCTION

Materials science and engineering plays a vital role in this modern age of science and technology. Various kinds of materials are used in industry, housing, agriculture, transportation, etc. to meet the plant and individual requirements. The rapid developments in the field of quantum theory of solids have opened vast opportunities for better understanding and utilization of various materials.

The spectacular success in the field of space is primarily due to the rapid advances in high-temperature and high-strength materials. The selection of a specific material for a particular use is a very complex process.

However, one can simplify the choice if the details about operating parameters, manufacturing processes, functional requirements and cost considerations are known. Factors affecting the selection of materials are summarized in table

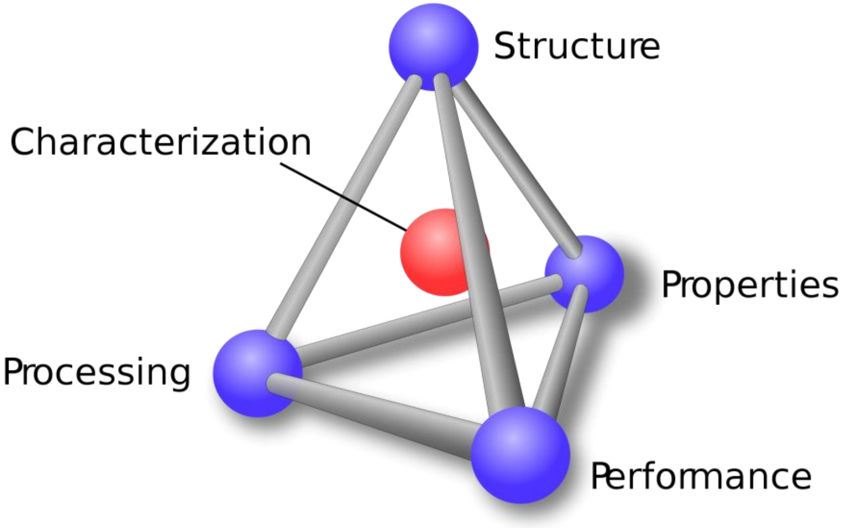


Factors affecting selection of materials

Manufacturing processes	*Functional requirements*	*Cost considerations*	*Operating parameters*
• Plasticity	• Strength	• Raw material	• Pressure
• Malleability	• Hardness	• Processing	• Temperature
• Ductility	• Rigidity	• Storage	• Flow
• Machinability	• Toughness	• Manpower	• Type of material
• Casting properties	• Thermal conductivity	• Special treatment	• Corrosion requirements
• Weldability	• Fatigue	• Inspection	• Environment
• Heat	• Electrical treatment	• Packaging properties	• Protection from fire
• Tooling	• Creep	• Inventory	• Weathering
• Surface finish	• Aesthetic look	• Taxes and custom duty	• Biological effects

Materials science finds the correlation between composition, structure, treatment from one side and properties of material from the other. This helps to select material for thet or other application properly.

The same piece of material after various methods of treatment will posses various properties. Sometimes even unexpected…



This also means, that improper handling of materials may cause change in properties, and entire the product may come out of serviceable state

There are thousands and thousands of materials available and it is very difficult for an engineer to possess a detailed knowledge of all the materials. However, a good grasp of the fundamental principles which control the properties of various materials help one to make the optimum selection of material. In this respect, materials science and engineering draw heavily from the engineering branches, e.g. metallurgy, ceramics and polymer science.

The subject of material science is very vast and unlimited. Broadly speaking, one can sub-divide the field of study into following four branches: (i) Science of metals, (ii) Mechanical behaviour of metals (iii) Engineering metallurgy and (iv) Engineering materials.

Engineering requirenments to materials

While selecting materials for engineering purposes, properties such as impact strength, tensile strength, hardness indicate the suitability for selection but the design engineer will have to make sure that the radiography and other properties of the material are as per the specifications.

One can dictate the method of production of the component, service life, cost etc. However, due to the varied demands made metallic materials, one may require special surface treatment, e.g. hardening, normalising to cope with the service requires.

Besides, chemical properties of materials, e.g. structure, bonding energy, resistance to environmental degradation also effect the selection of materials for engineering purposes. In recent years polymeric materials or plastics have gained considerable popularity as engineering materials. Though inferior to most metallic materials in strength and temperature resistance, these are being used not only in corrosive environment but also in the places where minimum wear is required, e.g. small gear wheels, originally produced from hardened steels, are now manufactured from nylon or teflon.

These materials perform satisfactorily, are quiet and do not require lubrication. Thus, before selecting a material or designing a component, it is essential for one to understand the requirements of the process thoroughly, operating limitations like hazardous or non-hazardous conditions, continuous or non-continuous operation, availability of raw materials as well as spares, availability of alternate materials vis-a-vis life span of the instrument/equipment, cost etc.

Different materials possess different properties to meet the various requirement for engineering purposes.

The properties of materials which dictate the selection are as follows:

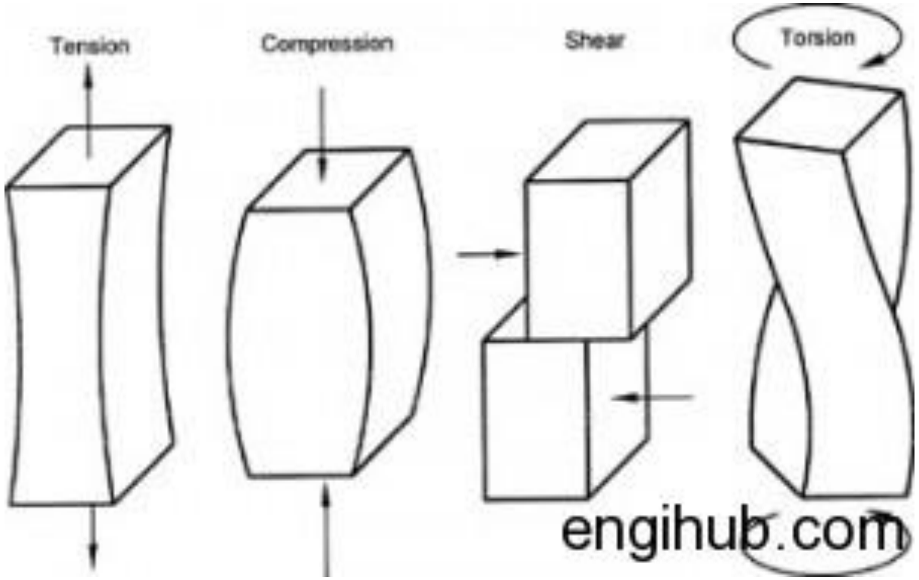
(a) Mechanical Properties The important mechanical properties affecting the selection of a material are:

(i) Tensile Strength: This enables the material to resist the application of a tensile force. To withstand the tensile force, the internal structure of the material provides the internal resistance.

(ii) Hardness: It is the degree of resistance to indentation or scratching, abrasion and wear. Alloying techniques and heat treatment help to achieve the same.

(iii) Ductility: This is the property of a metal by virtue of which it can be drawn into wires or elongated before rupture takes place. It depends upon the grain size of the metal crystals.
(iv) Impact Strength: It is the energy required per unit cross-sectional area to fracture a specimen, i.e., it is a measure of the response of a material to shock loading.

(v) Wear Resistance: The ability of a material to resist friction wear under particular conditions, i.e. to maintain its physical dimensions when in sliding or rolling contact with a second member.



(vi) Corrosion Resistance: Those metals and alloys which can withstand the corrosive action of a medium, i.e. corrosion processes proceed in them at a relatively low rate are termed corrosion-resistant.

(vii) Density: This is an important factor of a

material where weight and thus the mass is critical, i.e. aircraft components.

Thermal Properties

The characteristics of a material, which are functions of the temperature, are termed its thermal properties. One can predict the performance of machine components during normal operation, if he has the knowledge of thermal properties. Specific heat, thermal conductivity, thermal expansion etc. are few important thermal properties of materials.

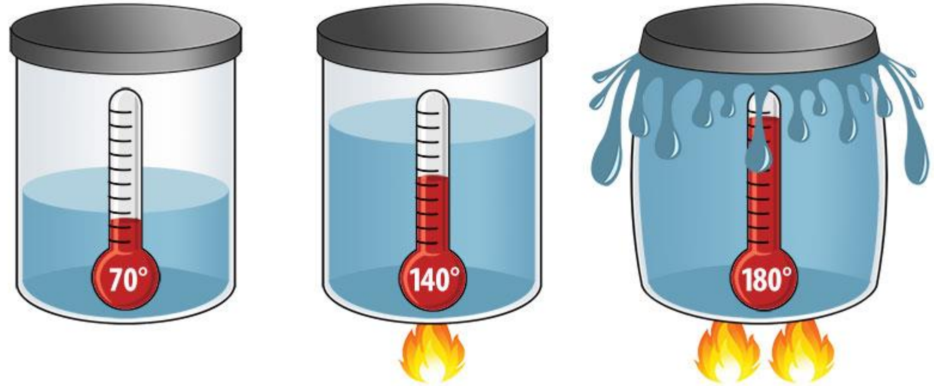
These properties play a vital role in selection of material for engineering applications, e.g. when materials are considered for high temperature service.

(i) *Specific Heat (c)*: It is the heat capacity of a unit mass of a homogeneous substance. For a homogeneous body, $c = C/M$, where C is the heat capacity and M is the mass of the body. One can also define it as the quantity of heat required to raise the temperature of a unit mass of the substance through 1°C. Its units are cal/g/°C.

(ii) *Thermal Conductivity (K):* This represents the amount of heat conducted per unit time through a unit area perpendicular to the direction of heat conduction when the temperature gradient across the heat Classification and Selection of Materials conducting element is one unit. Truly speaking the capability of the material to transmit heat through it is termed as the thermal conductivity. Higher the value of thermal conductivity, the greater is the rate at which heat will be transferred through a piece of given size. Copper and aluminium are good conductors of heat and therefore extensively used whenever transfer of heat is desired. Bakelite is a poor conductor of heat and hence used as heat insulator.

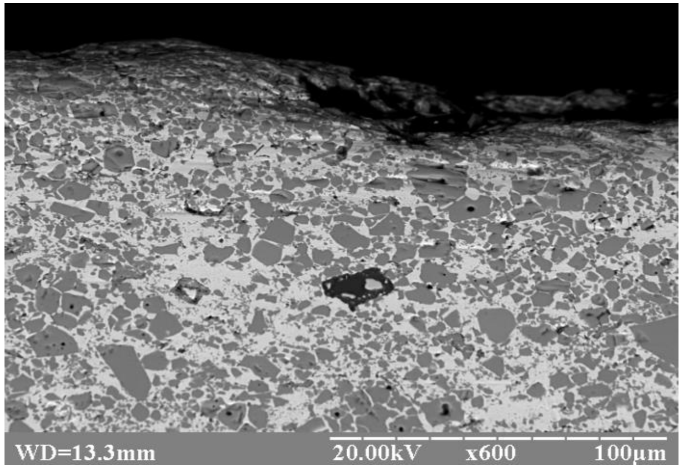
(iii) Thermal Expansion: All solids expand on heating and contract on cooling. Thermal expansion may take place either as linear,

circumferential or cubical. A solid which expands equally in three mutually orthogonal directions is termed as *thermally isotropic*. The increase in any linear dimension of a solid, e.g. length, width, height on heating is termed as *linear expansion*. The *coefficient of linear expansion* is the increase in length per unit length per degree rise in temperature. The increase in volume of a solid on heating is called *cubical expansion*. The thermal expansion of solids has its origin in the lattice vibration and lattice vibrations increases with the rise in temperature.



'Classification of materials

The factors which form the basis of various systems of classifications of materials in material science and engineering are:
(i) the chemical composition of the material,
(ii) the mode of the occurrence of the material in the nature,
(iii) the refining and the manufacturing process to which the material is subjected prior it acquires the required properties,
(iv) the atomic and crystalline structure of material and
(v) the industrial and technical use of the material.
Common engineering materials that falls within the scope of material science and engineering may be classified into one of the following six groups:
(i) Metals (ferrous and non-ferrous) and alloys
(ii) Ceramics
(iii) Organic Polymers
(iv) Composites
(v) Semi-conductors
(vi) Biomaterials
(vii) Advanced Materials



Metals*:* All the elements are broadly divided into metals and non-metals according to their properties. Metals are element substances which readily give up electrons to form metallic bonds and conduct electricity. Some of the important basic properties of metals are:

(a) metals are usually good electrical and thermal conductors,
(b) at ordinary temperature metals are usually solid,
(c) to some extent metals are malleable and ductile,
(d) the freshly cut surfaces of metals are lustrous,
(e) when struck metal produce typical sound, and
(f) most of the metals form alloys.

When two or more pure metals are melted together to form a new metal whose properties are quite different from those of original metals, it is called an *alloy*. Metallic materials possess specific properties like plasticity and strength. Few favourable characteristics of metallic materials are high lustre, hardness, resistance to corrosion, good thermal and electrical conductivity, malleability, stiffness, the property of magnetism, etc. Metals may be magnetic, non-magnetic in nature.

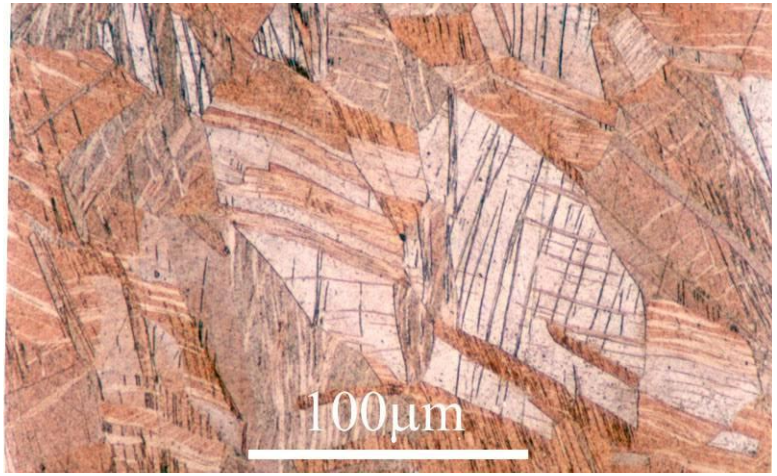
These properties of metallic materials are due to:
(1) the atoms of which these metallic materials are composed and

(2) the way in which these atoms are arranged in the space lattice.
Metallic materials are typically classified according to their use in engineering as under:

(i) Pure Metals: Generally it is very difficult to obtain pure metal. Usually, they are obtained by refining the ore. Mostly, pure metals are not of any use to the engineers. However, by specialised and very expensive techniques, one can obtain pure metals (purity ~ 99.99%), e.g. aluminium, copper etc.

(ii) Alloyed Metals: Alloys can be formed by blending two or more metals or atleast one being metal. The properties of an alloy can be totally different from its constituent substances, e.g. 18-8 stainless steel, which contains 18%, chromium and 8% nickle, in low carbon steel, carbon is less than 0.15% and this is extremely tough, exceedingly ductile and highly resistant to corrosion. We must note that these properties are quite different from the behaviour of original carbon steel.

(iii) Ferrous Metals: Iron is the principal constituent of these ferrous metals. Ferrous alloys contain significant amount of non-ferrous metals. Ferrous alloys are extremely important for engineering purposes. On thebasis of the percentage of carbon and their alloying elements present, these can be classified into several groups.

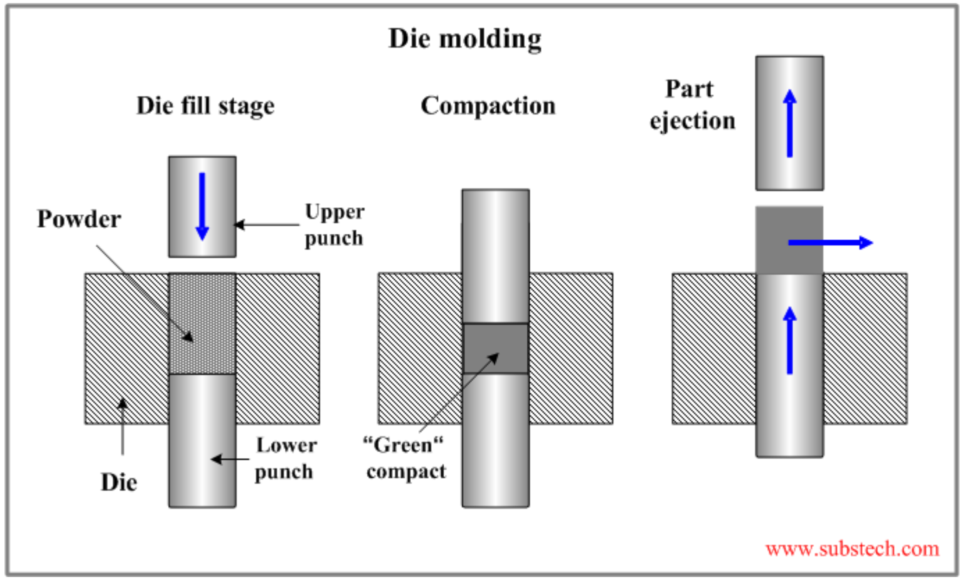


(iv) Non-Ferrous Metals: These substances are composed of metals other than iron. However, these may contain iron in small proportion. Out of several non-ferrous metals only seven are available in sufficient quantity reasonably at low cost and used as common engineering metals.

These are aluminium, tin, copper, nickle, zinc and magnesium. Some other non-ferrous metals, about fourteen in number, are produced in relatively small quantities but these are of vital importance in modern industry. These includes, chromium, mercury, cobalt, tungsten, vanadium, molybdenum, antimony, cadmium, zirconium, beryllium, niobium, titanium, tantalum and manganese.

Sintered Metals

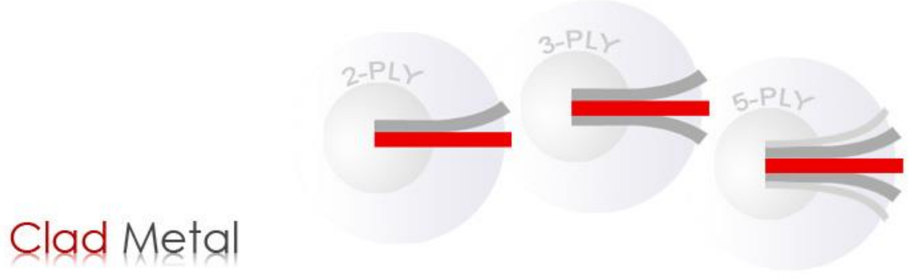
These materials possess very different properties and structures as compared to the metals from which these substances have been cast. Powder metallurgy technique is used to produced sintered metals. The metals to be sintered are first obtained in powered form and then mixed in right calculated proportions. After mixing properly, they are put in the die of desired shape and then processed with certain pressure. Finally, one gets them sintered in the furnace. We must note that the mixture so produced is not the true alloy but it possesses some of the properties of typical alloys.



Clad Metals

A ‘sandwich’ of two materials is prepared in order to avail the advantage of the properties of both the materials. This technique is termed as cladding. Using this technique stainless steel is mostly embedded with a thick layer of mild steel, by rolling the two metals together while they are red hot.

This technique will not allow corrosion of one surface. Another example of the use of this technique is cladding of duralium with thin sheets of pure aluminium. The surface layers, i.e. outside layers of aluminium resist corrosion, whereas inner layer of duralumin imparts high strength. This technique is relatively cheap to manufacture.



Organic materials

Organic materials are carbon compounds and their derivatives. They are solids composed of long molecular chains. The study of organic compounds is very important because all biological systems are composed of carbon compounds. There are also some materials of biological origin which do not possess organic composition, e.g., limestone.

These materials are carbon compounds in which carbon is chemically bonded with hydrogen, oxygen and other non-metallic substances. The structure of these compounds is complex. Common organic materials are plastics and synthetic rubbers which are termed as *organic polymers*. Other examples of organic materials are wood, many types of waxes and petroleum derivatives. Organic polymers are prepared by polymerisation reactions, in which simple molecules are chemically combined into long chain molecules or threedimensional structures. Organic polymers are solids composed of long molecular chains. These materials have low specific gravity and good strength. The two important classes of organic polymers are:

(a) Thermoplastics: On heating, these materials become soft and hardened again upon cooling, e.g., nylon, polythene, etc.

(b) Thermosetting plastics: These materials cannot be resoftened after polymerisation, e.g., urea-formaldehyde, phenol formaldehyde, etc. Due to cross-linking, these materials are hard, tough, non-swelling and brittle.

These materials are ideal for moulding and casting into components. They have good corrosion resistance. The excellent resistance to corrosion, ease of fabrication into desired shape and size, fine lusture, light weight, strength, rigidity have established the polymeric materials and these materials are fast replacing many metallic components. PVC (Polyvinyl Chloride) and polycarbonate polymers are widely used for glazing, roofing and cladding of buildings. Plastics are also used for reducing weight of mobile objects, e.g., cars, aircrafts and rockets.

Polypropylenes and polyethylene are used in pipes and manufacturing of tanks.

Thermo-plastic films are widely used as lining to avoid seepage of water in canals and lagoons. To protect metal structure from corrosion, plastics are used as surface coatings. Plastics are also used
as main ingredients of adhesives. The lower hardness of plastic materials compared with other materials makes them subjective to attack by insects and rodents. Because of the presence of carbon, plastics are combustible. The maximum service temperature is of the order of 100°C. These materials are used as thermal insulators because of lower thermal conductivity. Plastic materials have low modulus of rigidity, which can be improved by addition of filters, e.g., glass fibres.

Natural rubber, which is an organic material of biological origin, is an thermoplastic material. It is prepared from a fluid, provided by the rubber trees. Rubber materials are widely used for tyres of automobiles, insulation of metal components, toys and other rubber products.

Inorganic materials

These materials include metals, clays, sand rocks, gravels, minerals and ceramics and have mineral origin. These materials are formed due to natural growth and development of living organisms and are not biological materials. Rocks are the units which form the crust of the earth.

Biological materials

Leather, limestone, bone, horn, wax, wood etc. are biological materials.

Wood is fibrous composition of hydrocarbon, cellulose and lignin and is used for many purposes. Apart from these components a small amount of gum, starch, resins, wax and organic acids are also present in wood. One can classify wood as *soft wood* and *hard wood*.

Fresh wood contains high percentage of water and to dry out it, seasoning is done. If proper seasoning is not done, defects such as cracks, twist, wrap etc. may occur. Leather is obtained from the skin of animals after cleaning and tanning operations. Nowadays, it is used for making belts, boxes, shoes, purses etc. To preserve the leather, tanning is used. Following two tanning techniques are widely used:

(a) Vegetable Tanning: It consist of soaking the skin in tanning liquor for several days and then dried to optimum conditions of leather.

(b) Chrome Tanning: This technique involves pickling the skin in acid solution and then revolving in a drum which contains chromium salt solution. After that the leather is dried and rolled.

Limestone is an important material which is not organic but has biological origin. It mainly consist of calcium carbonate and limestone. It is widely used to manufacture cement. In Iron and Steel Industries, limestone in pure form is used as flux.

In early days bones of animals were used to make tools and weapons. Nowadays bones are used for the manufacture of glue, gelatin etc. Bones are laminate of organic substances and phosphates and carbonates of calcium. These are stronger in compression as compared to tension.

These are the materials which have electrical properties that are intermediate between the electrical conductors and insulators. The electrical characteristics of semiconductors are extremely sensitive to the presence of minute concentrations of impurity atoms; these concentrations may be controlled over very small spatial regions. Semiconductors form the backbone of electronic industry. The semiconductors have made possible the advent of *integrated circuitary* that has totally revolutionized the electronics and computer industries. They affect all walks of life whether it is communications, computers, biomedical, power, aviation, defence, entertainment, etc. The field of semiconductors is rapidly changing and expected to continue in the next decade. Organic semiconductors are expected to play prominent role during this decade. Diamond as semiconductor will also be important. Optoelectronic devices will provide threedimensional integration of circuits, and optical computing.

Ceramics and Glasses

Ceramics and glasses are inorganic, nonmetallic materials consisting of metallic and nonmetallic elements bonded primarily with ionic and covalent bonds. These high strength bonds give rise to the special characteristics of these materials. They occupy a unique place in the spectrum of engineered materials offering many desirable alternatives to the metals and polymers in common usage.

There are wide variations in the properties of ceramics and glasses due primarily to differences in bonding and wide variations in chemical composition. However, as a materials class, the following characteristics are typical

Ceramics for engineering applications can be broadly broken into “traditional” and “new” materials. We define traditional materials as those produced from minerals mined directly from the earth. The newer ceramic materials, those with well defined and controlled properties are produced from nearly chemically and phase pure starting materials. Accuratus is capable of working with most of these material types.

An inventory of “new” ceramic materials is maintained at Accuratus for rapid fulfillment of your design requirements. We have a network of quality materials suppliers so that we can assure you of consistent quality materials for your applications.

Glass is a non-crystalline amorphous solid that is often transparent and has widespread practical, technological, and decorative usage in, for example, window panes, tableware, and optoelectronics. Scientifically, the term "glass" is often defined in a broader sense, encompassing every solid that possesses a non-crystalline (that is, amorphous structure at the atomic scale and that exhibits a glass transition when heated towards the liquid state.

The most familiar, and historically the oldest, types of glass are "silicate glasses" based on the chemical compound silica (silicon dioxide, or quartz), the primary constituent of sand. The term *glass*, in popular usage, is often used to refer only to this type of material, which is familiar from use as window glass and in glass bottles. Of the many silica-based glasses that exist, ordinary glazing and container glass is formed from a specific type called soda-lime glass, composed of approximately 75% silicon dioxide (SiO_2), sodium oxide (Na_2O) from sodium carbonate (Na_2CO_3), calcium oxide, also called lime (CaO), and several minor additives. A very clear and durable quartz glass can be made from pure silica, but the high melting point and very narrow glass transition of quartz make glassblowing and hot working difficult. In glasses like soda lime, the compounds added to quartz are used to lower the melting temperature and improve workability, at a cost in the toughness, thermal stability, and optical transmittance.

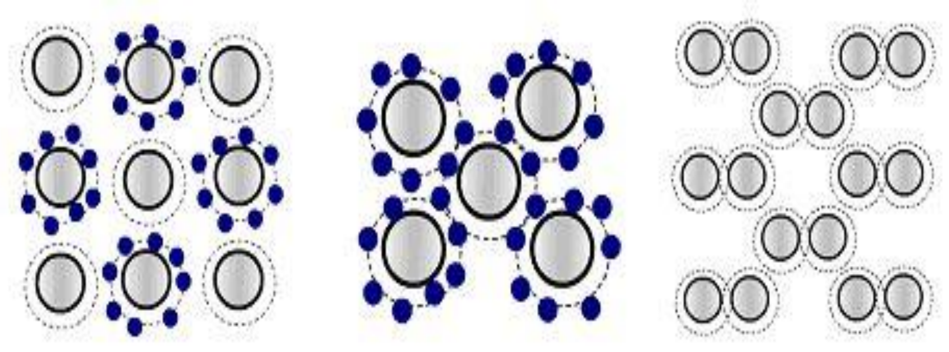
Chemical bonds

Solids consist of small particles - atoms. An atom has a nucleus composed of protons, neutrons and mesons that are placed in a small volume in the center of the atom and electrons orbiting around the nucleus in orbitals. Protons have a positive charge, electrons - negative. Mesons and neutrons have no charge. In the normal state the number of protons equals the number of electrons, and the atom has neutral charge

Electrons orbiting in their outer orbitals can leave the atom and the atoms can attach electrons to their external orbitals. These atoms are "charged" and are called ions (positively and negatively charged, respectively)

The electrons are on the outer energy levels (orbitals) are constantly moving and are called valent electrons.

Depending on the interaction of atoms and molecules, there are 4 types of chemical bonds: ionic, covalent, molecular and metallic. Ionic bond is formed by two atoms, one of which gives its valent electrons to the other atom, so that between them the forces of electrostatic attraction arise. This feature is a characteristic of oxides and salts (NaCl, MgO, LiF).



a *b* *c*

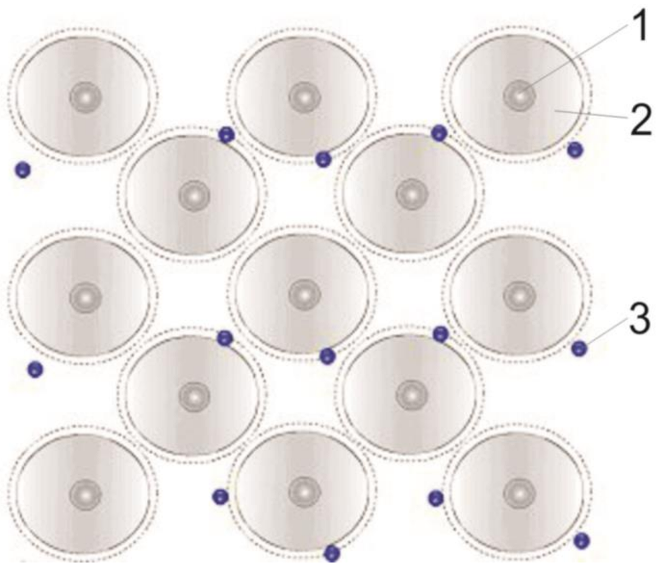
a – ionic *NaCl*); *b* – covalent;
c – мolecular (Van der Vaals)

Covalent bond arise when atoms form shared electron pair(s). This bond is weaker than ionic, but covalent crystals are characterized by a high melting point, hardness. Covalent bond formation occurs when molecules are formed by the atoms of the same element (Si2, O2)

The molecular bond is formed due to the instantaneous polarization of molecules (formation of dipoles). Oppositely charged parts of neighboring molecules are attracted. The atoms within molecules bound very strongly, while the interraction between neighboring molecules is relatively weak. This type of bonding is typical for polymers. Molecular crystals have low hardness and melting point

.

Metallic bond occurs when very dense packaging of atoms and electric fields of nuclei overlap. Under their influence the valence electrons lose contact with the nuclei and move freely between them. All these electrons are called "electron gas". Thus, metals consist of regularly arranged atoms (positively charged ions) - atomic frame, and free electrons.



1 – nucleus;
2 – atomic frame;
3 – free electrons (electron gas)

1.1. Solid body structure

The internal structure of the materials may be crystalline and amorphous.

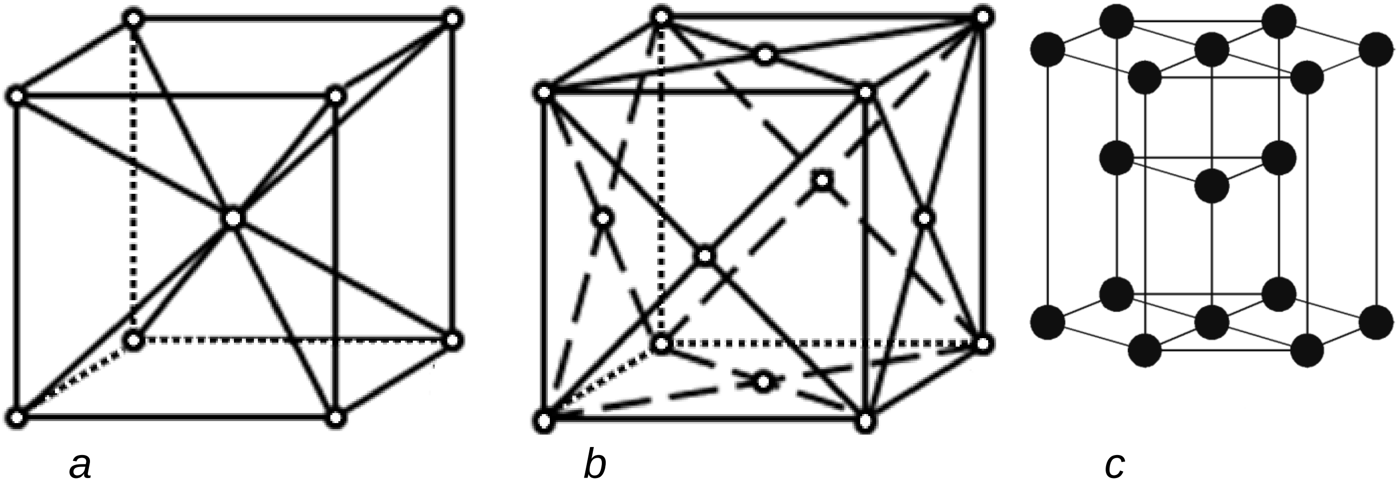
Crystalline materials are characterized by regular arrangement of atoms and molecules, for example, metals and alloys.

Amorphous materials have chaotic disposition of atoms and molecules, for example, resins and some polymers. Amorphous-crystalline state may be observed in some materials, for example, in some polymers. Amorphous state is less stable, than crystalline. So spontaneous transformation from amorphous to crystalline state may take place. For example, amorphous glass is spontaneously crystallized at high temperature and pressure.

Monocrystal – is a single nondefective crystal of the material with correct arrangement of atoms through the crystal. It has anisotropic properties (they depend on crystallographic orientation). Monocrystals are commonly used for semiconductor engineering products.

Polycrystalline material is composed of many small individual randomly oriented crystals with irregular shape, which are called grains. Polycrystalline materials are isotropic, their properties are the same in different directions. To describe crystalline structure of a material the term “crystalline lattice” is used.

Crystalline lattice is a geometric arrangement of the points in space at which the atoms, molecules, or ions of a crystal occur, also called *space lattice*. So, atoms and molecules are placed in lattice apexes and between them. The smallest building block of a crystal, consisting of atoms, ions, or molecules, whose geometric arrangement defines a crystal's characteristic symmetry and whose repetition in space produces a crystal lattice is called a unit cell. There are fourteen types of unit cells, but the most widely spread are the next: body-centred cubic (bcc, *a*), face-centred cubic (fcc, *b*) and hexagonal close-packed (hcp, *c*).



The most widely spread types of unit cells

Material’s properties strongly depend on crystalline lattice. The metals with the same type of unit cells have the same or very close properties. For example, gold, copper and silver have high thermal and electric conductivity, high ductility and formability. All these metals have fcc-type crystalline lattice.

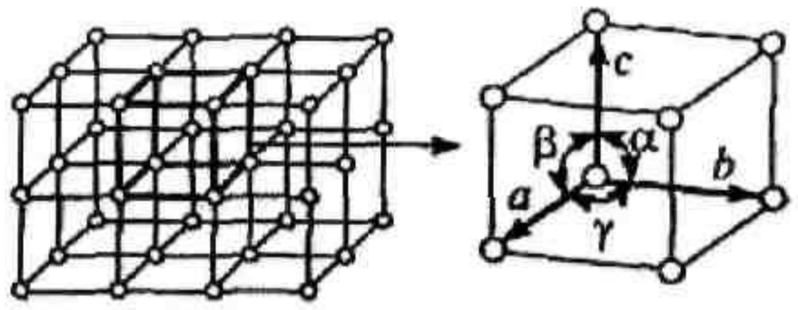
The unit cell has linear dimensions, called the lattice parameters. Cubic lattice has only one parameter *a* (edge length of the cube), hexagonal has twoo parameters - *a* and *c*

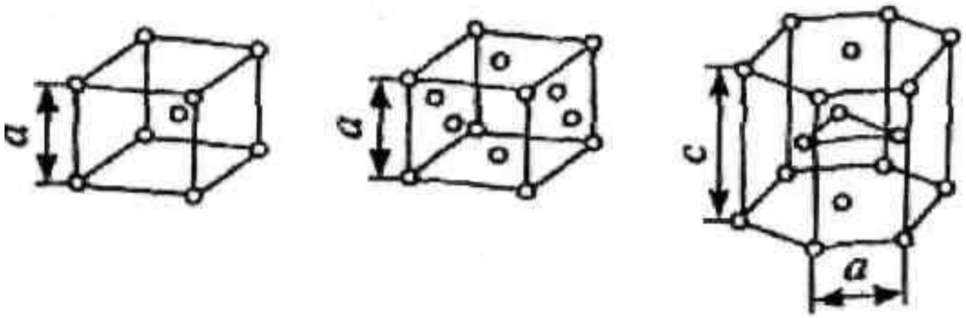
Basis of the lattice - is the number of atoms that occur in one unit cell.

In one unit cell of simple cubic lattice there is only one atom, as each of the eight atoms at the vertices of the cube belongs to 8 cells simultaneously (1/8 * 8 = 1)

To one unit cell bcc lattice (along with neighboring) belong two atoms: one - in the center of the cube and 1 in analogy to previous example (1/8 * 8 + 1 = 2.)

In fcc lattice on one cell falls four atoms: one if formed from eight atoms of neighboring cells, making three atoms located in the center of each face belonging to two neighboring cells, (½ * 6 + 1/8 * 8 = 4).





The density of the crystal lattice - a volume that is occupied by atoms. For a simple cubic lattice the density is 52%. For bcc lattice the density is 68%, for fcc and hcp lattices - 74%. So, these two are the most compact lattices.

The higher the density of packing of atoms, the stronger the bonding

Isotropy and anisotropy

Metals and alloys have a crystalline structure. Due to very low heat dissipation during crystallization we can get a sample of the metal, which is a one crystal in the whole volume. This crystal is called single crystal. Observed in single crystals different distances between the atoms in the crystal lattice in different crystallographic directions and the resulting properties are different in different crystallographic directions. Dependency of properties (chemical, mechanical) on the direction in a single crystal is called anisotropy.

Commercial metals and alloys are polycrystalline substances that consist of a large number of small, differently oriented crystals. In the process of crystallization they get an irregular shape and are called crystallites or grains. The different orientation of crystallites is causing more or less the same properties in all directions, ie polycrystalline body is isotropic.

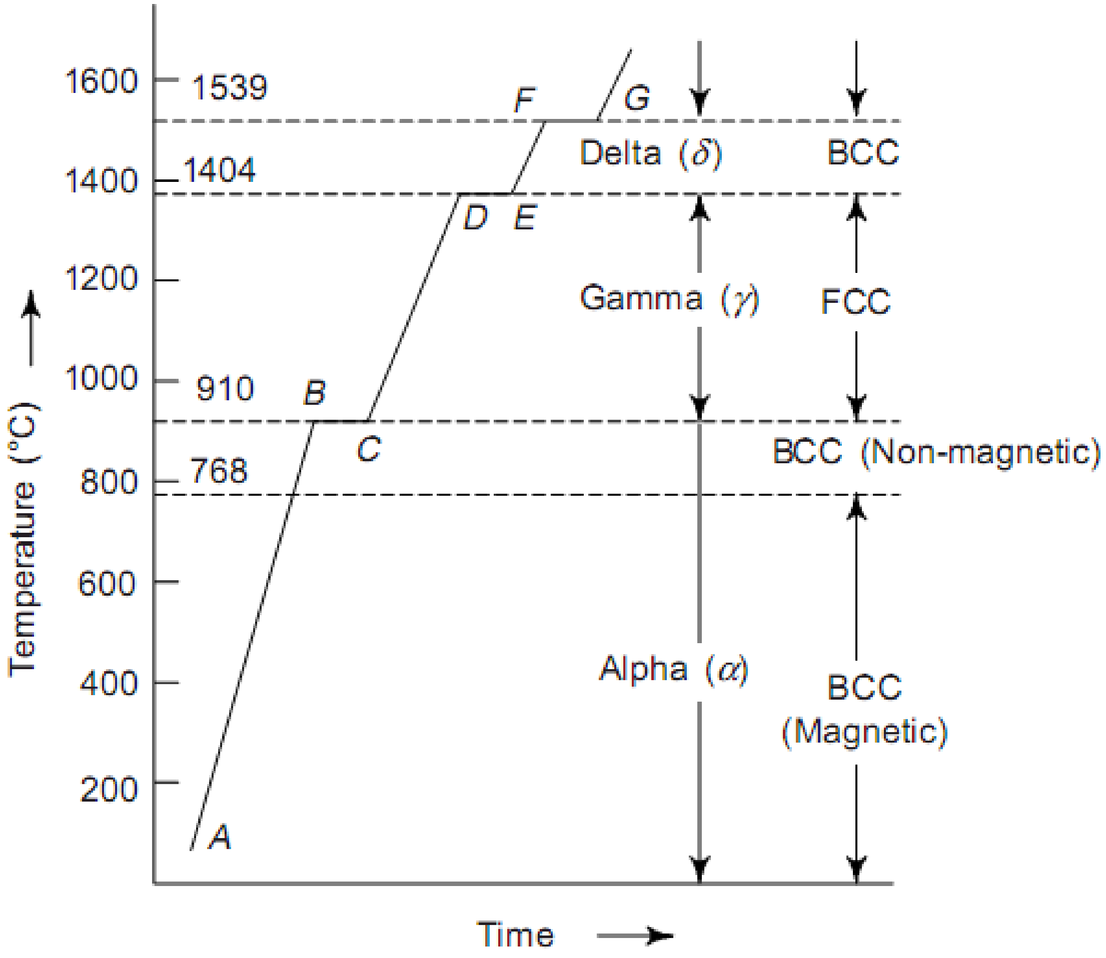
Allotropy

The atoms of each element can form any type of crystal lattice, but in reality there will be a lattice that has the lowest free energy. A large number of metals (iron, titanium, tin, cobalt, manganese, lithium) can exist in different crystallographic forms depending on temperature and pressure. This property is called polymorphism or allotropy. The temperature at which this transformation takes place is called polymorphic transformation temperature

Different crystalline lattices of the same material are called allotropic modifications and marked by letters of Greek alphabet: *α, β, γ* and so on. The first letter is given to the modification, which exists at the lowest temperature. Many materials, such as iron, titanium, lanthanum, zirconium and others have more than one crystalline lattice. On iron cooling curve (fig. 2) iron modifications are shown.

Below 910 – *α*-iron with bcc crystalline lattice, in temperature range 910-1392C *γ* – iron with fcc crystalline lattice, and above 1392C – δ – iron with bcc crystalline lattice.

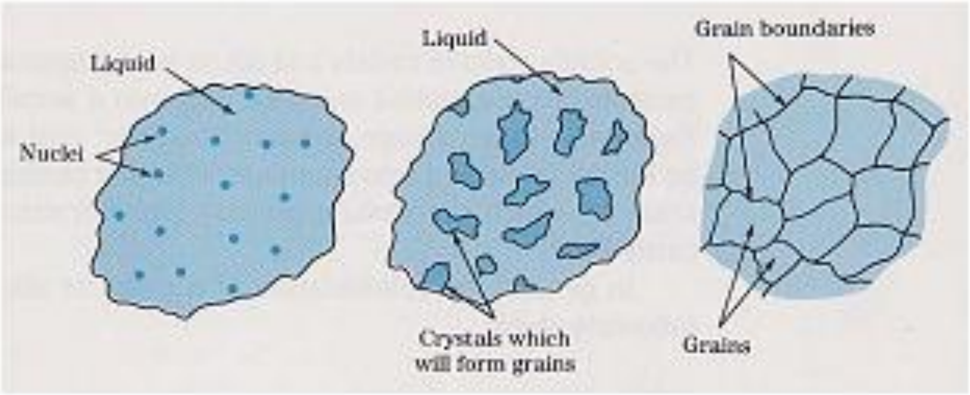
Allotropic transformation in iron is used to change mechanical characteristics and microstructure of steel and cast-iron applying various types of heat treatment.



Iron cooling curve

Solidification and crystall growth

Crystallization of alloys, like pure metals, occurs only in conditions of supercooling when the free energy of the liquid phase (melt) higher than of solid. The process of crystallization occurs due to the formation of nuclei (crystallization centers) and their growth.



For the formation of stable solid nuclei its chemcal content in small volumes of liquid should temporarily be different from the average of its content. These different chemical content is the result of thermal motion in the liquid phase.

Many alloys in solid state phase transformations occur due to polymorphisms or components of solid solution. The transformation in the solid state is also due to the formation of nuclei of new phase of growth and reduce energy of system, according to the laws of thermodynamics.

Crystal growth generally occurs by means of following sequence of process:

(i) diffusion of the moleculesof the crystallizing substance through the surrounding environment (or solution) to the surface of crystal.

(ii) diffusion of these molecules over the surface of the crystal to special sites on the surface.

(iii) incorporation of molecules into the crystal of these sites, and

(iv) diffusion of the heat of crystallization away from the crystal surface. The rate of crystal growth may be limited by any of these four steps. The initial formation of the centres from which crystal growth proceeds is known as *nucleation*. Increasing the supersaturation of the crystallizing component or increasing the temperature independently increases the rate of crystal growth. However, in many physical situations the supersaturation is increased by decreasing the temperature. In these circumstances the rate of crystal growth increases with decreasing temperature at first, goes through a maximum, and then decreases. Often the growth is greatly retarded by traces of certain impurities.

After nucleation, the crystals in the medium grow isolated from one another for a time. However, if several differently oriented crystals are growing, they may finally impinge on one another, and intercrystalline (grain) boundaries will be formed. At relatively high temperatures, the average grain size in these polycrystalline aggregates increases with time by a process called grain growth, whereby the larger grains grow at the expense of the smaller.

Imperfections of crystalline lattice

Perfectly regular crystal structures, are called ideal crystals. In ideal crystals atoms are arranged in a regular way. However, the structure of real crystals differs from that of ideal ones. Real crystals always have certain defects or imperfections, and therefore, the arrangement of atoms in the volume of a crystal is far from being perfectly regular. Imperfection, or defect – is any irregularity of crystalline structure. They are classified on the basis of their geometry.

0*D* – point defects: vacancies and interstitials, impurities.

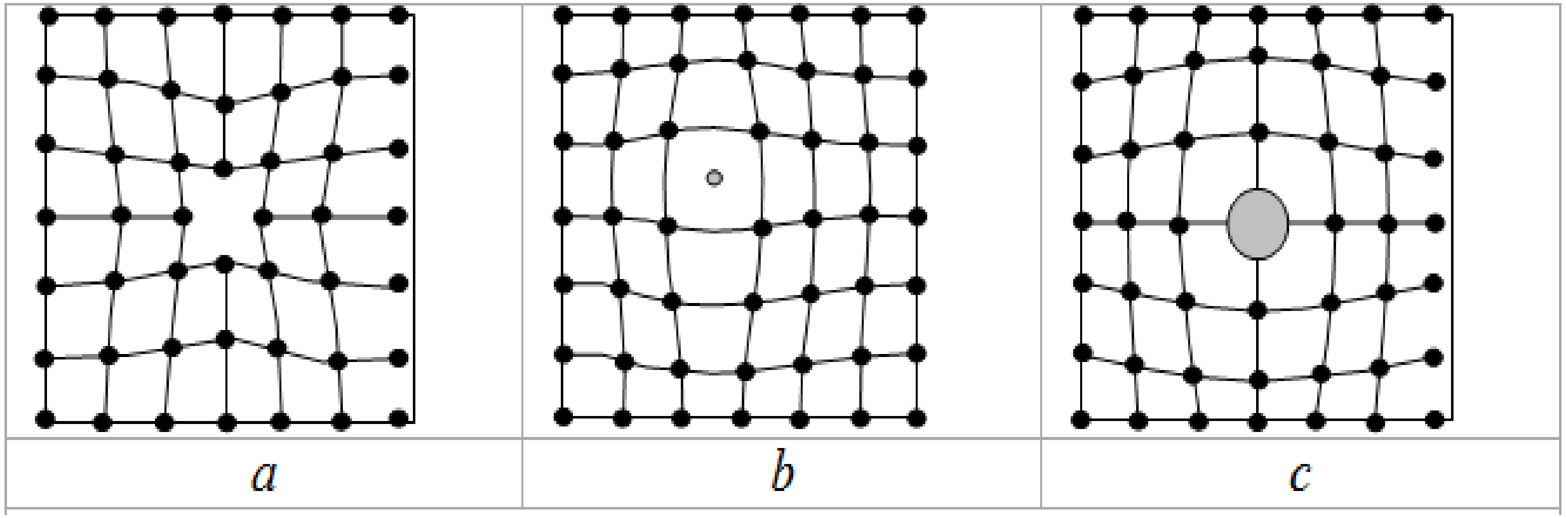
1*D* – linear defects: dislocations (edge, screw, mixed)

2*D* – planar or surface defects: grain boundaries, surfaces.

3*D* – extended or volume defects: pores, cracks.

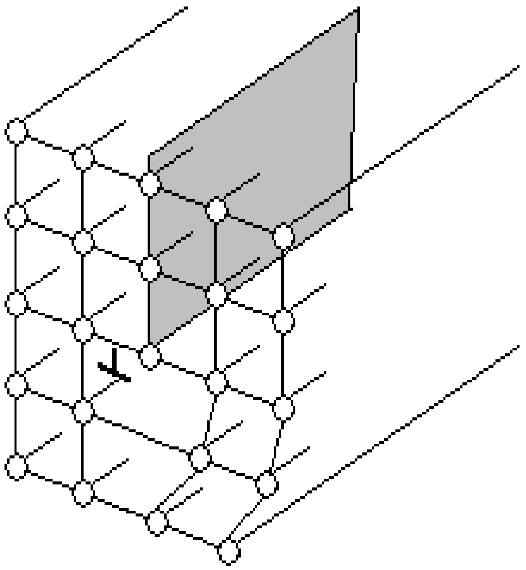
Point defects are small in three dimensions. Vacancy is a lattice position that is vacant because the atom is missing. An interstitial is an atom that occupies a place outside the normal lattice position (*b*). It may be the same type of atom as the others (self interstitial) or an impurity atom. Also impurity atoms may substitute atoms in crystalline lattice (*c*).

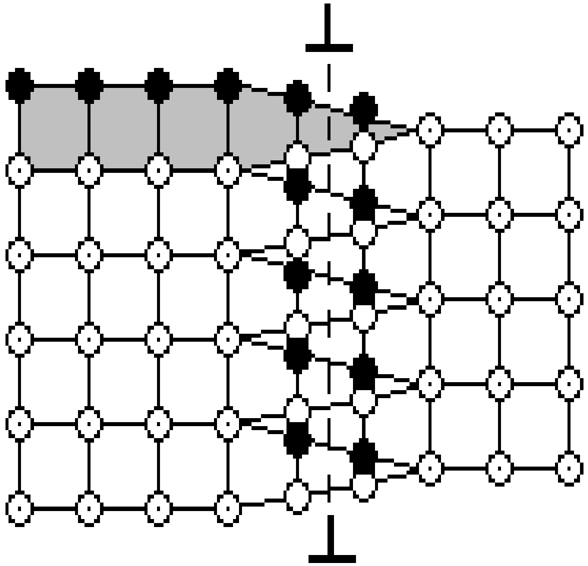
Point defects influence on electrical and magnetic properties of a materials. For example, ideal crystals of silicon have no use in electronics.



Linear defects or dislocations are abrupt Linear defects, or dislocations are abrupt changes in the regular ordering of atoms, along a line (dislocation line) in the solid. They are small in two dimensions. There are two main types of dislocations: edge and screw. Edge dislocations occur when an extra plane is inserted.

Screw dislocations result when displacing planes relative to each other through shear. It is possible to imagine it as a spiral slope with imperfection line on its edge.. So, any material properties strongly depend on number of dislocations in it, or on density of dislocations.



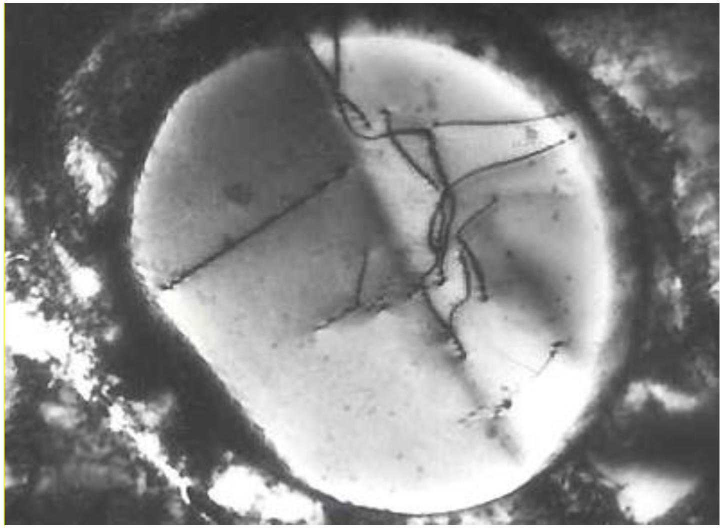


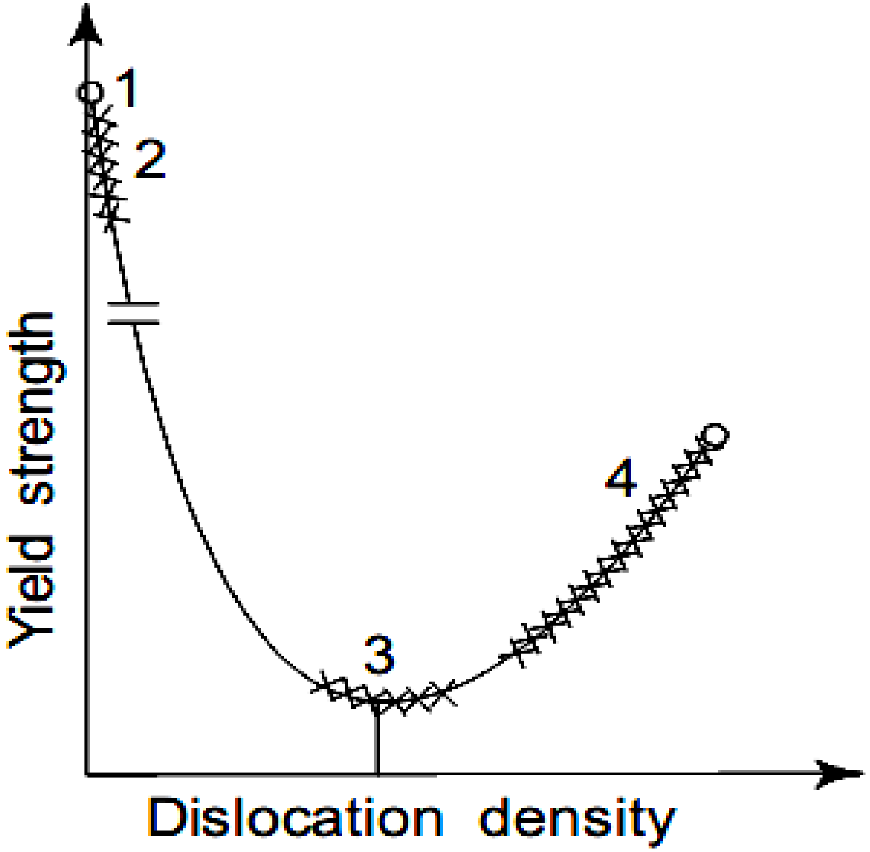
The dislocation density is a measure of how many dislocations are present in a quantity of a material. Since a dislocation is a line defect, this is defined as the total length of dislocation

per unit volume: $\rho = \frac{\Sigma l}{V}$. Consequently the units are m/m^3 = m^{-2}. Equivalently, it is the number of dislocation lines intersecting a unit area.Dislocation density is usually of the order of 10^{10} m^{-2} in a metal, increasing to ~10^{-15} m^{-2} after work hardening.

Dislocations affect not only such mechanical properties of solids as plasticity and strength, for which the existence of dislocations is essential, but also other physical properties of crystals. For example, an increase in the number of dislocations leads to a decrease in crystal density and internal friction, a change in the optical properties, and an increase in electrical resistance. Without the imperfections, materials would have little ductility and thus cannot be formed into useful shapes.

Dependence between density of dislocations and material’s mechanical properties is illustrated by Oding’s curve.

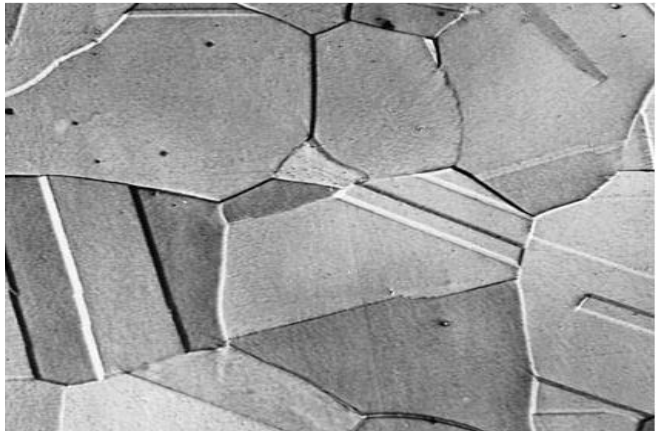


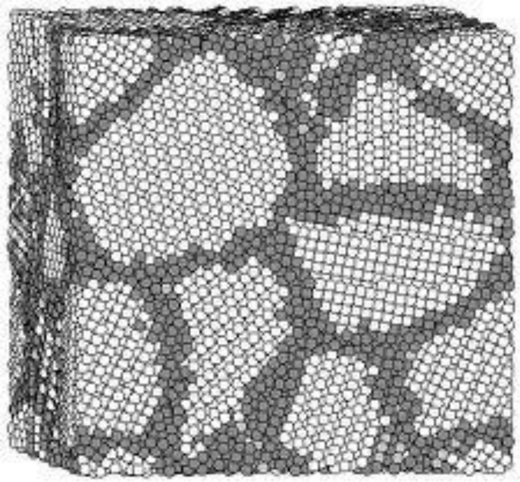


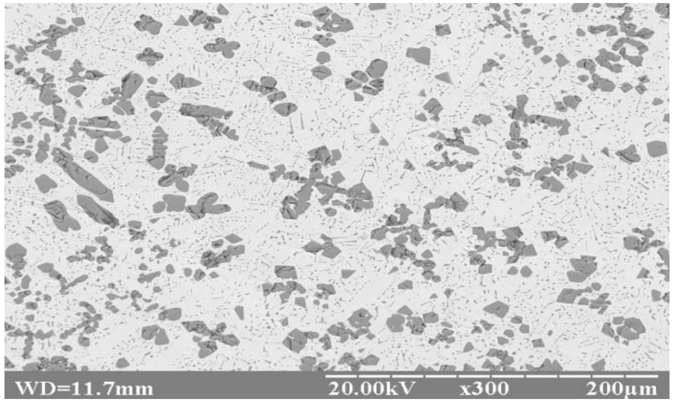
Oding’s curve

Point 1 corresponds to the theoretical strength. Section 2 corresponds to the strength of thin, long “thread-like” single crystal, which is called “whisker”. Section 3 shows the strength of nonstrengthaned pure metals. Section 4 corresponds to the commercial alloys, which are strengthaned by alloying, deformation, heat treatment and thermomechanical treatment.

Planar (surface) defects are small in one dimension. They are grain boundaries, that are narrow zones between grains in which crystallographic orientation is changed. The density of atoms here is smaller than the bulk value, since void space occurs in the interface. Surfaces and interfaces are very reactive and it is usual that impurities segregate there.

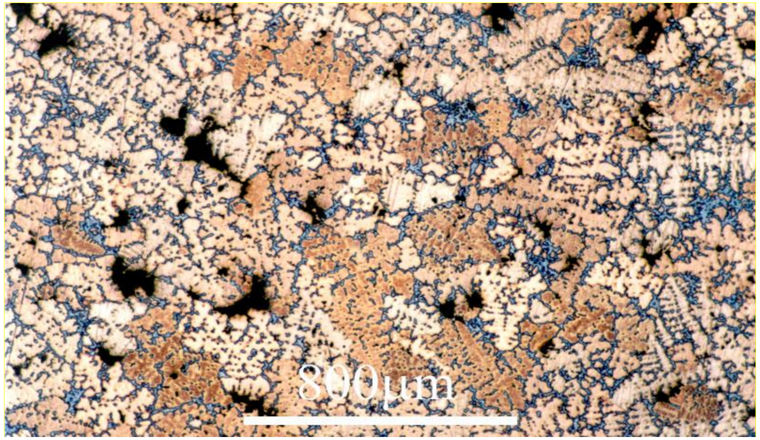


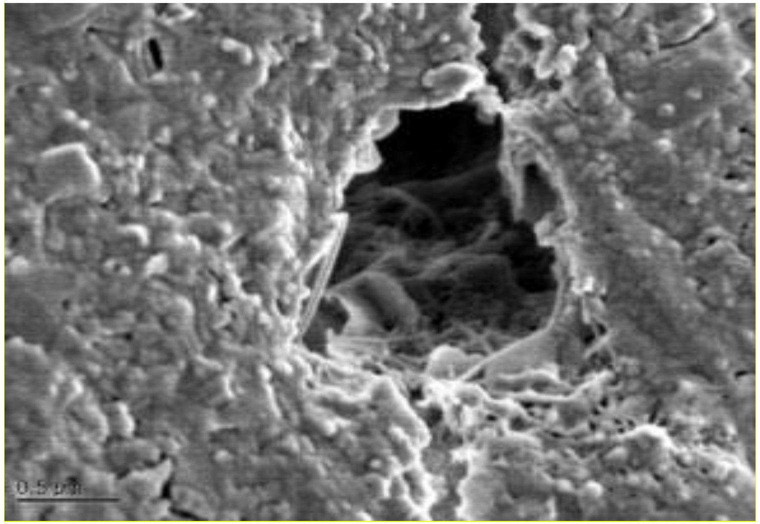




Extended defects occur on a much bigger scale than the rest of the crystal defects. A typical volume defect is porosity or cracks, often introduced in the solid during processing.

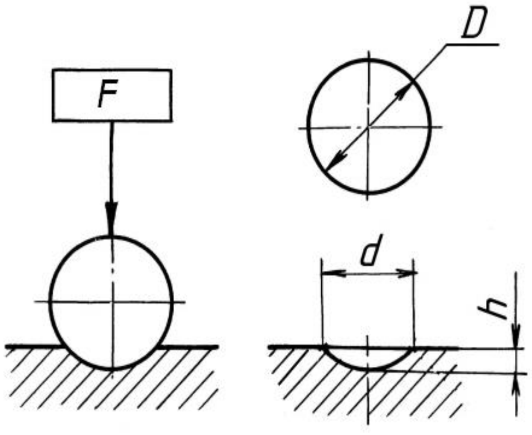
Another type of extended defect occurs when impurity atoms cluster together to form small regions of a different phase. A phase is a physically separable part of the system with distinct physical and chemical properties. These regions are often called precipitates





Hardness measuring

Hardness – is a property of a material to resist penetration of a hard object into considered material. The hardness test is widely used because it simplicity. Value of hardness correlates with tensile and yield strength, hardness, grain size. It is also relatively nondestructive. For steels the yield strength and tensile strength are directly proportional to the hardness. Therefore, hardness test allows to check or determine these important properties.



A variety of hardness tests have been developed, but most convenient and simple are Brinell test, Rockwell test and Vickers test.

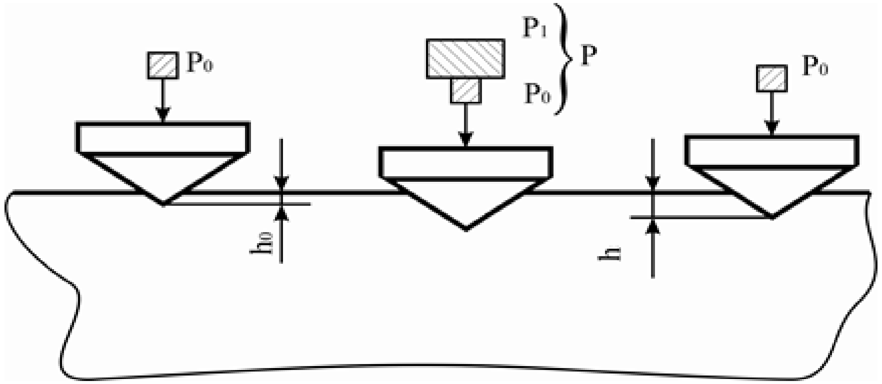
In a **Brinell** test as an indenter a 10 mm hard steel ball is used. The function of an indenter – is to penetrate the tested material surface. The indenter under load *F* penetrates the surface of the material; d – is a diameter of the impression, h – depth of penetration. This is illustrated on fig. 16. The indentation is measured and hardness calculated as follows:

$$BH = \frac{F}{(\pi/2)\cdot D\cdot(D-\sqrt{D^2-d^2})}$$

Where F is applied load in kilograms (500, 1500, 3000); *D* is the diameter of the indenter in mm, d is the diameter of indentation in mm. This test is recommended for inhomogeneous materials and large elements. There are also some restrictions. If material is very soft (below

BH8), the indentation will be too large and calculated hardness will be much lower than real. If material is very hard, the indentation edges will not be clear and it will be not possible to measure the diameter of impression correctly.

The Rockwell test involves the application of a minor load P_0 followed by a major load, P_1 and than noting the depth of penetration h after the major load removed (and minor load is still applied).



Hardness value is read directly from the dial indicator. There are several scales depending on type of indenter and load value. As an indenter steel or hard metal ball with diameter d = 1.5875 mm or diamond cone with apex angle 120^o may be used. The cone is used for hard materials, and the ball – for softer ones.

Rockwell A (HRA) – diamond cone, load – 60 kg. It is used for hard materials or coatings.

Rockwell B (HRB) – steel or hard metal ball, load – 100 kg. It is used for low strength or annealed steel, nonferrous alloys.

Rockwell C (HRC) – diamond cone, load – 150 *kg*. It is used for high strength or hardened steel, hard materials and coatings.

The minor load for all tests is 10 *kg.* Its purpose – to reduce influence of roughness on the test results.

The variety of indenters and available loading conditions makes this method the most developed, universal and videly used.

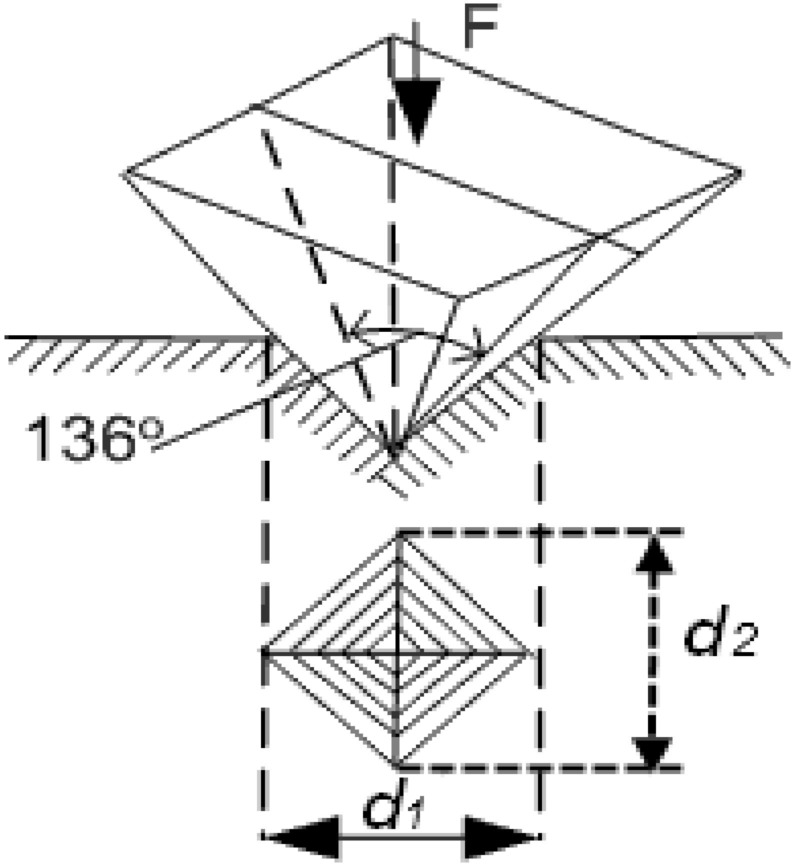
For **the Vickers** hardness test as an indenter a diamond four-sided pyramid with apex angle 136° is used. The load varies from 5 to 120 kg. with step equal to 5 kg. The indentation of this pyramid – is a rombus.

To determine hardness it is necessary to measure the length of its diagonals with aid of microscope. Results are substituted into a formula:

$$HV = \frac{F}{A} = \frac{1.8544F}{d^2},$$

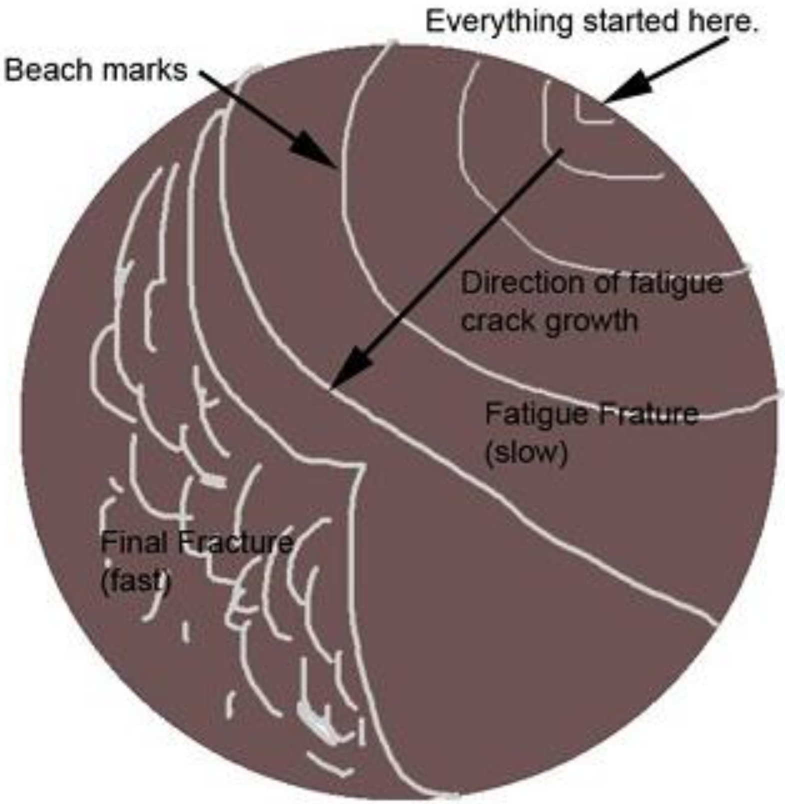
where *F* – is applied load, *A* – area of indentation, *d* – average length of indentation diagonal. This is determined by formula: d-(d_1+d_2)/2. The difference between d_1 and d_2 should be less than 5%. This method is very convenient fo measuring hardness of thin surface coatings. For convenience, tables are used. Using them, it is necessary to determine only average length of indentation diagonal and to find corresponding value of hardness.

To transfer from one hardness units to another tables, formulas or charts may be used.

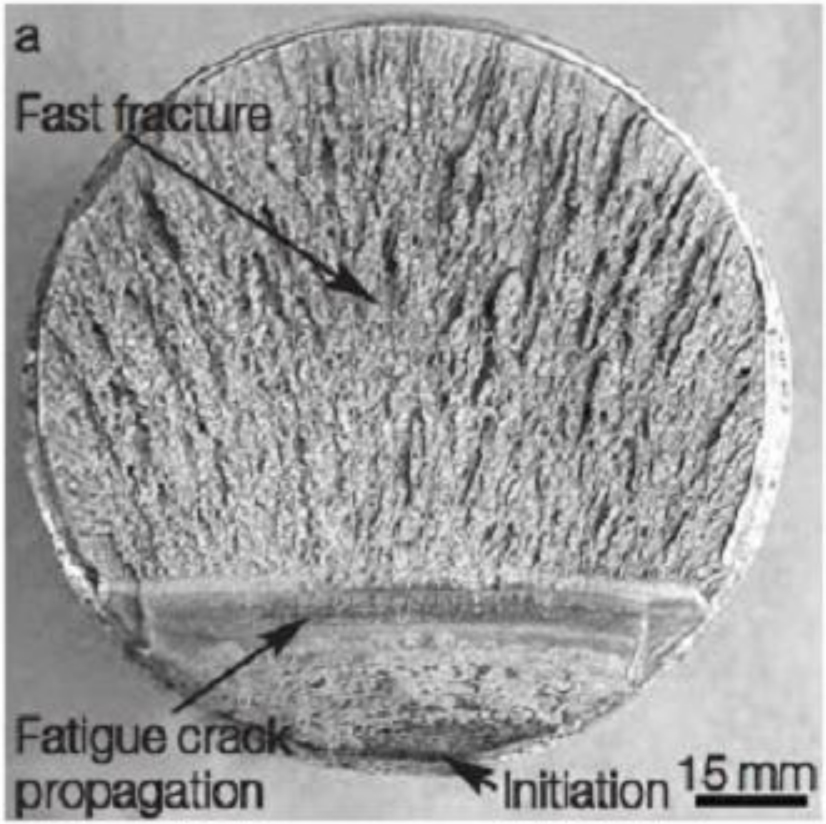


Fatigue Strength

If a material is subjected to repeated or cyclic stress, it may eventually fail even though the maximum stress in anyone cycle is considerably less than the ultimate tensile stress of the material. This type of failure is defined as fatigue failure. Two most important factors in the fatigue process are; - Tension stress level - Number of cycles Fatigue failure is the result of micro cracks which form and initiate on the surface of the material. In the case of a component inheriting a crack during manufacture, failure is brought about by the application of cyclical stresses. The appearance of a fatigue fracture surface has two distinctive portions. The smooth portion or fatigue zone, which has concentric lines called ‘beach marks’ or ‘clamshells’. The other part of the fracture surface has a rough coarse crystalline appearance resulted from the final catastrophic crack propagation



Fatigue Fracture Surface

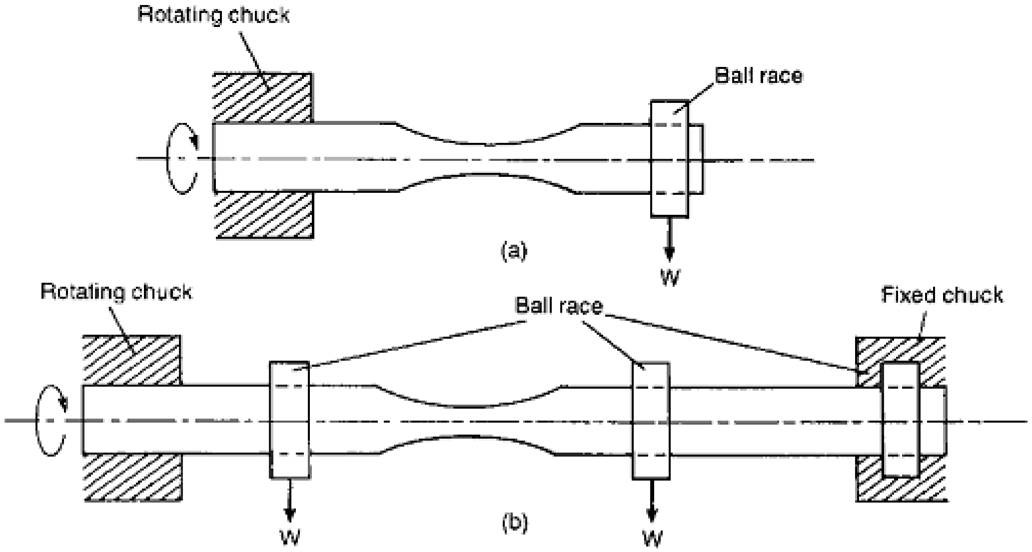


Picture of Fatigue Fracture

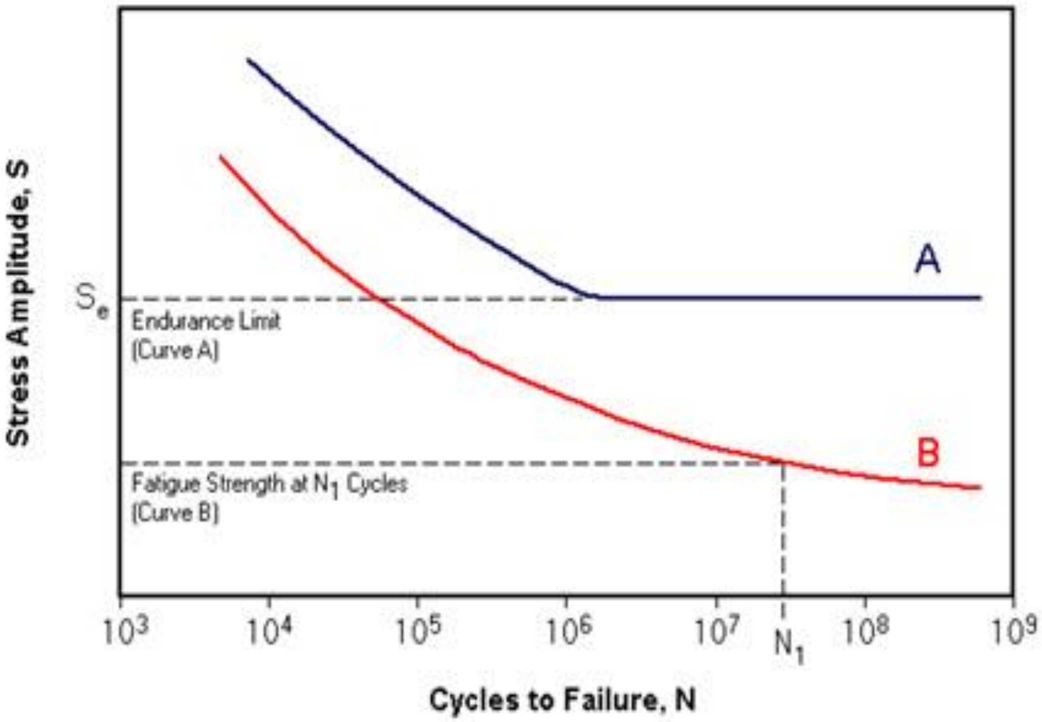
Fatigue Testing

Fatigue test machines vary in design, but are generally based around the Wöhler principal. The rotating specimen in form of a cantilever is driven by an electric motor. The specimen is loaded by the force W.

Basic Fatigue Tests. applied to the ball bearing, mounted on the end of the specimen. Since the force direction does not change, the direction of the stress applied to the specimen will be reversed each 180º of the shaft rotation. This provides cycling loading of the specimen

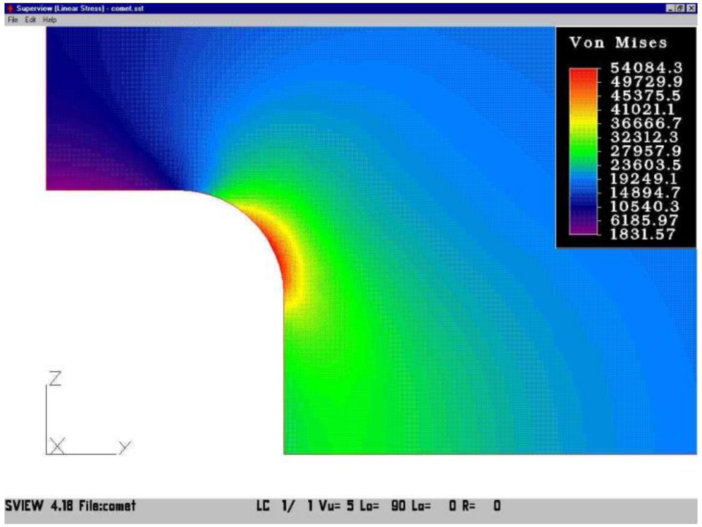


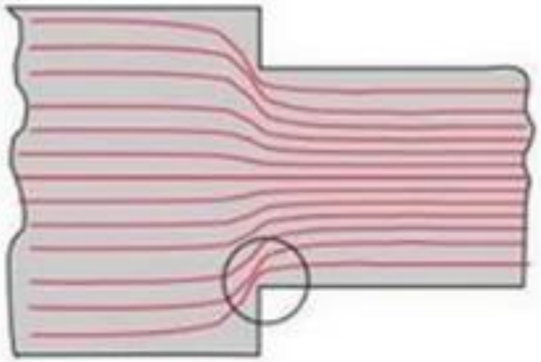
To determine the fatigue limit or endurance strength, a number of pieces are tested to determine the material characteristics. These results are plotted on an S-N curve . Whereby ‘S’ stands for stress and ‘N’ stands for number of cycles. Most steels show an S-N curve, with definite fatigue limit or endurance strength. See curve ‘i’ in fig. S-N Curves of Steel and Aluminium. The fatigue limit is usually approximately one-half of the value of the tensile strength, as measured in a static test. This means that if the Maximum stress in the stress cycles is less than this fatigue limit, fatigue should never occur. The S-N curve of non-ferrous metals and ductile materials do not show a fatigue limit. Theoretically they will fail under any load, if enough cycles are applied. See curve ‘ii’ in fig. ‘S-N Curves of Steel and Aluminium’.



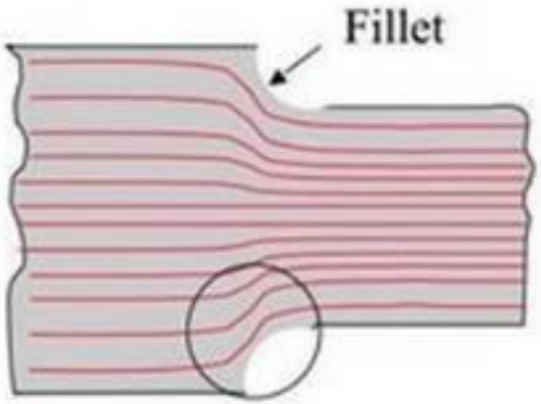
Prevention of Fatigue

- Hardening; fatigue cracks form and initiate on the surface therefore hardened surfaces (by means of heat treatment or cold work) will increase the fatigue limit.
- Smooth surface; scratches on the surface of a component can lead to stress concentrations from which fatigue cracks can originate. - Smooth design; sharp edges and notches in a component result in local high stress concentrations from which fatigue cracks can originate.
- Corrosion protection; corrosion-fatigue cracks initiate at the surface of a metal. Surface treatments like plating, cladding, nitriding and shot peening improve the material’s resistance to this phenomenon. - Reduce vibrations in constructions. Aircraft structures and components are subjected to fluctuating or alternating cycles of stress. Following the Comet aircraft pressure cabin failure in 1951, there has been an airworthiness requirement, for certification of “new” aircraft, to undergo a Full Scale Fatigue Test of an airframe, to destruction





Abrupt change
Stress "flow lines" crowd
High stress concentration



Smoother change
"Flow lines" less crowded
Lower stress concentration

Diffusion in metals

Substitution of one atoms by another in a solid body caused by their motion is called DIFFUSION.
Elementary act of diffusion – is atom jump on a distance close to the period of the lattice.

Types of diffusion in metals
(i) Inter Diffusion: This is observed in binary metal alloys such as the Cu-Ni system.
(ii) Volume Diffusion: This type of diffusion is caused due to atomic movement in bulk in materials.
(iii) Grain Boundary Diffusion: This type of diffusion is caused due to atomic movement along the grain boundaries alone.
(iv) Surface Diffusion: This type of diffusion is caused due to atomic movement along the surface of a phase.

The motion of atoms in their own crystalline lattice if the gradient of concentrations is absent is called self diffusion. Diffusion of impurity or alloying atoms if the concentration gradient is present is called heterodiffusion.
In both cases diffusion is possible if the atom posses enough energy for motion (jumping). It is called a diffusion activation energy.

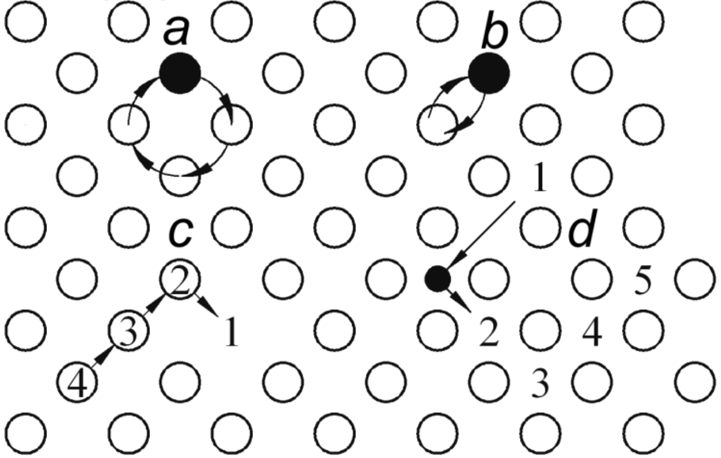
Diffusion may run according to the following mechanisms:

cyclic (a), when we have a cyclic motion of a group of atoms;

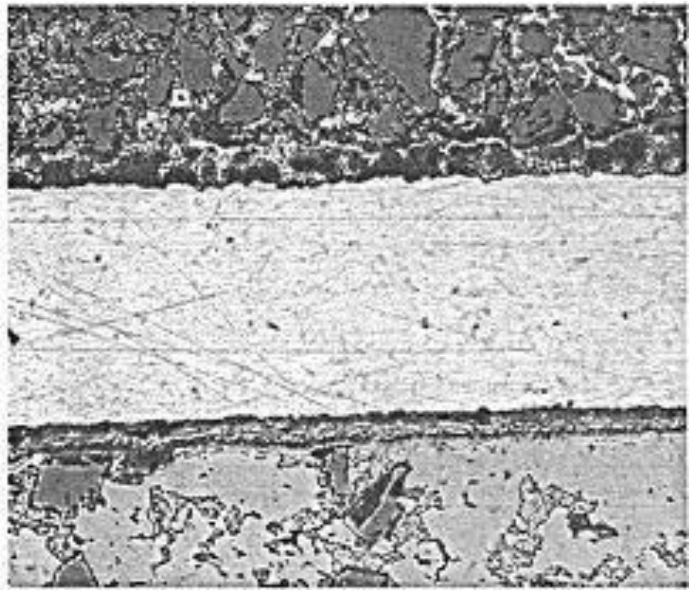
exchange (b), when two neighboring atoms change their positions

vacancy (c), the most essential for metals, when the atom 2 “closes” the vacancy 1, and new vacancy is “closed” by atom 3;

interstitial (d), which is essential for atoms with small radius. The atom 1 step by step may occupy positions 2, 3, 4, 5.



Diffusion processes form the base of many structural and phase transformations in metals and alloys (grain growth, recrystallization, separation, coagulation and dissolving of dispersed particles etc.)



Optical Microscopy

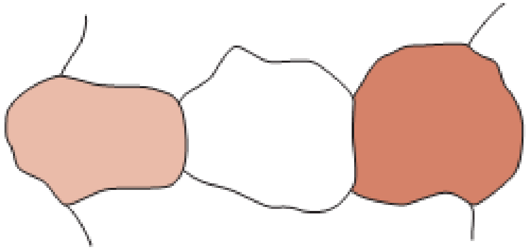
With optical microscopy, the light microscope is used to study the microstructure; optical and illumination systems are its basic elements.

For materials that are opaque to visible light (all metals and many ceramics and polymers), only the surface is subject to observation, and the light microscope must be used in a reflecting mode.

Contrasts in the image produced result from differences in reflectivity of the various regions of the microstructure. Investigations of this type are often termed *metallographic,* since metals were first examined using this technique. Normally, careful and meticulous surface preparations are necessary to reveal the important details of the microstructure. The specimen surface must first be ground and polished to a smooth and mirrorlike finish. This is accomplished by using successively finer abrasive papers and powders. The microstructure is revealed by a surface treatment using an appropriate chemical reagent in a procedure termed *etching*. The chemical reactivity of the grains of some single-phase materials depends on crystallographic orientation. Consequently, in a polycrystalline specimen, etching characteristics vary from grain to grain.

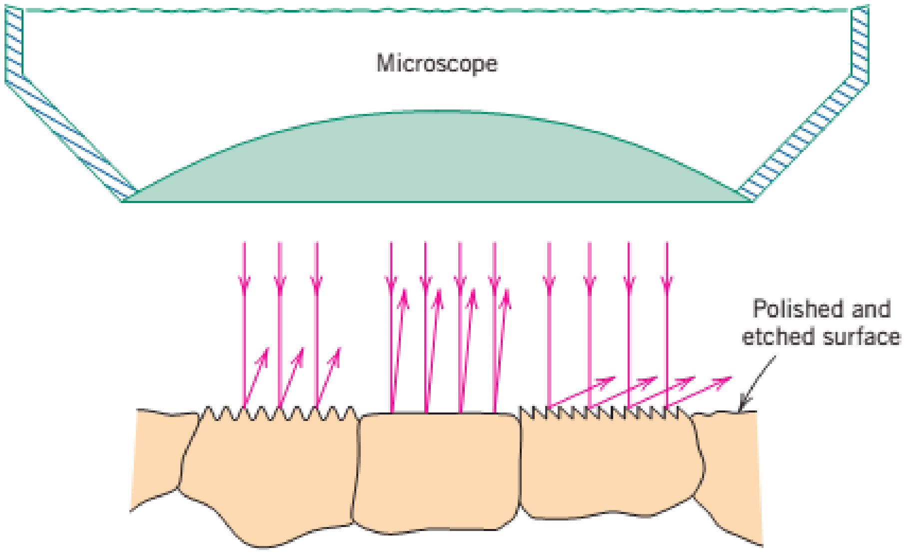
Normally incident light is reflected by three etched surface grains, each having a different orientation.

The surface structure as it might appear when viewedwith the microscope; the luster or texture of each grain depends on its reflectance properties.



(a)

(*a*) Polished and etched grains as they might appear when viewed with an optical microscope.

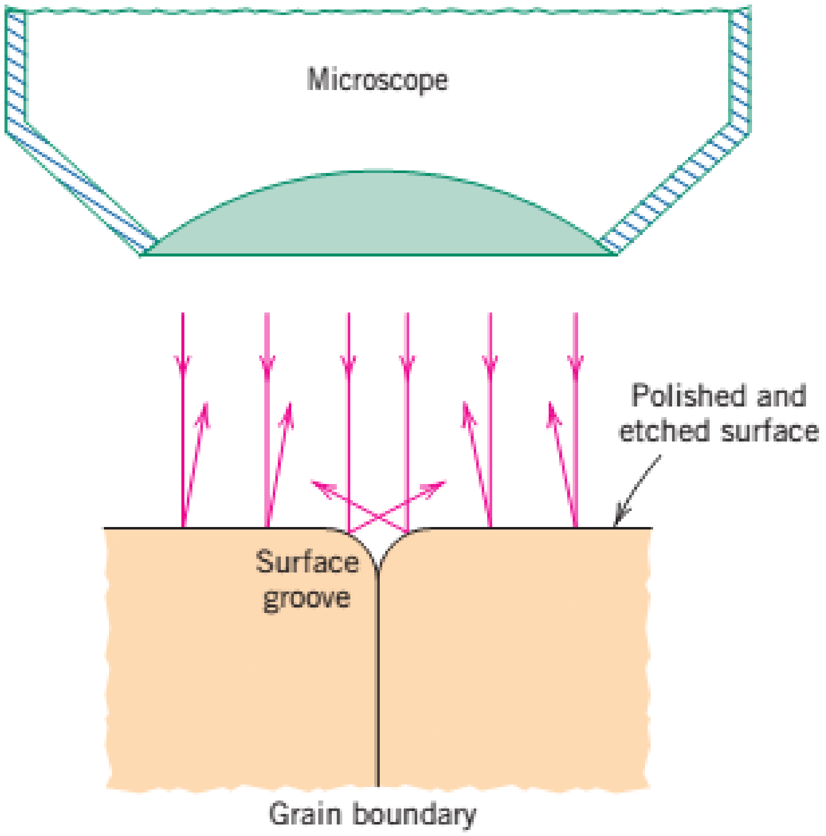


(b)

(*b*) Section taken through these grains showing how the etching characteristics and resulting surface texture vary from grain to grain because of differences in crystallographic orientation.

Also, small grooves form along grain boundaries as a consequence of etching. Since atoms along grain boundary regions are more chemically active, they dissolve at a greater rate than those within the grains. These grooves become discernible when viewed under a microscope because they reflect light at an angle different from that of the grains themselves; this effect is displayed in Figures

Photomicrograph of a polycrystalline specimen in which the grain boundary grooves are clearly visible as dark lines. When the microstructure of a two-phase alloy is to be examined, an etchant is often chosen that produces a different texture for each phase so that the different phases may be distinguished from each other.

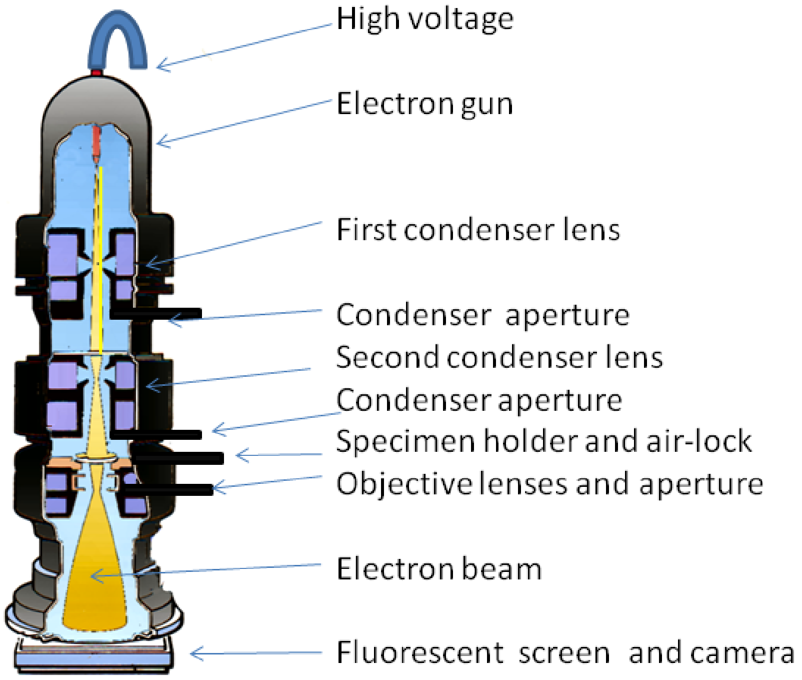


Section of a grain boundary and its surface groove produced by etching; the light reflection characteristics in the vicinity of the groove are also shown

Electron Microscopy

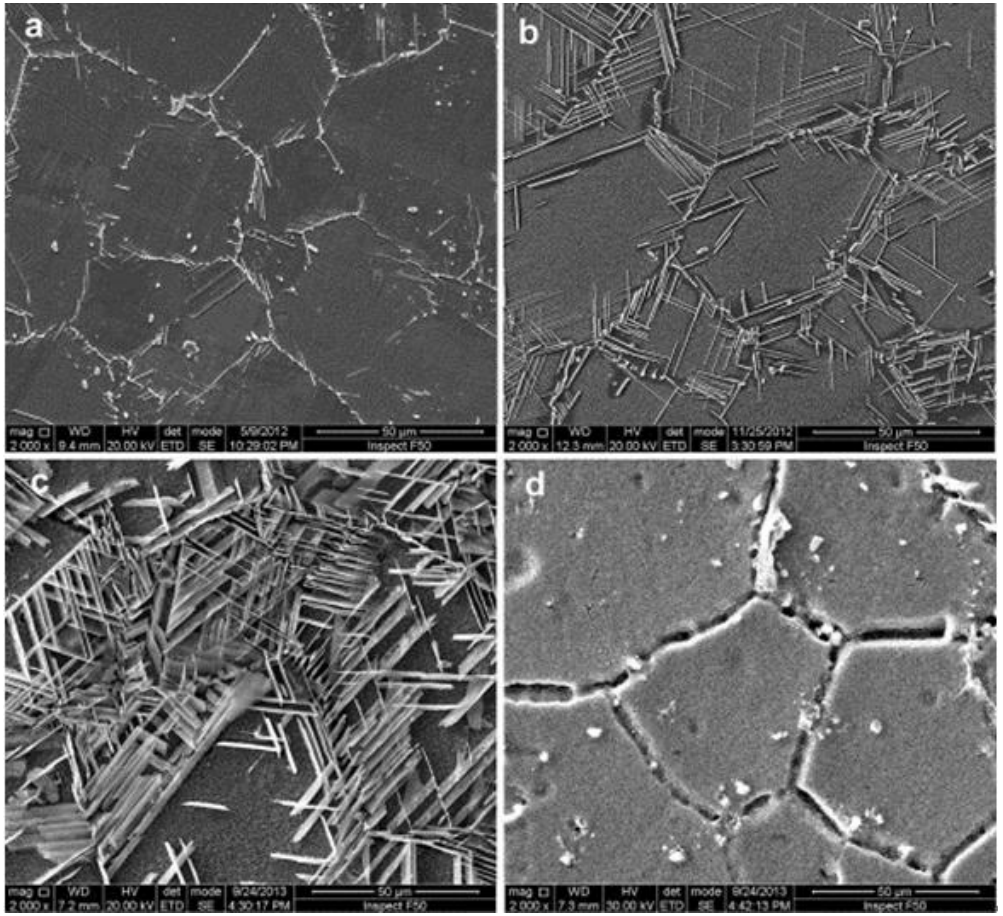
The upper limit to the magnification possible with an optical microscope is approximately 2000 times. Consequently, some structural elements are too fine or small to permit observation using optical microscopy. Under such circumstances the electron microscope, which is capable of much higher magnifications, may be employed.

An image of the structure under investigation is formed using beams of electrons instead of light radiation. According to quantum mechanics, a high-velocity electron will become wave-like, having a wavelength that is inversely proportional to its velocity. When accelerated across large voltages, electrons can be made to have wavelengths on the order of 0.003 nm (3 pm). High magnifications and resolving powers of these microscopes are consequences of the short wavelengths of electron beams. The electron beam is focused and the image formed with magnetic lenses; otherwise the geometry of the microscope components is essentially the same as with optical systems. Both transmission and reflection beam modes of operation are possible for electron microscopes.



Transmission Electron Microscope

2. ALLOY THEORY



INTRODUCTION

Metals in actual commercial use are almost exclusively alloys, and not pure metals, since it is possible for the design engineer to realize an infinite variety of physical properties in the product by varying the metallic composition of the alloy. A homogeneous mixture of two or more metals or a metal and a non-metal when fused together at a certain temperature forms a new metal after solidification, termed as an alloy.

Alloys are normally harder than their components, less ductile and may have a much lower conductivity, whereas the highly purified single crystal of a metal is very soft and malleable, with high electrical conductivity. This is why pure metals are used only for specific applications. The alloy is usually more corrosion resistant endless affected by atmospheric conditions. The conductivity of an alloy varies with the degree of order of the alloy and the hardness varies with the particular heat treatment

The elements of alloy theory

Alloy systems

Pure substances are seldom used as constructional or special porpoise materials. The majority of materials used for engineering applications are some forms of an alloy. An alloy – is a mixture or a solid solution of two or more elements (called components), the major of which is a metal. There are three basic forms of an alloy: solid solution, chemical compounds and mechanical mixtures.

The improvement in the properties of an alloy system depends upon the following factors:

(i) Manner in which the two or more metals are mixed with each other.

(ii) The percentage of different alloying metals/or elements.

(iii) Temperature at which these are cooled, etc.

It is possible that two or more metals may be soluble in each other in liquid state but may or may not be soluble in each other in solid state. It is possible that they may retain their identity even if they are soluble in liquid state, e.g. cadmium and bismuth are soluble in each other in liquid state but insoluble in each other in the solid state. It is also possible that the two or more metals may be soluble in each other in liquid as well as solid state, e.g. copper and nickel are soluble in each other in the liquid as well as in solid state. Obviously, one cannot distinguish copper from nickel. When an alloy is in a liquid state the atoms of the constituent are distributed randomly through the liquid. When solidification takes place, there appears number of possibilities.

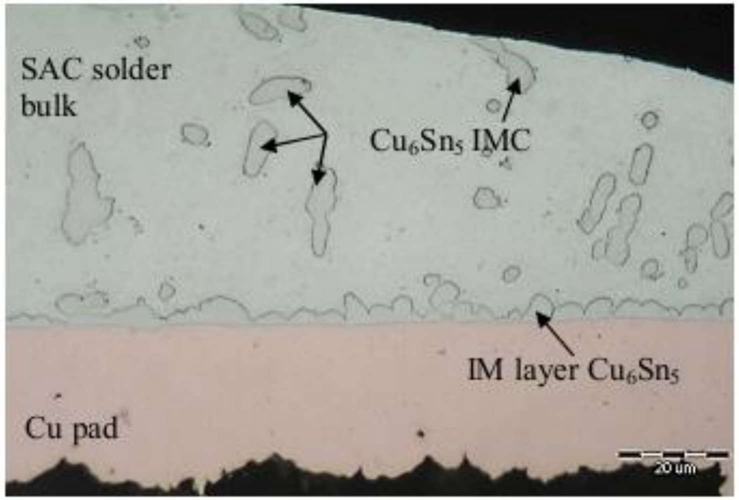
A number of different types of solutions may form, as follows:

(a) Simple Eutectic Type In this case the two components of a alloy system (binary) are soluble in liquid state but separate out in the solid state, each maintaining its own separate identity. In the solid state, the two components are said to be insoluble in each other. The solution is called *eutectic type*.

(b) Solid Solution Type When the two components of a binary alloy remain completely mixed in each other both in liquid and solid state, the two components are said to be soluble in each other and a different type of solution may be formed. It is called a solid solution.

(c) Combination Type On solidifying, the two components of a binary alloy may show limited solubility in each other. This type of solution combines characteristics of both components.

(d) Inter-metallic Compounds It is observed that the elements may combine to form inter-metallic compounds on solidification, when their affinity is great. These types of compounds may find place in between the solid solution and chemical compound. A familiar example is of copper-zinc system. When the solutility, of copper in zinc is exceeded, a zinc rich -phase appears with the Cu-rich -phase. In general, inter-metallic compounds are hard and brittle and can be used as bearing metals. These compounds wear resistant pads with a low co-efficient of friction, set in a matrix of a tough solid solution.



Ssolid solution

A solid solution forms when, as the solute atoms are added to the host material, the crystal structure is maintained, and no new structures are formed. In other words, when elements completely dissolve in each other in liquid and or solid state the resulting phase is called *solid solution*.

Solid solutions form readily when solvent and solute atoms have similar sizes and electron structures, so that it is compositionally or chemically homogeneous and the component atoms of the elements cannot be distinguished physically or separated mechanically. There is a homogeneous distribution of the constituents in the solid state so as to form a single phase or solid solution.

There are three main types of solid solutions: substitutional, interstitial and subtractional.

(a) Substitutional Solid Solution When the two metals in solid solution form a single face centred cubic lattice, i.e., in general solute or impurity atoms replace or substitute for the host atoms, is called as substitutional solid solution.

One may also define solid solutions as crystalline phases of a variable composition. Atoms of a solute *B* can be arranged in the crystal lattice of a solvent *A* either by substituting for some atoms of the latter in the crystal lattice or by occuping the interatomic spaces between atoms, or interstices. We may note that the atoms of the two metals be of almost same size, i.e., the difference in atomic radii between the two atom types be less than about 15%. Otherwise the solute atoms will create substantial lattice distortion and a new phase will form.

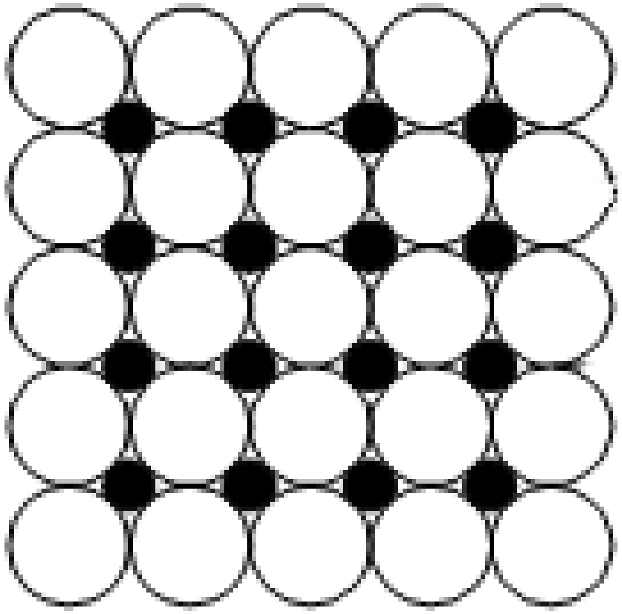
For appreciable solid solubility the crystal structures for metals of both atoms must be same. If one element has more electropositivity and the other more electronegativity, then there is greater likelihood that they will form an intermetallic compound instead of a substitutional solid solution. It is also observed that other factors being equal, i.e. atomic size, crystal structure and electronegativity, a metal will have more of a tendency to dissolve another metal of higher valency than one of a lower valency. A familiar example of substitutional solid solution is found for copper and nickel to form monel. These two elements are completely soluble in another at all proportions.

Brass, an alloy of copper and zinc, is another example, which forms solid solutions most readily as the atoms of these two elements have similar sizes and electronic structure unlimited solubility in the solid state can be observed in copper-gold, and germanium-silicon alloys. Polymorphous metals may possess unlimited solubility within a single modification of the space lattice. For example, Fe can form a continuous series of solid solutions with Cr (BCC lattices) and Fe, a continuous series of solid solutions with Ni (FCC lattices).

Solid solutions are usually less plastic (except for copper-based solid solutions) and always harder and stronger than pure metals.

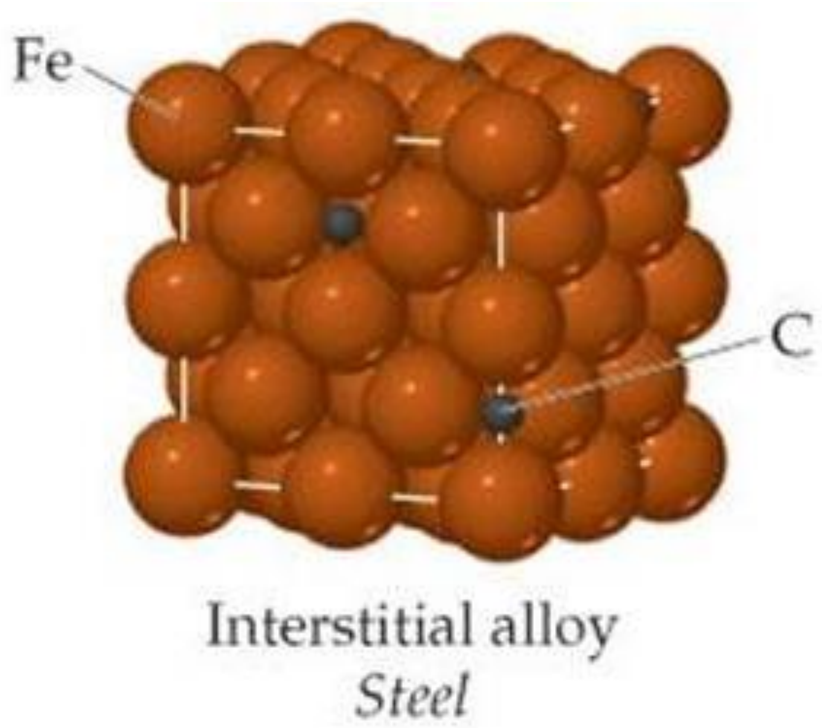
Interstitial Solid Solutions These can form, for instance, on melting together transition metals and non-metals with a small atomic radius (*H*, *N*, *C* or *B*).

The possibility of obtaining an interstitial solution is mainly determined by the size factor; i.e., the size of a solute atom must be equal to or slightly smaller than the size of an interstitial void. Interstitial solid solutions always have a limited solubility and form preferably in solvents having an HCP or FCC lattice with interstices of a radius of 0.41 *R*, where *R* is the radius of a solvent atom. In BCC lattices, the solubility is low, since the size of interstices does not exceed 0.29 *R*.

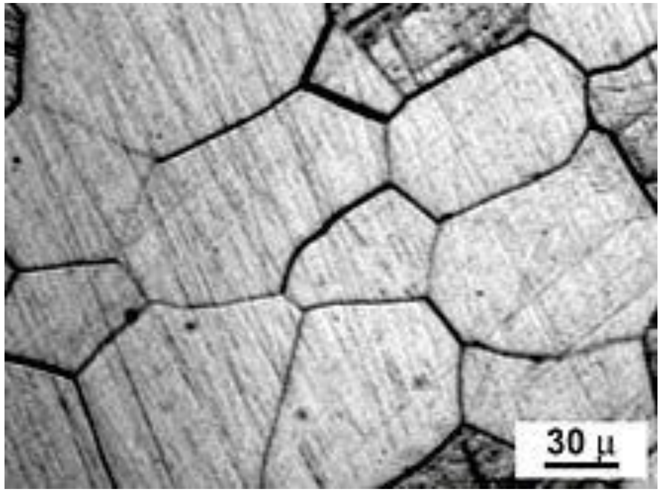


The schematic of interstitial solid solution

Examples of interstitial solid solutions of commercial application are solid solution of carbon in Fe, and Fe , Fe*r*, which has an FCC lattice, can dissolve upto 2.14% (by mass) of carbon; Fe (BCC lattice) does not practically dissolve carbon, the maximum solubility being around 0.02 (by mass).



Other elements like: nitrogen for maintaining stainless steel in austenitic condition for nitriding condition and hydrogen when introduced into steels during welding operations, acid cleaning and plating results in hydrogen embrittlement and causes a sharp decrease in ductility. Lattice distortions appearing on the formation of interstitial solid solutions are stronger than those in the substitutional solid solutions, because of which the properties of alloys can be changed more drastically.



Solid solution microstructure

As the concentration of a solute in a solid solution increases, this increases noticeably the electric resistance, coercive force, hardness and strength, but decreases the ductility and toughness. Interstitial solid solutions usually have very limited solubility and are normally considered of secondary importance.

Alloys containing more than two elements can form either substitutional or interstitial solution. For example, when iron is melted together with manganese and carbon, manganese and iron form substitutional solid solution while carbon and iron, interstitial solid solution. In conclusion we can say that solid solutions are crystals whose properties are close to those of the solvent, since they retain the same crystal lattice and type of bond. In particular, solid solutions of metals are distinguished by high plasticity: they are readily deformable in the hot state and many of them, in the cold state. Solid solutions are the bases of most commercial structural and special alloys.

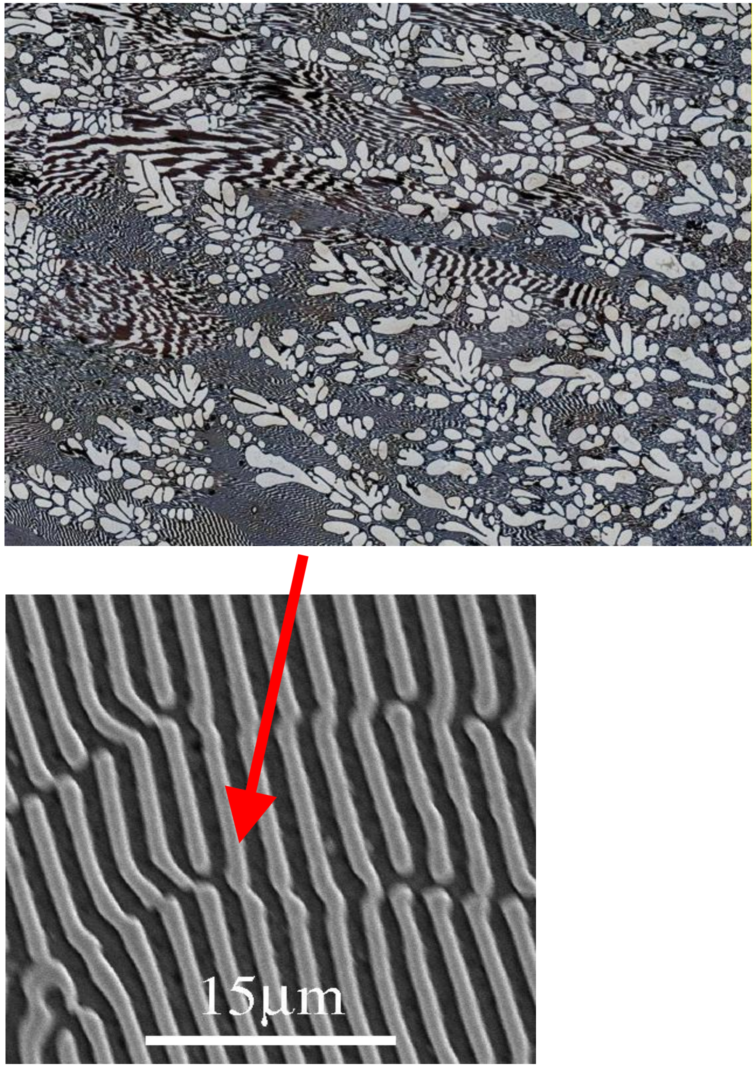
Chemical compounds

Chemical compounds are composed of two or more elements, producing a new phase with another composition, crystalline structure and properties. There are three basic groups of these compounds: chemical compounds formed according to normal valences law, intermetallic and electronic compounds, which structure is determined by the size of forming atoms. Solid solution and chemical compounds are single phase structures.

Mechanical mixture

Mechanical mixture consists of two or more solid phases or components, which don’t interact with each other and do not form solid solution. They crystallize independently. Typical micrograph of mechanical mixture (eutectic alloy)

The eutectoid structure, frequently lamellar, is produced by precipitation from the solid solution. The crystal structure of new phase is known as the *Widmanstatten structure*. The eutectoid reaction occurs in Fe-C diagram in which austenite (a solid solution C in - Fe) is decomposed into pearlite. The most important example of the use of this reaction is heat treatment of steel.



The microstructure of mechanical mixture

Phase diagrams

The characteristic of any series of alloys can be easily studied by using alloy *phase diagrams*. A phase diagram is a graphical description of the kinds and amounts of the phases that can be expected in an alloy as a function of its composition, temperature, and pressure, when it has reached thermodynamic equilibrium.

The phases may be liquid, vapour or solid with various ordered and disordered crystal structures. A phase diagram does not provide information about how rapidly equilibrium can be reached. When a phase diagram is determined experimentally, it is necessary not only to find out what phases are present but also to assure that the alloy is in the stable equilibrium state.

Equilibrium is reached when the Gibbs free energy of the system has reached its lowest possible value. The thermodynamic principle of minimum Gibbs free energy imposes restrictions on the possible forms a phase diagram can take, and even a complicated diagram with many phases is composed of only a few geometrical features.

Definitions

System: A system may be composed of solids, liquids, gases or their combinations and may have metals and non-metals separately or in any combination. It is explained as the whole complex of phases of one or several components at different pressures and compositions. A system is so isolated from its surroundings that it is unaffected by solids, liquids, gases or their combinations and is subjected to the change in the overall composition, temperature, pressure or total volume, only to the extent permitted by the investigator..

Components: they are the substances, either chemical elements or chemical compounds making a system. A pure metal is called a one-component system, an alloy of two metals is called two component or binary system.

Phase: It is a homogeneous portion of a system that has uniform physical and chemical characteristics. The number of phases in a system is the number of different substances that exist in it.

Much of the information about the control of microstructure or phase structure of a particular alloy system is properly displayed in phase diagram.

Phase Equilibrium: The state of a system where the phase characteristics remain constant over indefinite time periods.

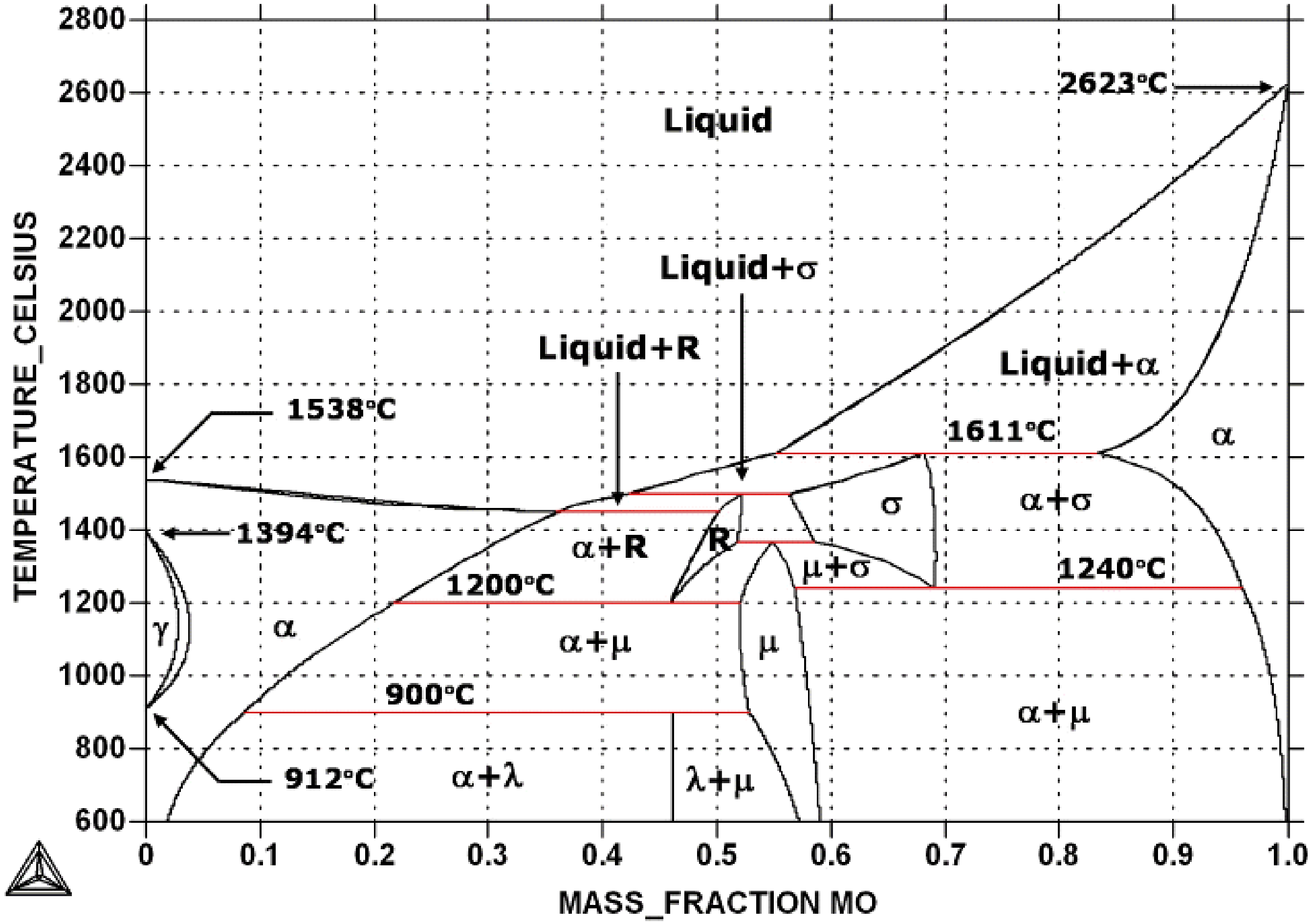
Phase Transformation: A change in the number and/or character of the phases

BINARY PHASE DIAGRAMS

Another type of extremely common phase diagram is one in which temperature and composition are variable parameters, and pressure is held constant - normally 1 atm.

There are several different varieties; in the present discussion, we will concern ourselves with binary alloys - those that contain two components. If more than two components are present, phase diagrams become extremely complicated and difficult to represent. An explanation of the principles governing and the interpretation of phase diagrams can be demonstrated using binary alloys even though most alloys contain more than two components.

Binary phase diagrams are maps that represent the relationships between temperature and the compositions and quantities of phases at equilibrium, which influence the microstructure of an alloy. Many microstructures develop from phase transformations, the changes that occur when the temperature is altered (ordinarily upon cooling). This may involve the transition from one phase to another, or the appearance or disappearance of a phase. Binary phase diagrams are helpful in predicting phase transformations and the resulting microstructures, which may have equilibrium or nonequilibrium character.



2-component phase diagram (Fe-Mo system)

Most phase diagrams are prepared by using slow cooling conditions whereby phases are in equilibrium. One can get following important informations from the phase diagrams

(a) Phases at different composition and temperature

(b) Equilibrium solubility of one element or compound in another element.

(c) Melting points of different phases in an alloy.

(d) Temperature of solidification or range of solidification of an alloy.

(v) Phase Equilibrium: The state of a system where the phase characteristics remain constant over indefinite time periods. At equilibrium the free energy is a minimum. In an equilibrium diagram, liquid is one phase and solid solution is another phase.

(vi) Phase Transformation: A change in the number and/or character of the phases that constitute the microstructure of an alloy.

Gibbs phase rule

This expresses mathematically the general relationships for the existence of stable phases corresponding to the equilibrium conditions. It enables us to predict and check the processes that occur in alloys during heating or cooling. Using this rule, it is possible to determine whether the solidification process takes place at a constant temperature or within a certain temperature interval; it can also indicate the number of phases that can exist simultaneously in a system. The phase rule enunciated by J.W. Gibbs relating number of phases P, number of components C, and number of degrees of freedom F has a simple form:

$$P + F = C + n \quad (1)$$

$$P + F = C + 2$$

n = number of external factors = 2 (temperature and pressure) In applying the phase rule to metal systems the effect of pressure is neglected, leaving only one variable factor,— temperature.

Equation (1) reduces to

$$F = C + 1 - P$$

The number of degrees of freedom is essentially the number of independent variables, both internal and external ones, which can be changed without changing the number of phases in equilibrium.

The number of indepenent variables cannot be more than the number of variables, i.e.

$$F = C - P + 2 \leq P(C - 1) + 2$$

where $P(C - 1)$ denotes the total number of compositional variables when P phases are there in the system. Including the two external variables (pressure and temperature), the total number of variables is $P(C–1)+2$.

In equilibrium all factors have definite values, hence the degrees of freedom cannot be less than zero, $C–P+1 \geq 0$, then $P \leq C+1$

Obviously, the number of phases in a system cannot exceed the number of components plus one.

The components of a system may be elements, ions or compounds. The components refer to the independent chemical species that comprise the system. In the ice-steam system, the component is H_2O, in the Cu-Ni system the components are the elements Cu and Ni, whereas in the Al_2O_3-Cr_2O_3 system, one can take the two oxides to be components. In the Fe-C system, although Fe and graphite can be taken as components, but it may be convenient to choose Fe and Fe3C (iron carbide) as the components.

As follows from the phase rule, the number of phases existing simultaneously in a binary system cannot be more than three. These three phases can only exist at a definite phase composition and a definite temperature. If the number of phases in a binary system turns out to be more than three, this means that either the alloy is not in the equilibrium state or the number of phases and constituents has been determined incorrectly. In a ternary system no more than four phases may be in equilibrium. When only one phase is present in a system, the degrees of freedom are equal to the total variables, with the increase in number of phases, the degrees of freedom decrease.

The degree of freedom cannot be less than zero. Obviously, we have an upper limit to the number of phases that can exist in equilibrium in a given system.

At solidification temperature, a pure metal is a one-component system consisting of two phases of identical composition

$$F = 1 + 2 - 2 = 0$$

Clearly, the number of phases and number of degrees of freedom equals zero, i.e. $F = 0$. This is known as *non-variant equilibrium*.

When the number of phases is less than the maximum possible number by one, the number of degrees of freedom will also increase by one ($F = 1$). Such type of system is called as *monovariant*.

An alloy of two metals is a two-phase and two-component system at solidification, $F = 1$.

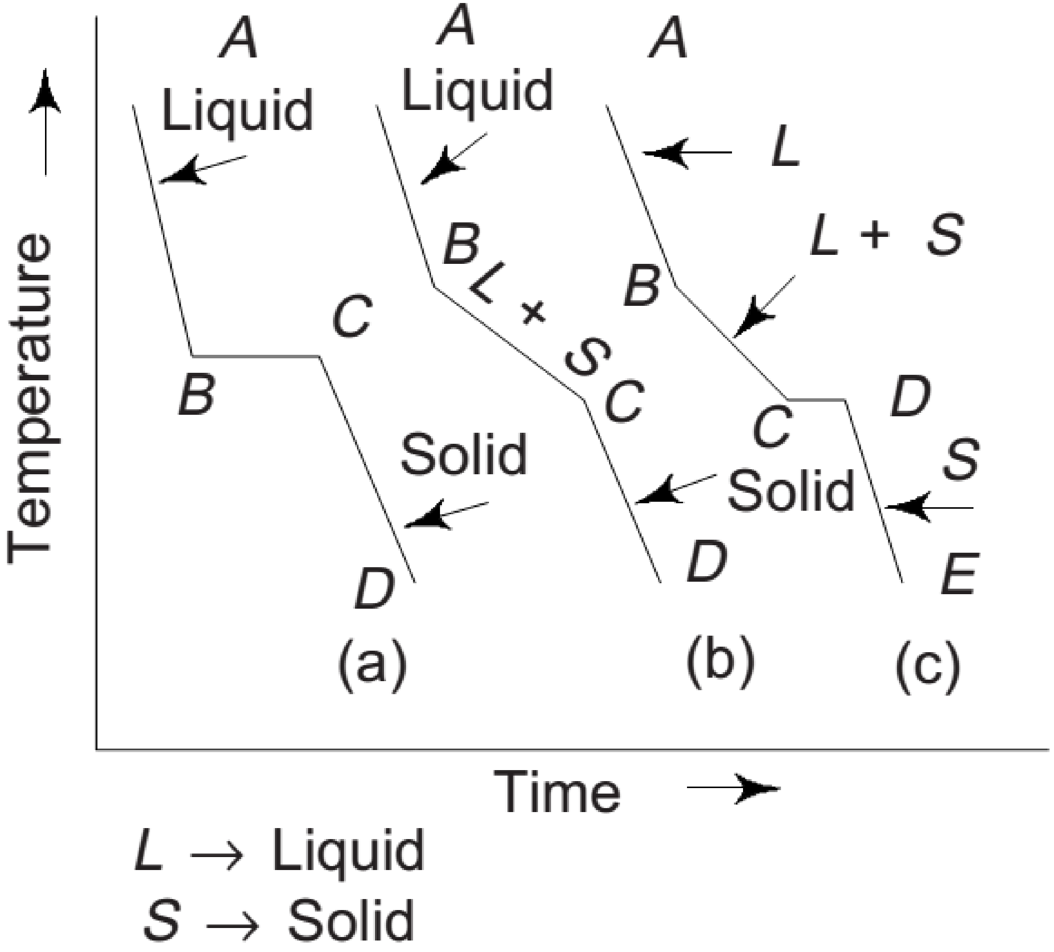
When $F = 2$, the system is said to be a *divariant*. Obviously, a system may be in equilibrium at different temperatures and concentrations. One can represent all transformations occurring in alloys and depending on temperature and concentration ($C = 2$) by equilibrium diagrams. The equilibrium diagrams are plotted with concentration as the abscissa and temperature as ordinate.

COOLING CURVES

It is interesting to study the manner in which temperature changes with time as the liquid metal solidifies. Figure shows a cooling curve which is distinctly divided into two portions while exhibiting the fall of temperature of time, the cooling curve exhibit that the temperature remains practically constant over a period of time.

This constant temperature is called as the point of arrest. The solidification occurs during temperature arrest. During this period, heat is still lost from the mass of metal but release of kinetic energy compensates the heat loss whereby temperature remains constant. The released heat at constant temperature is called the *latent heat*. Due to this, at certain stages the fall in temperature of the metal or alloy is totally arrested for a specific time. Such points are termed *critical points*. One can determine the critical points by the abrupt inflection of curves due to thermal effects in transformations. Following three types of cooling curves are commonly used in plotting the phase diagrams.

(i) Curve (a): Applying Eq. 1 under constant pressure, for region *AB* when *P* = 1, *C* = 1, *F* = 1, i.e. system has single degree of freedom (called univariant). Obviously, only variant that changes is temperature. Between *B* and *C* both liquid and solid phases are present, *P* = 2, *C* = 1 so that *F* = 0, i.e. system has no degree of freedom (called as *non-variant*). Obviously, temperature remains constant (pressure is already constant) and the mass between *B* and *C* is *marshy* (partly liquid and partly solid). On further cooling from *C* to *D* the system reaches room temperature. The slips of lines *AB* and *CD* indicate specific heat of liquid and solid metals, respectively. There is also another way to plot the cooling curve. One can plot the temperature against time taken to cool through a specific temperature interval (say 5°C) Such cooling curves are called derived or inverse rate curve.


Temperature
A
Liquid
B
C
Solid
D
(a)
A
Liquid
B
L + S
C
Solid
D
(b)
A
L
L + S
B
C
D
S
E
(c)
Time
L → Liquid
S → Solid

CONSTRUCTING PHASE DIAGRAMS

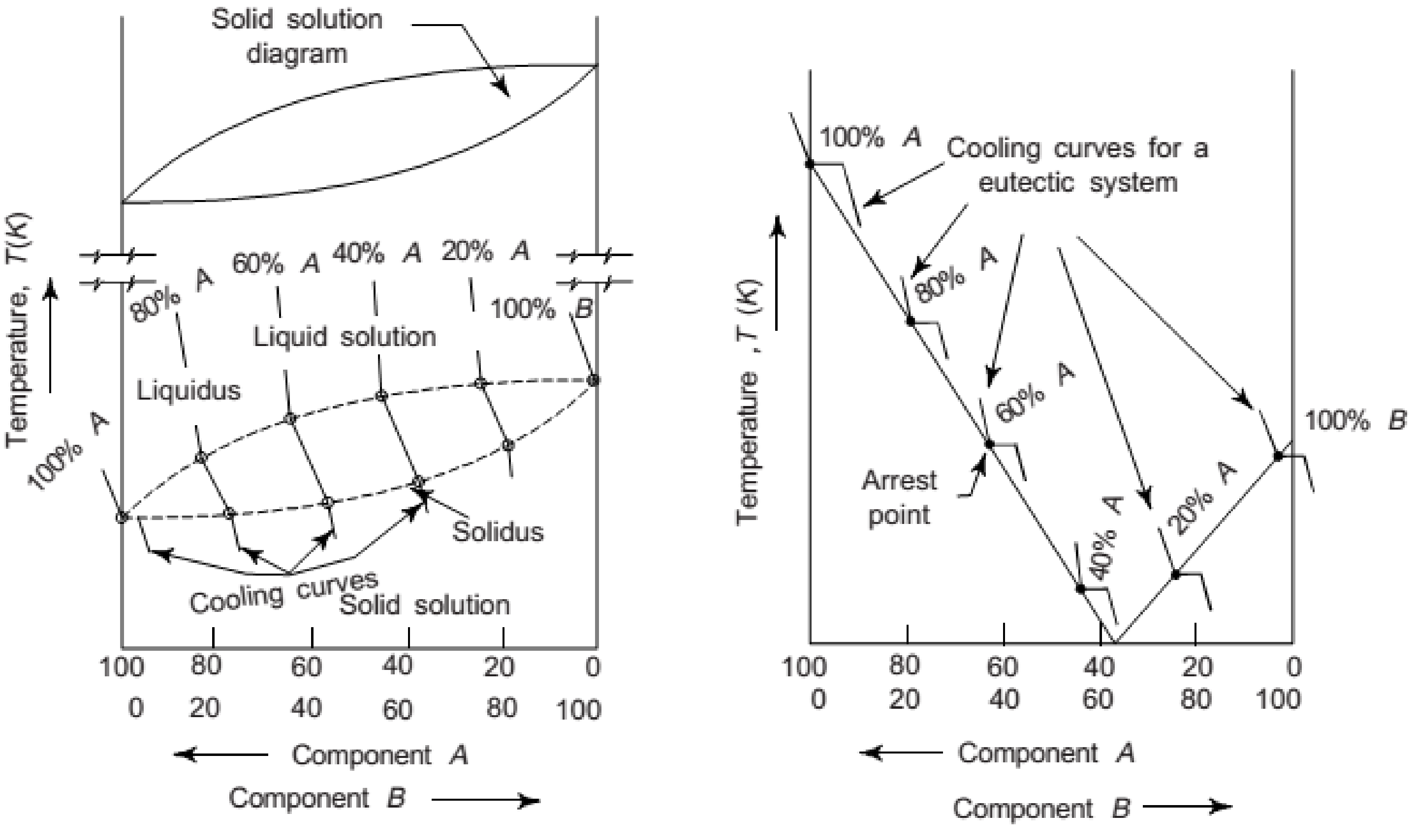
Depending upon the number of components and solubility characteristic, the phase diagrams are usually categorised as follows: *(i) Solid Solution Type:* In this case two metals are completely soluble in solid as well as in liquid state. They have the same type of lattice and similar atomic size. Copper and Nickel form an isomorphous system. *(ii) Eutectic Type:* When two metals are completely soluble in the liquid state but partly or completely insoluble in the solid state, is termed as *eutectic type*. Fe-C, Al-Mn, Pb-Sn form an eutectic system.

Construction of a phase diagram for alloys of two metals *A* and *B* in their various compositions, using the data from the cooling curves is shown in Figure below.

In order to get the actual phase diagram, the arrestment points have been joined. There is complete intersolubility in the liquid and solid phases in the diagram. The upper line corresponds to the temperature at which the alloys starts to solidify the liquids.

The lower line shows the complete solidification and is called the *solidus*. A mixture of solid and liquid exists between two lines. i.e. between *liquidus* and solidus and represents the alloys in a *semisolid* state. The figure is known as *equilibrium diagram*. To designate solid solutions in phase diagrams. Greek letters α, β, γ, δ, ε, μ etc. are commonly used.

Phase diagrams are classified on the basis of the number of components in the system. Single component systems have unitary diagrams, two component systems have binary diagrams, three component systems give rise to ternary diagrams and so on.



(a) (b)

Deriving phase diagrams from a series of cooling curves

THE LEVER RULE

This rule helps to calculate the relative proportions of solid and liquid material present in the mixture at any given temperature. The number and composition of phases can be obtained from the phase diagram. If the composition and temperature position is located within a two-phase region, things are more complex.

In a two-phase region, one can determine the relative amount of each phase that is present from the phase diagram, using a relationship known as *lever rule* (or the inverse lever rule), which is applied as follows:

(i) Construct the tie line across the two-phase region at the temperature of the alloy.
(ii) The overall alloy composition is located on the tie line.
(iii) The fraction of one phase is computed by taking the length of the line from the overall alloy composition to the phase boundary for the other phase, and dividing the total tie line-length. *(iv)* One can determine the fraction of the other phase in the same manner.

(v) In case if phase percentages are desired, each phase fraction is multiplied by 100. When the compo sition axis is scaled in weight percent; the phase fractions computed using the lever rule are *mass fractions* – the mass (or weight) of a specific phase divided by the total alloy mass (or weight).

The mass of each phase is computed from the product of each phase fraction and the total alloy mass. In order to determine the relative amounts of two phases, errect an ordinate or vertical line at a point on composition scale which gives the total composition of the alloy. The intersection of this ordinate with the given isothermal line denotes the fulcrum of a simple lever system.

It is clear that the ordinate *KL* intersects the temperature line at a point *M*. However, the relative lengths of lever arm *OM* and *MP* multiplied by the amount of phases present must balance. It is clear that the length *MP* represents the amount of liquid and the length *OM* represents the amount of solid.

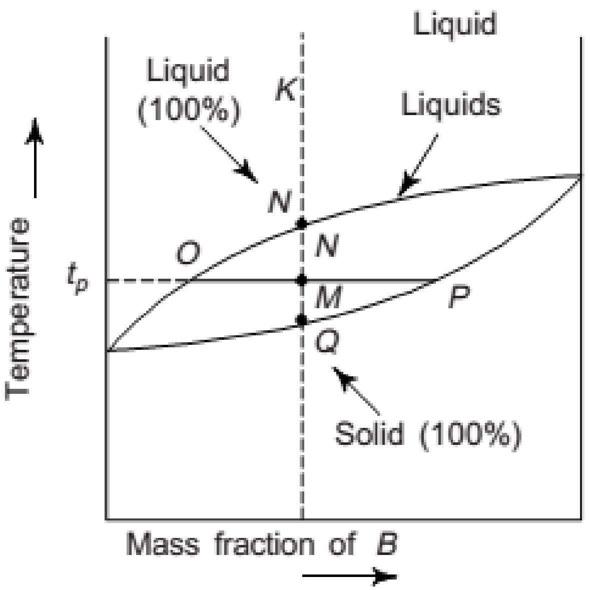
Therefore, The percentage of solid present = *OM*

$$\frac{OM}{OP} \times 100 = \frac{OP - MP}{OP} \times 100$$

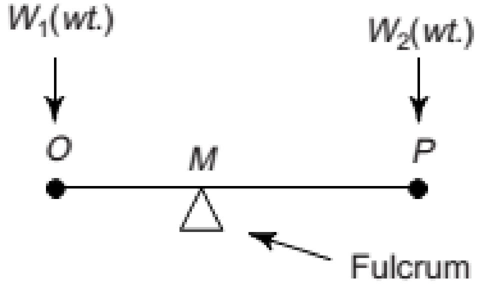
The percentage of liquid present =

$$\frac{MP}{OP} \times 100 = \frac{OP - OM}{OP} \times 100$$

From the figure, MP + OM = OP, which represents the total composition of alloy between liquids and solidus, say at temperature *t p*. The *OMP* (isothermal) can be considered a tie line since this line joins the composition of two phases in equilibrium at a specific temperature t_p



(a)



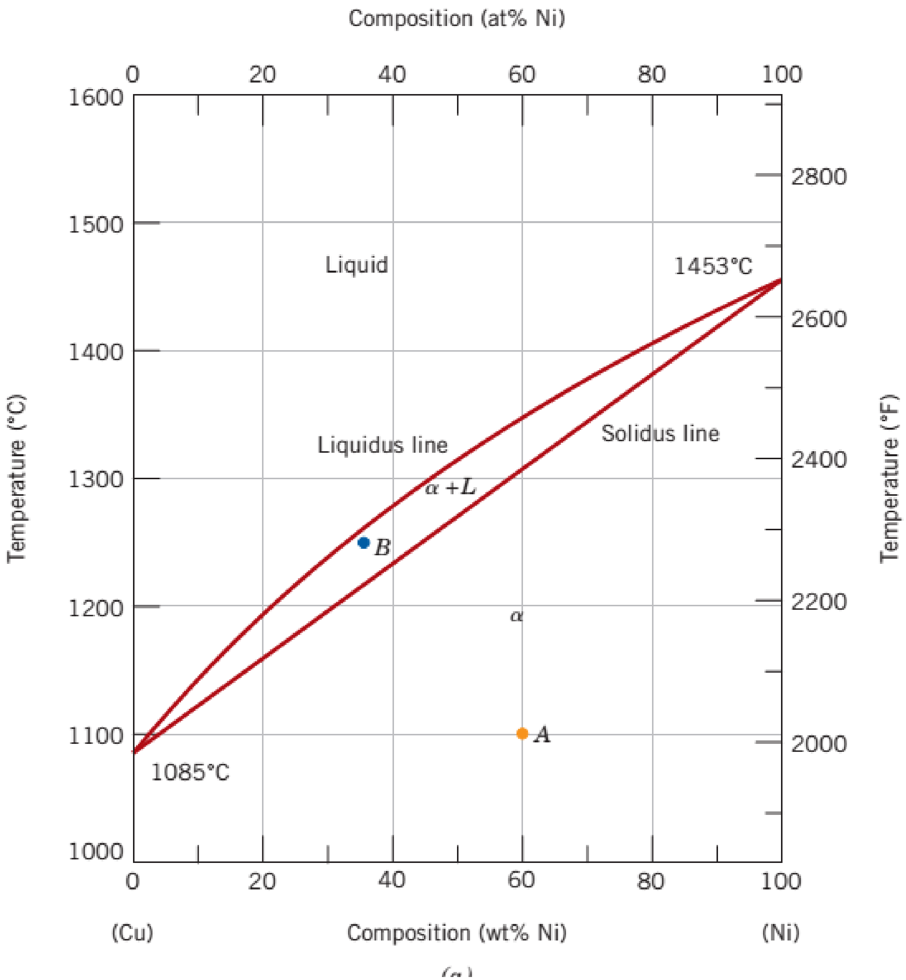
Simple lever

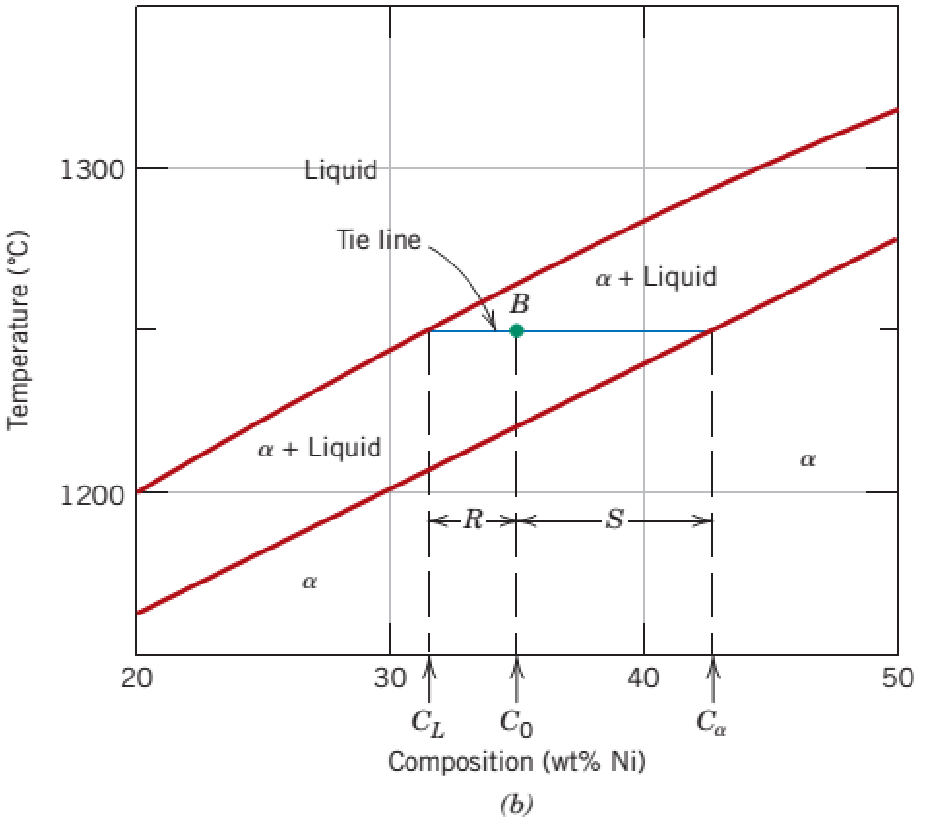
p.

4.3. Phase diagram with unlimited solubility of components in solid and liquid states

Possibly the easiest type of binary phase diagram to understand and interpret is the type that is characterized by the copper–nickel system.

Temperature is plotted along the ordinate, and the abscissa represents the composition of the alloy, in weight percent (bottom) and atom percent (top) of nickel. The composition ranges from 0 wt% Ni (100 wt% Cu) on the left horizontal extremity to 100 wt% Ni (0 wt% Cu) on the right. Three different phase regions, or fields, appear on the diagram, an alpha ( ) field, a liquid (*L*) field, and a two-phase field. Each region is defined by the phase or phases that exist over the range of temperatures and compositions delimited by the phase boundary lines. The liquid *L* is a homogeneous liquid solution composed of both copper and nickel. The phase is a substitutional solid solution consisting of both Cu and Ni atoms, and a having an FCC crystal structure. At temperatures below about copper and nickel are mutually soluble in each other in the solid state for all compositions. This complete solubility is explained by the fact that both Cu and Ni have the same crystal structure (FCC), nearly identical atomic radii and electronegativities, and similar valences. The copper–nickel system is termed **isomorphous** because of this complete liquid and solid solubility of the two components.





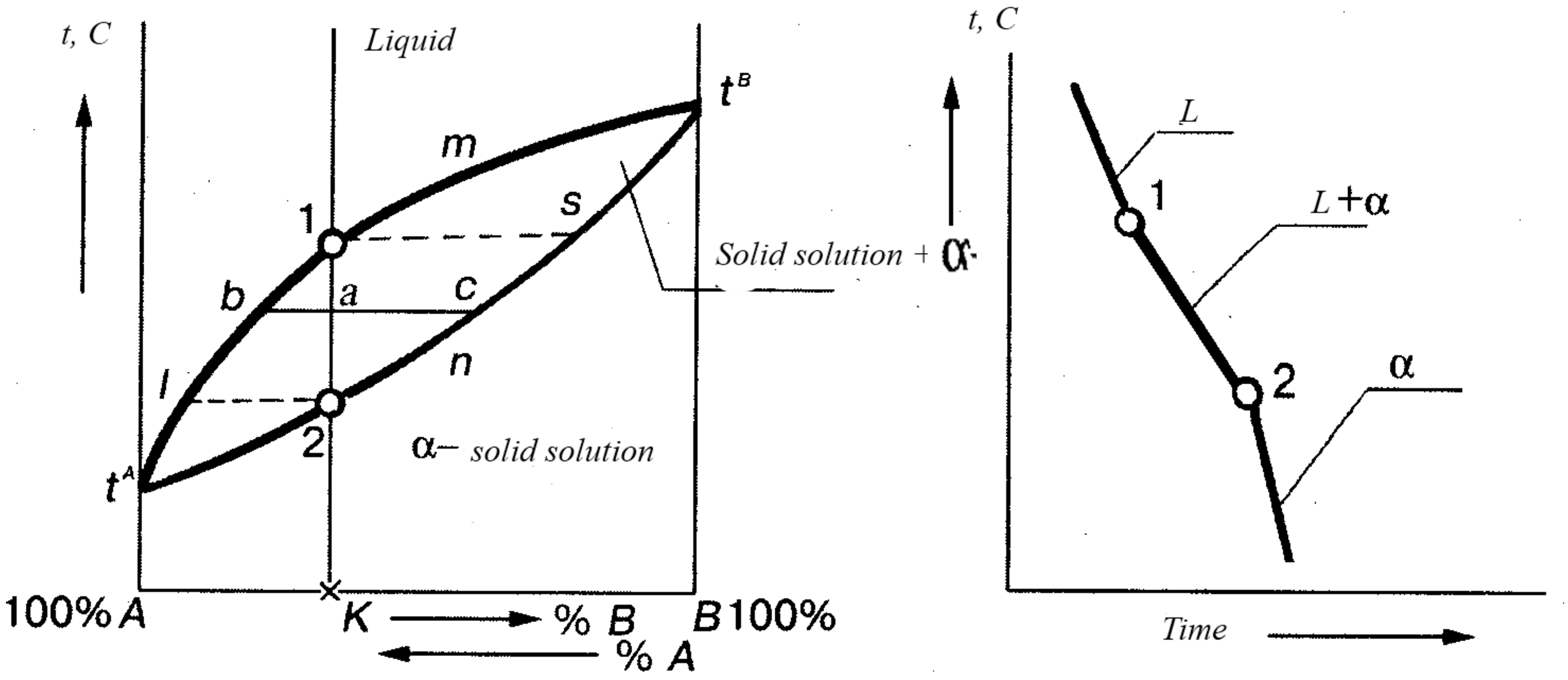
(*a*) The copper–nickel phase diagram. (*b*) A portion of the copper–nickel phase diagram for which compositions and phase amounts are determined at point *B*.

A couple of comments are in order regarding nomenclature. First, for metallic alloys, solid solutions are commonly designated by lowercase Greek letters. Furthermore, with regard to phase boundaries, the line separating the *L* and L+α phase fields is termed the *liquidus line,* as indicated in Figure; the liquid phase is present at all temperatures and compositions above this line.

The *solidus line* is located between the α and α+L regions, below which only the solid α-phase exists. For Figure above, the solidus and liquidus lines intersect at the two composition extremities; these correspond to the melting temperatures of the pure components.

For example, the melting temperatures of pure copper and nickel are 1085 and 1453 respectively. Heating pure copper corresponds to moving vertically up the left-hand temperature axis. Copper remains solid until its melting temperature is reached. The solid-to-liquid transformation takes place at the melting temperature, and no further heating is possible until this transformation has been completed. For any composition other than pure components, this melting phenomenon will occur over the range of temperatures between the solidus and liquidus lines; both solid and liquid phases will be in equilibrium within this temperature range.

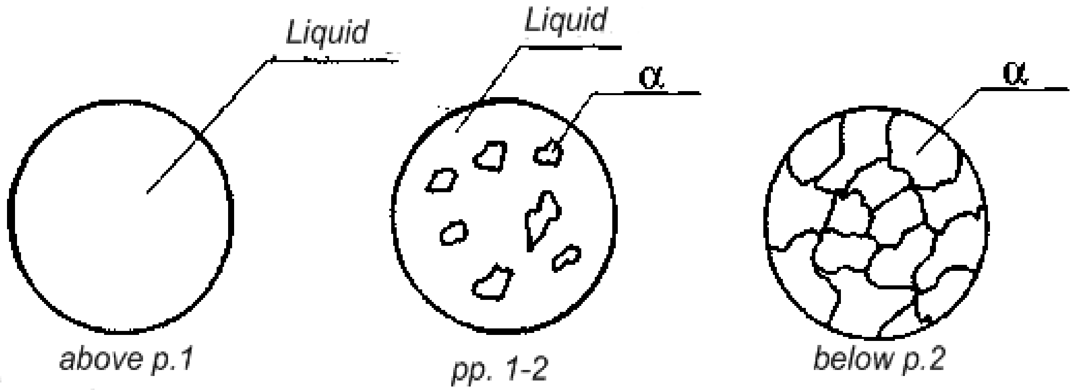
For example, upon heating an alloy of composition 50 wt% Ni–50 wt% Cu, melting begins at approximately 1280; the amount of liquid phase continuously increases with temperature until about 1320, at which the alloy is completely liquid.



Only 2 phases may exist: solid and liquid solutions

Phase diagram consists of three regions: liquid, two-phase region (L+S) liquid; and solid solution. Let’s consider an alloy with components concentration of point K.

All points of alloys crystallization form line tA n tB – solidus, and all melting point form line – tA m tB – liquidus. Between these lines liquid and α-solid solution exist simultaneously. Point 1 – is a beginning of crystallization of α-solid solution, point 2 – is the end of crystallization



As the alloy is cooled, the concentration of components in liquid and solid phases changes. To determine them the lever rule is used.

The phase mass (in %) is equal to the length of the opposite arm of the lever divided by the length of the tie line.

It consists of the stages:

1. Pass a line through the point of double-phase region (point a on 1-2 line). This line is called as tie-line (bc).
2. Projections of point b and c on the concentration axis (horisontal) shows the phase composition

So, the mass of liquid phase equals:

ac/bc*100%

The mass of solid solution is determined as follows:

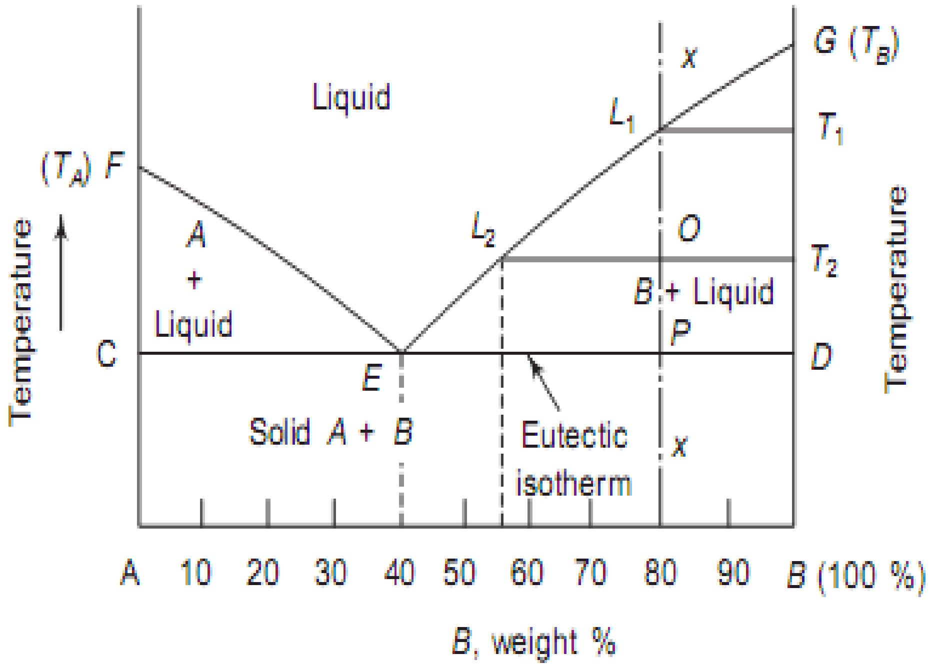
ba/bc*100%

Phase diagrams with limited solubility of components in solid state

The solubility of one metal into the other in the solid state is important criterion for the formation of alloy because the alloy is finally used in solid state.

Any two given metals may have varying solubilities. Two cases of interest are: (a) alloys of two metals which are mutually soluble in liquid but completely insoluble in solid state and (b) alloys of two metals which are mutually soluble in liquid state but partially soluble in solid. We shall now consider these cases: phase diagram with limited solubility of components in solid state and phase diagram with no solubility in solid state

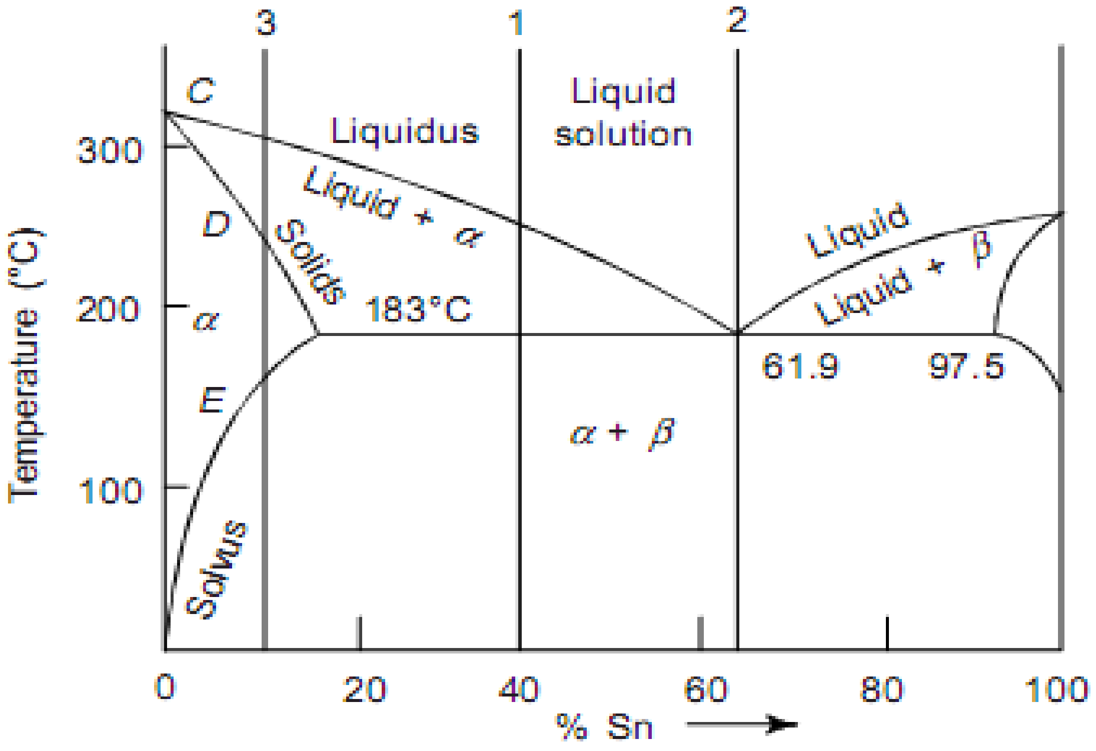
Phase diagrams with no solubility of components in solid state



Points F and G are denoting the melting points of metals A and B respectively. E shows the position of eutectic point. CED line is termed eutectic isotherm while it is also solidus. Depending upon the composition, the solidification of alloy of any composition will begin anywhere on the liquids. The temperature corresponding to eutectic point is called eutectic temperature.

Below the eutectic temperature the material is fully solid for all compositions.
The composition which remains fully liquid upto the eutectic temperature during cooling is called eutectic composition

Solidification of an alloy of eutectic type takes place at a constant temperature, called eutectic temperature, at which liquid of eutectic composition decomposes into two solid solutions. Temperatures remains constant till the transformation is completed.



Phase diagram of the system with limited solubility of components in solid state

There are certain solvent metals, which can accommodate only a certain percentage of solute metal. This results in limited solid solution. It is observed that the partial solid solubility varies tremendously with temperature and almost in every case decreases with decreasing temperatures. A eutectic is formed in some such solid solutions. It is observed that the solubility of a constituent (solute) in the other (the solvent) mainly depends upon relative size of two atoms. With the rise in temperature the distance between the atoms increases whereby the lattice is capable of absorbing greater amount of solute atoms and hence the solubility increases.

The alloy of Pb and Sn, commonly know as solders is a typical example of this type.
The phase which solidifies first is termed as α-phase while the one which separates later is termed as β-phase. For example, in the solution of Sn in Pb is referred as α while that of Pb in Sn is β. OE line shows the amount of Sn which can be dissolved in Pb at temperature below the solidus. This amount is referred as solvus. 20% of Sn can

be accommodated in Pb at 183°C. At room temperature this falls to 3%.

The rejected tin from the solid solution sets up its own lattice into which some Pb is dissolved.

IRON-CARBON PHASE DIAGRAM

Introduction

The alloys of iron and carbon are extensively used for industrial applications. These alloys gave the birth to the materials science in the state we know it today. The phase diagram of the Fe-C system is polymorphous and have both eutectic and eutectoid points and is most universal for further studying of heat treatment. Knowing the general pattern of Fe-C system alloys heat treatment, it is easy to understand the heat treatment of any other alloy.

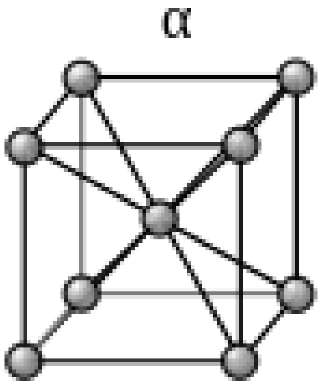
Definitions

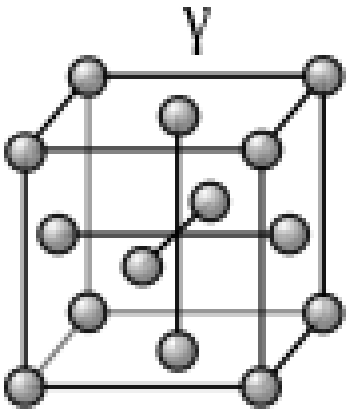
All iron-carbon alloys are divided into two major classes: steel (carbon content to 2.14%) and cast iron (with a carbon content to 6.67%).

Deep study of Fe-C diagram is a precondition for proper selection of steels and cast irons, modes and technologies of heat treatment.

The iron-carbon phase diagram is universal, it can help you learn all kinds of heat treatment and phase transformations that are inherent for structural materials.

From room temperature to 910°C pure iron has a BCC structure and is called alpha (α) iron (Feα). It is highly ferromagnetic and remains so upto 768°C (Curie point). On heating it becomes non-magnetic however, the crystal structure still remains BCC.

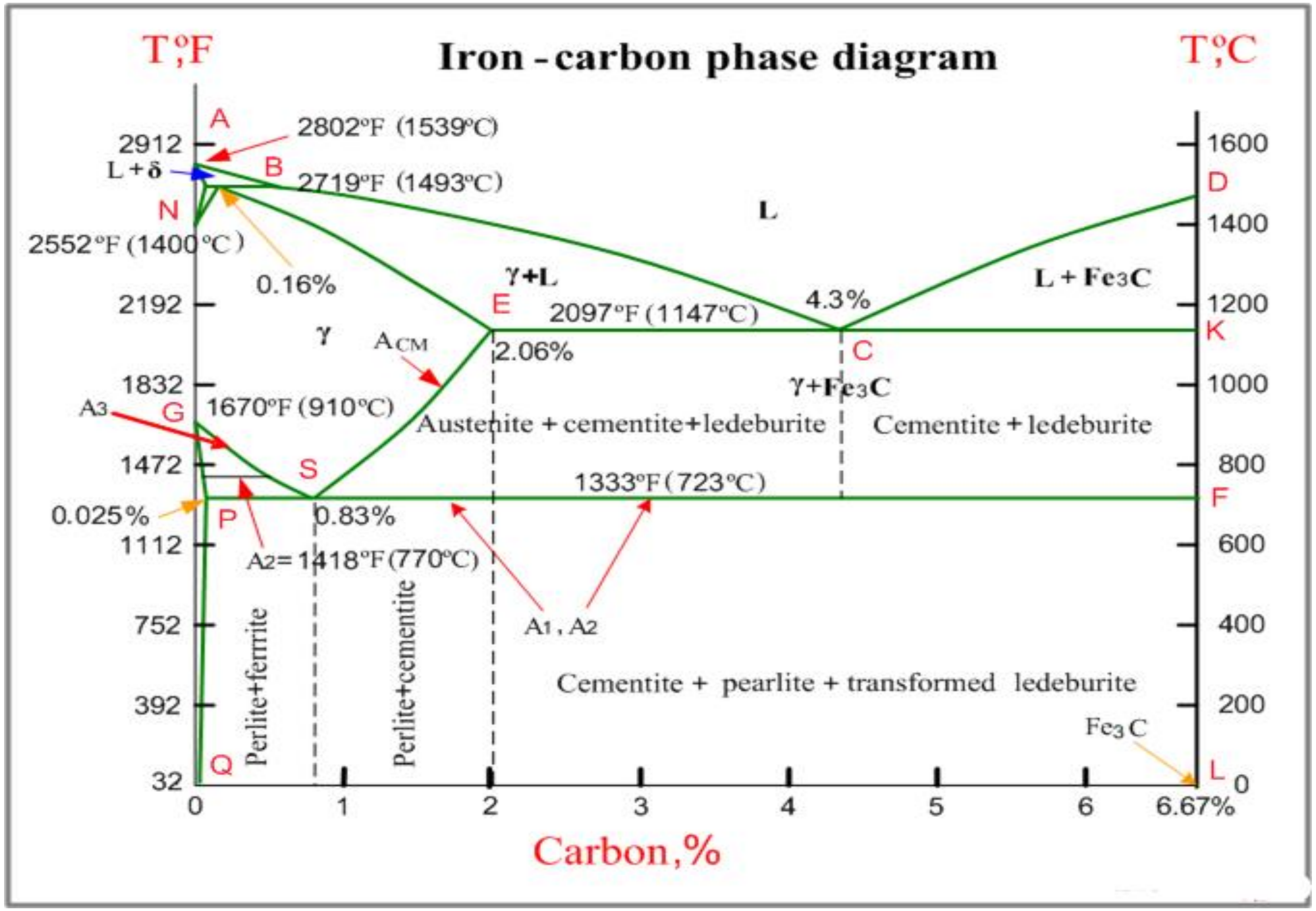




Above 910°C, it is transformed into FCC and allotropic transformation takes place. It is transformed from α γ -iron structure.

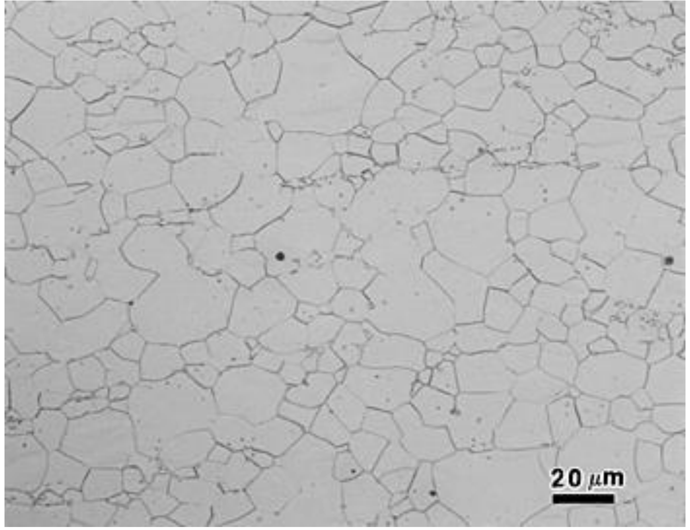
Upon heating to 1404°C, again allotropic transformation takes place and γ -iron is transformed back into the BCC structure called δ-iron. It is stable up to the melting point, 1539°C of pure iron. The BCC structure δ -iron has a longer cube edge than BCC structure of α-iron.

Iron-carbon phase diagram

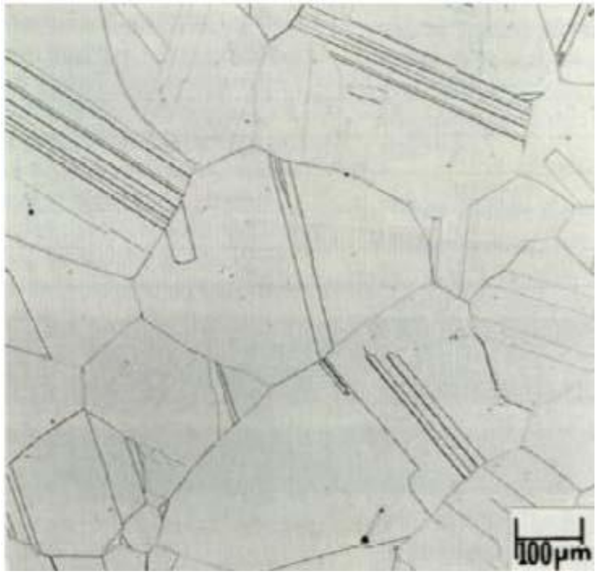


Phases in Fe-C system. Single phase structures

- Ferrite – is a solid solution of carbon in α-iron with bcc structure. The carbon concentration is 0.01% at room temperature (point Q on a diagram) and 0.03% at 723 ˚C (point P). It has high ductility, machineability, low hardness and strength.



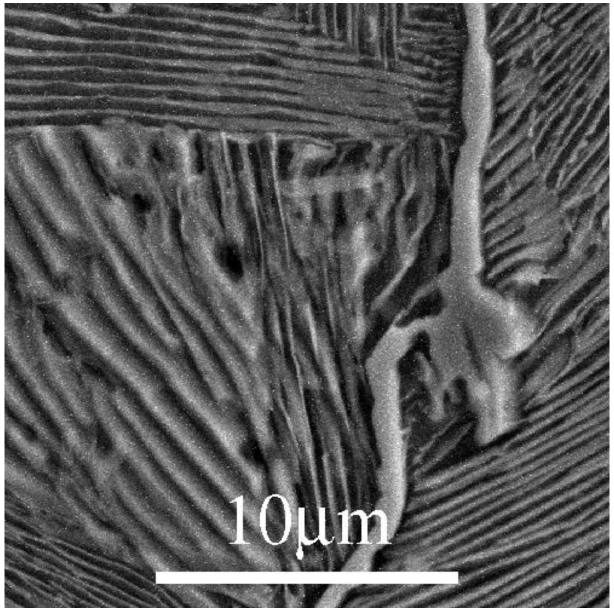
Austenite – is a solid solution of carbon in γ – iron with fcc structure. The maximum carbon solubility of carbon in γ – iron is 2.06% at 1147 ˚C (point E). It’s properties are very similar to ferrite, but it has higher hardness.



Cementite – is a chemical compound Fe3C – iron carbide with constant carbon concentration – 6.67% (line DFK).

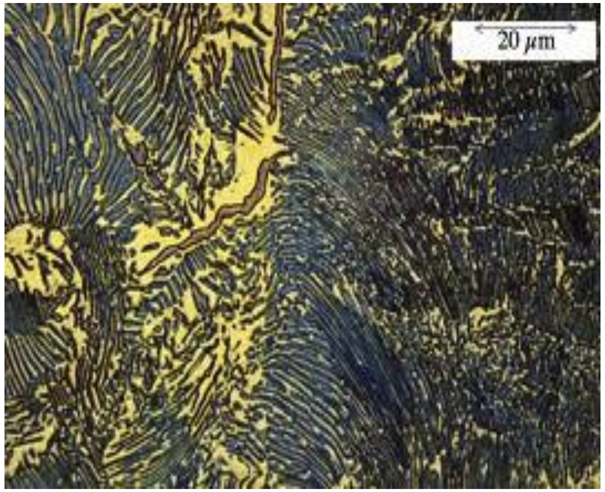
Cementite (Fe3C) forms when the solubility limit of carbon in ferrite is exceeded below) (for compositions within the Fe3C phase region). As indicated in Figure 9.24, Fe3C will also coexist with the phase between 727 and (1341 and). Mechanically, cementite is very hard and brittle; the strength of some steels is greatly enhanced by its presence.

Strictly speaking, cementite is only metastable; that is, it will remain as a compound indefinitely at room temperature. However, if heated to between 650 and 1200 and for several years, it will gradually change or transform into iron and carbon, in the form of graphite, which will remain upon subsequent cooling to room temperature. Thus, the phase diagram in is not a true equilibrium one because cementite is not an equilibrium compound. However, inasmuch as the decomposition rate of cementite is extremely sluggish, virtually all the carbon in steel will be as Fe3C instead of graphite, and the iron–iron carbide phase diagram is, for all practical purposes, valid.



Secondary and ternary cementite

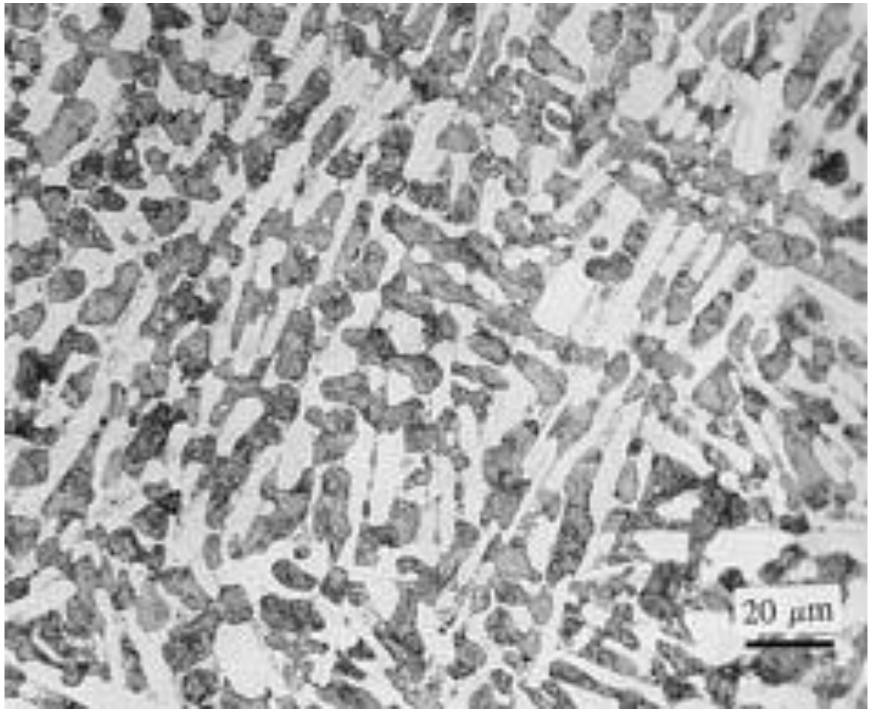
Phases in Fe-C system. Heterogeneuos structures



In the system two heterophase structures are formed – perlite and ledeburite.

Pearlite is a product of eutectoid reaction. It is similar to eutectic, but proceeds at solid state. Two phases appear – ferrite and cementite. The eutectoid temperature is constant and equals to 723˚C (line PSK), and carbon eutectoid concentration – is 0.8% (point S). So, pearlite – is a mechanical mixture of cementite and ferrite formed from austenite

Ledeburite – is a mechanical mixture of austenite and cementite and is a product of eutectic reaction. Eutectic reaction is a crystallization of two phases simultaneously from liquid phase. It proceeds at constant temperature and components concentration. For Fe-C system eutectic temperature equals to 1147 ˚C (line ECF). Carbon content in ledeburite is 4.3% (point C).



General description of the system

From room temperature to 910°C pure iron has a BCC structure and is called alpha (α) iron (Feα). It is highly ferromagnetic and remains so upto 768°C (Curie point). On heating it becomes non-magnetic however, the crystal structure still re-mains BCC.

Above 910°C, it is transformed into FCC and allotropic transformation takes place. It is transformed from α to γ -iron structure.

Upon heating to 1404°C, again allotropic change takes place and γ -iron is transformed back into the Upon heating to 1404°C, again allotropic transformation takes place and γ -iron is transformed back into the BCC structure called δ-iron. It is stable upto the melting point, 1539°C of pure iron. The BCC structure δ -iron has a longer cube edge than BCC structure of α-iron.

Line ABCD – liquidus.

Point E shows the maximum solubility of carbon in austenite (2.06% at 1147˚C) в, point P - maximum solubility of carbon in ferrite (0.03% at 723˚C), and point Q – at room temperature (0.01%)

At temperatures of line AC, austenite starts to solidify, and of line CD – cementite, which is called primary.

Point C with carbon concentration 4,3% and temperature 1147˚C is an eutectic point, at which ledeburite is formed.

Line AHУECF is a solidus.

Austenite crystallization proceeds at temperatures of line AE, below which a singlephase structure appears (austenite).

At solidification of hypereutectic alloys (2,06% to 4.3% of carbon) austenite crystals appear at first. At 1147˚C liquid phase changes to ledeburite. At temperatures 1147˚C – 723˚C the structure of these alloys is austenite +cementite + ledeburite. Below 723˚C the perlite from austenite is formed, and their structure changes to perlite+cementite+ +ledeburite

- Line GS is a line of reversible austenite-to ferrite transformation

- Points of line GS, at cooling are marked as Ar3 and Ac3 at heating.

Line ES corresponds to carbon solid solubility in austenite. At cooling below this line cementite precipitates (it is called “secondary”). Critical points forming line ES, are marked as Acт

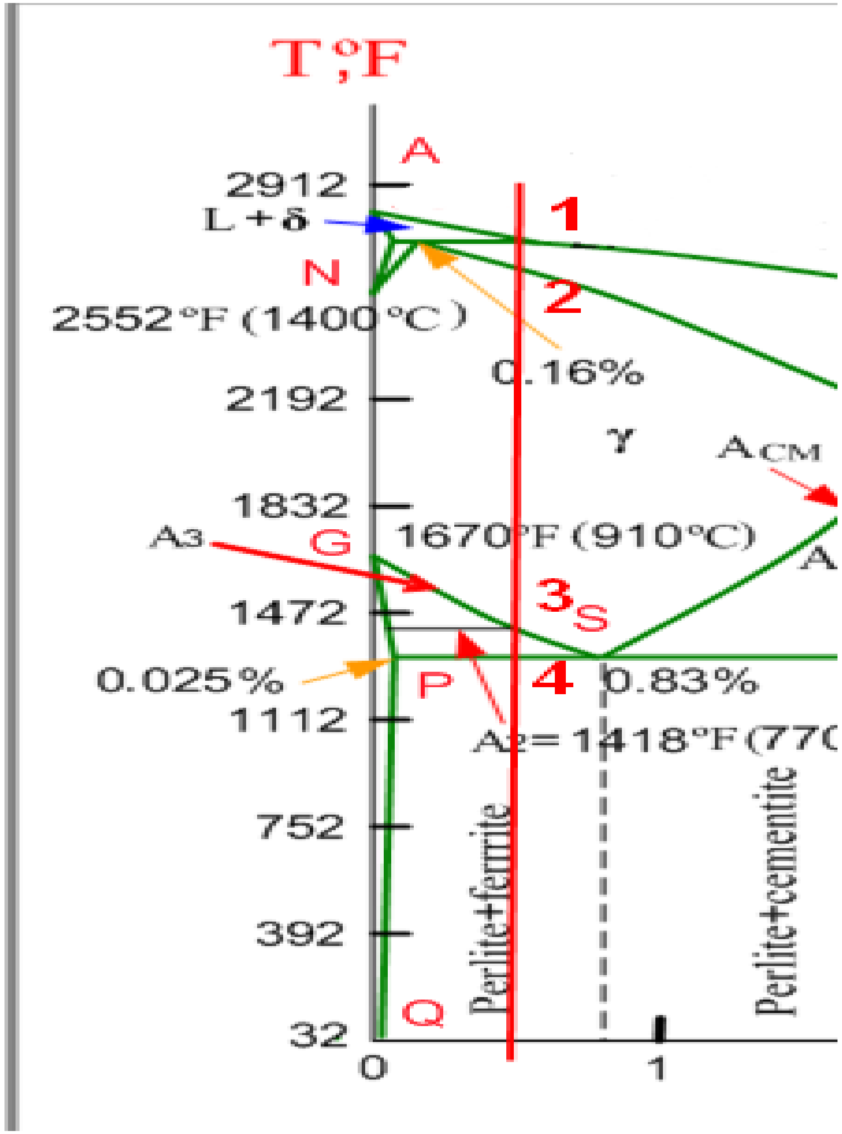
At point C (at 723˚C and carbon content 0,8 %) breaks to ferrite and cementite, forming an eutectiod (fine mechanical mixture) called ferrite.

The temperature of phase equilibrium (line PSK) is marked as Ar1 at cooling and Ac1 at heating.

At cast-iron below line PSK austenite breaks and perlite is formed
Hypouetectic cast-iron below line PSK consist of perlite, secondary cementite and ledeburite

Eutectic cast-iron below line PSK consist of ledeburite only

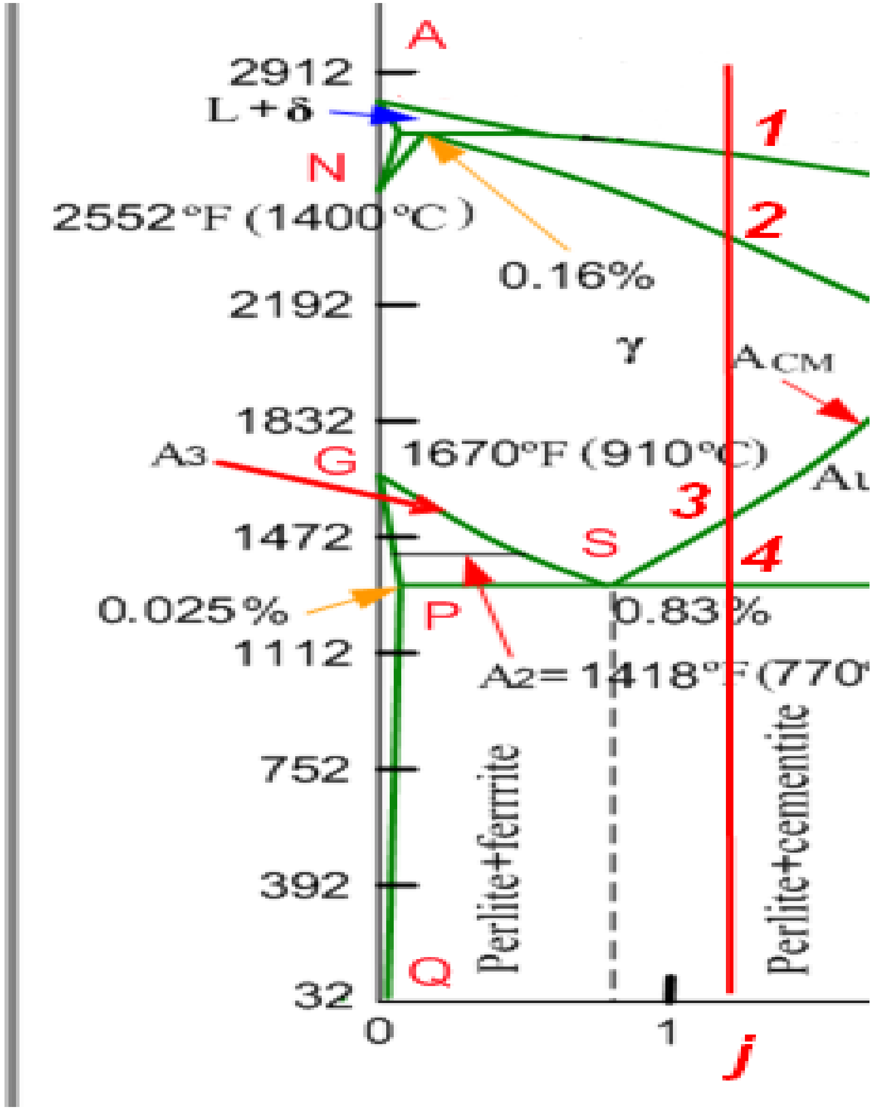
Hypereutectic cast-iron below line PSK consist of з ledeburite (perlite + cementite) and primary cementite



As an example, let's consider the process of crystallization of hypoeutectoid alloy with concentration t.

For temperature 1 (intersection with line ABCD) the solid phase (austenite) starts to separate. Upon cooling, its quantity increases, and in point 2 all the liquid is transformed into austenite. By further cooling the solubility of carbon in austenite changes. At point 3 the decomposition of austenite begins with the formation of ferrite.

In the GPS region the alloys exists in the double-phase state (α + γ). Further decrease in temperature will increase the quantity of ferrite. Carbon from ferrite (due to its low solubility) diffuses into austenite, where its concentration will increase along line GS (to the right from p. k), and at the temperature 723ºC will reach 0.8%. Next the eutectoid transformation austenite to pearlite will run. Below the line PSK alloy exist in two-phase state (ferrite + pearlite).



Let’s consider the transformation of hypereutectic alloy concentration j on cooling.

At temperature 1 start the solid phase – austenite starts to separate. At point 2 the alloy crystallization is completed. Between pp. 2 and 3 the austenite exist. Below p. 3 the allocation of secondary cementite begins (as with decreasing of temperature the solubility of carbon in austenite is reduced according to the line ES).

The secondary cementite allocateds on grain boundaries.

At p. 4 carbon concentration will decrease and reach a concentration of 0.8% at 723º, the eutectoid eutectoid transformation will run. The structure formed by the alloy at room temperature - pearlite + secondary cementite at grain boundaries.

Hypoeutectoid Alloys

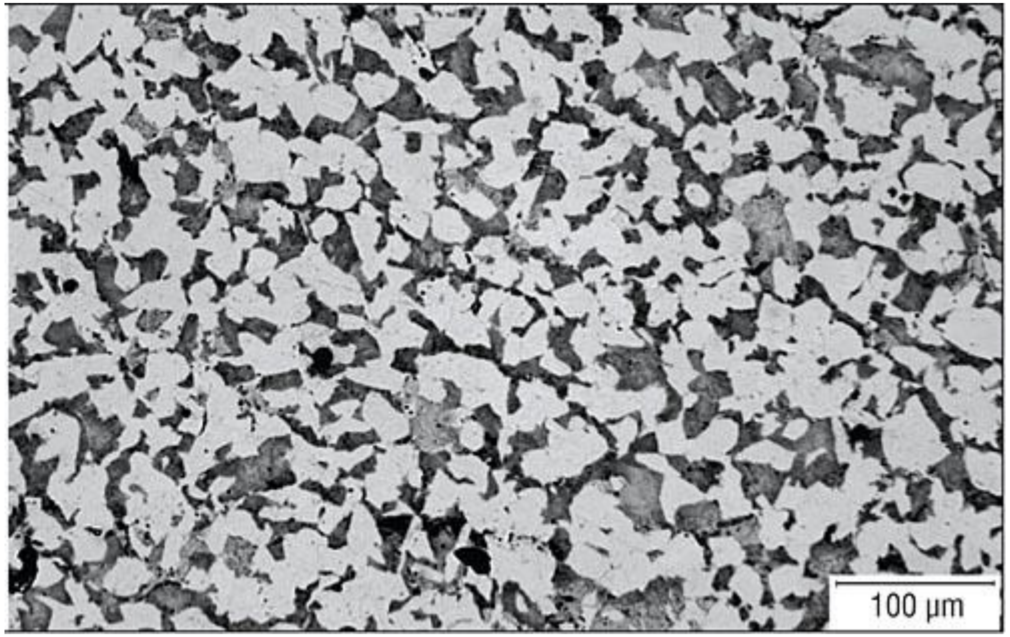
Microstructures for iron–iron carbide alloys having other than the eutectoid composition are now explored; these are analogous to the fourth case described and illustrated in Figure for the eutectic system. Consider a composition to the left of the eutectoid, between 0.022 and 0.8 wt% C; this is termed a **hypoeutectoid** (less than eutectoid) **alloy.** Cooling an alloy of this composition is represented by moving down the vertical line yy’ in figure below.

At about point 875*C*, the microstructure will consist entirely of grains of the γ-phase, as shown schematically in the figure. In cooling to point *d*, about *775C*, which is within the (α+γ) phase region, both these phases will coexist as in the schematic microstructure. Most of the small *α* particles will form along the original γ grain boundaries. The compositions of both α and γ phases may be determined using the appropriate tie line; these compositions correspond, respectively, to about 0.020 and 0.40 wt% C.

While cooling an alloy through the (α+γ) phase region, the composition of the ferrite phase changes with temperature along the α - (α+γ) phase boundary, line *MN*, becoming slightly richer in carbon. On the other hand, the change in composition of the austenite is more dramatic, proceeding along the (α+γ) - γ boundary, line *MO*, as the temperature is reduced.

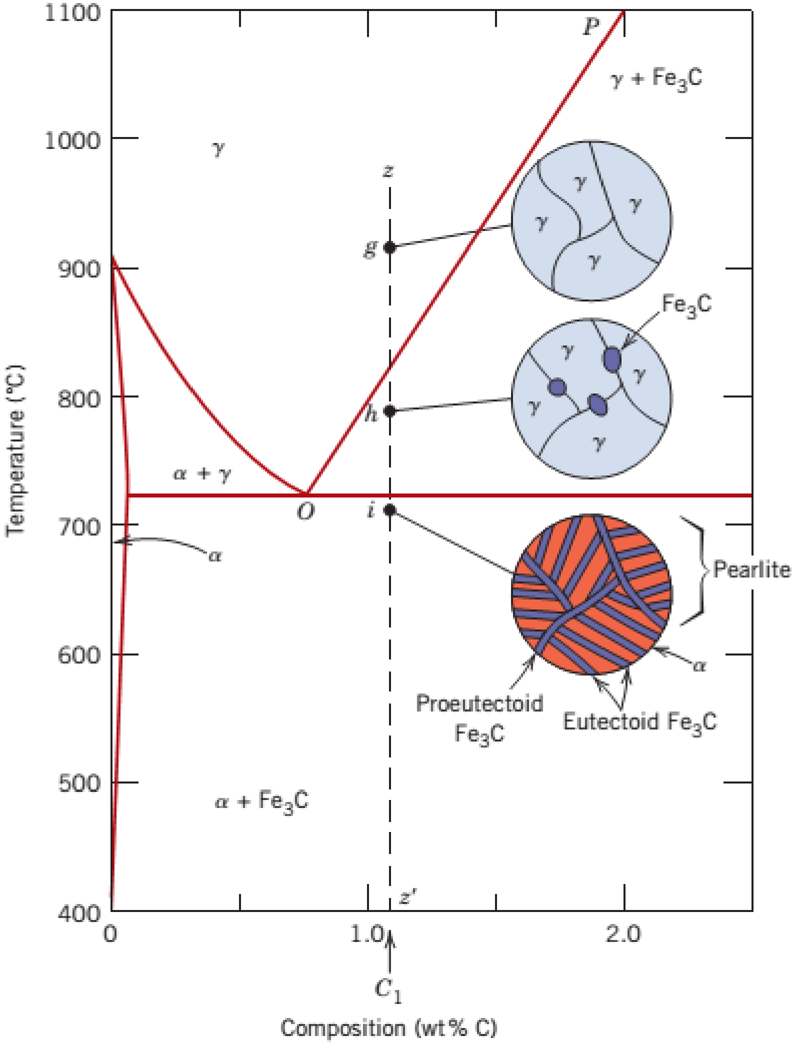
Cooling from point *d* to *e*, just above the eutectoid but still in the (α+γ) region, will produce an increased fraction of the phase and a microstructure similar to that also shown: the α particles will have grown larger. At this point, the compositions of the α and γ phases are determined by constructing a tie line at the temperature the phase will contain 0.022 wt% C, while the γ phase will be of the eutectoid composition, 0.8 wt% C

As the temperature is lowered just below the eutectoid, to point *f*, all the γ phase that was present at temperature (and having the eutectoid composition) will transform to pearlite, according to the reaction. There will be virtually no change in the α phase that existed at point *e* in crossing the eutectoid temperature – it will normally be present as a continuous matrix phase surrounding the isolated pearlite colonies. The microstructure at point *f* will appear as the corresponding schematic inset of Figure. Thus the ferrite phase will be present both in the pearlite and also as the phase that formed while cooling through the (α+γ) phase region. The ferrite that is present in the pearlite is called *eutectoid ferrite,* whereas the other, that formed above is termed **proeutectoid** (meaning pre- or before eutectoid) **ferrite,** as labeled in Figure is a photomicrograph of a 0.38 wt% C steel; large, white regions correspond to the proeutectoid ferrite. For pearlite, the spacing between the α and Fe_3C layers varies from grain to grain; some of the pearlite appears dark because the many closespaced layers are unresolved at the magnification of the photomicrograph.



Hypereutectoid alloys

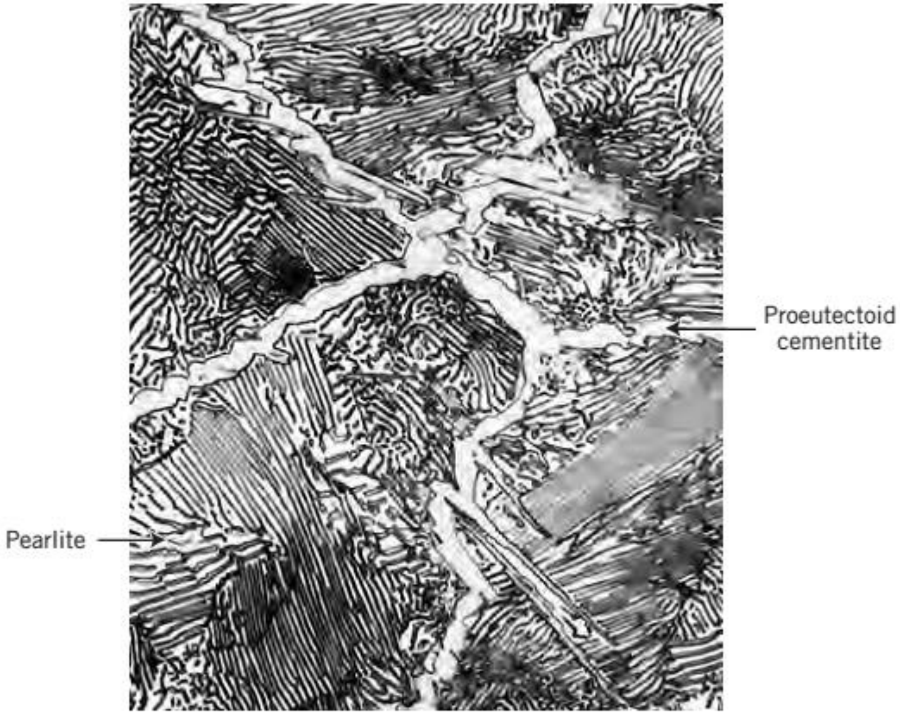
Analogous transformations and microstructures result for **hypereutectoid alloys,** those containing between 0.8 and 2.14 wt% C, which are cooled from temperatures within the γ phase field. Consider an alloy of composition in Figure below that, upon cooling, moves down the line zz'.



Schematic representations of the microstructures for an iron–carbon alloy of hypereutectoid composition C_1 (containing between 0.8 and 2.14 wt% C), as it is cooled from within the austenite phase region to below the eutectoid temperature.

At point *g* only the γ-phase will be present with a composition of the microstructure will appear as shown, having only grains. Upon cooling into the γ+Fe_3C phase field—say, to point *h*—the cementite phase will begin to form along the initial γ-grain boundaries, similar to the α-phase above, point *d*.

This cementite is called **proeutectoid cementite** – that which forms before the eutectoid reaction. Of course, the cementite composition remains constant (6.70 wt% C) as the temperature changes. However, the composition of the austenite phase will move along line *PO* toward the eutectoid. As the temperature is lowered through the eutectoid to point *i*, all remaining austenite of eutectoid composition is converted into pearlite; thus, the resulting microstructure consists of pearlite and proeutectoid cementite as microconstituents.



Photomicrograph of a 1.4 wt% C steel having a microstructure consisting of a white proeutectoid cementite network surrounding the pearlite colonies.

3. HEAT TREATMENT OF Fe-C ALLOYS

Introduction

Heat treatment operation is a means of controlled heating and cooling of materials in order to effect changes in their mechanical properties. Heat treatment is also used to increase the strength of materials by altering some certain manufacturability objectives especially after the materials might have undergo major stresses like forging and welding.

It was however known that mechanical properties of steel were strongly connected to their microstructure obtained after heat treatments which are performed to achieve good hardened and tensile strength with sufficient ductility. The material modification process, modify the behavior of the steels in a beneficial manner to maximize service life i.e stress relieving or strength properties e.g cryogenic treatment or some other desirable properties.

The Heat treatment generally is classified into (i) Thermal treatment which consists of softening process: Annealing and Normalizing, Hardening process: Hardening and Tempering; (ii) Thermochemical Process which consist of Carburizing, Nitriding, Boronising; (iii) Thermomechanical Processes which consist of mechanical working operation during heat treatment cycle.

Though heat treatment is not a new area, it has not been put into effective use in the fact that most of the researchers look at the process in general. It has not been localized for an improvement/ modification on getting the required results from these steel materials that are abound in our daily life, especially where most of the steel products are from recycled scrap materials.

Hence there is a need to carry out these tests and to be sure of the material compositions before they are put to final use. Present work is concerned with the effect of heat treatment on the mechanical properties of medium carbon steel with the objective of making sure that the steel is better suited structurally and physically for individual engaging in the design, fabrication and maintenance of steel products.

Heat treatment – is a technological process of heating and cooling used to alter the physical properties and structure of a material. The basic points of any heat treatment – are heating temperature, soaking time and cooling rate

During heat-treatment of a metal piece, when it is heated to a definite temperature followed by cooling at a suitable rate, there occur changes in the micro-constituents of the metal. These changes in the microconstituents of the metal may be in their nature, form, size and distribution in the metal piece.

Obviously, temperature of heating and rate of cooling are the main controlling factors of changes in micro-constituents. These changes in micro-constituents then control the changes in physical and mechanical properties of heat treated metal specimen. For various fabrication and manufacturing operations, heat treatment is a very important process. The purpose of heat treatment is to achieve any one or more objectives cited as follows:

(i) To remove strain hardening of a cold worked metal and to improve its ductility.

(ii) To relieve internal stresses set up during cold-working, casting, welding and hot-working treatments.

(iii) To remove gases from castings, to soften a metal to improve its machinability, and to increase theresistance to wear, heat and corrosion.

(iv) To improve the cutting ability, i.e., hardness of a steel tool, to improve grain structure after hot working a metal and to remove effects of previously performed heat-treatment operations.

(v) To improve magnetization property, especially of steels, for producing permanent magnets.

(vi) To refine grain structure after hot working a metal.
(vii) To soften and toughen a high carbon steel piece.

(viii) To produce a single phase alloy in stainless steel, and to produce a hard, wear resistant case on a tough core of a steel part.

(ix) To harden non-ferrous metals and alloys, especially aluminium alloys and to produce a single phase alloy in stainless steel.

(x) To produce a hard, wear resistant case on a tough core of a steel part and to toughen a hardened steel piece at the cost of its hardness.

The principle of the theory of heat treatment is that when an alloy has been heated above a certain temperature, it undergoes a structural adjustment or stabilization when cooled to room temperature. The cooling rate plays an important role in this operation. The structural modification is mainly based on the cooling rate. The heat treatments are normally applied to hypo-eutectoid carbon steels.

For steel the eutectoid reaction in the iron-carbon diagram involves the transformation and decomposition of austenite into pearlite, cementite or martensite. Common microstructure of steel obtained during heat treatment is shown Figure shows the iron-iron carbide phase diagram in the vicinity of the eutectoid. The horizontal line at the eutectoid temperature, conventionally labelled A1, is termed the lower critical temperature, below which, under equilibrium conditions, all austenite will have transformed into ferrite and cementite phases. The phase boundaries denoted as A3 and Acm represent the upper critical temperature lines, for hypoeutectoid and hyper-eutectoid steels respectively.

For temperatures and compositions above these boundaries, only the austenite phase will prevail. Other alloying elements will shift the eutectoid and the positions of these phase boundary lines.

The theory of heat treatment

The majority of heat treatments use phase transformations at heating or cooling.

Basic phase transformations for steels are:

Pearlite-to-austenite transformation at heating,

Isothermal transformation of austenite,

Thermokinetic transformation of austenite

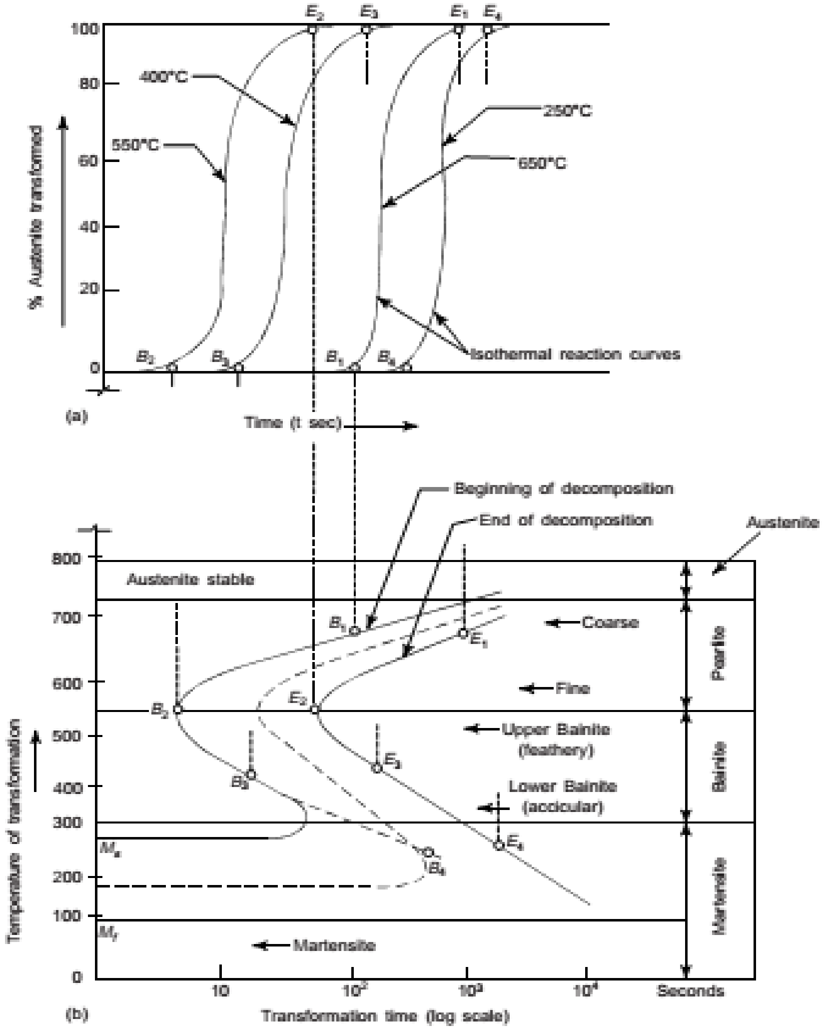
Decomposition of martensite at heating (annealing)

Isothermal transformation - TTT Diagrams

Time-Temperature-Transformation (TTT) diagram or S-curve refers to only one steel of a particular composition at a time, which is applicable to all carbon steels. This diagram is also called as C-curve isothermal (decomposition of austenite) diagram and Bain’s curve. The effect of time-temperature on the microstructure changes of a steel can be shown by TTT diagram.

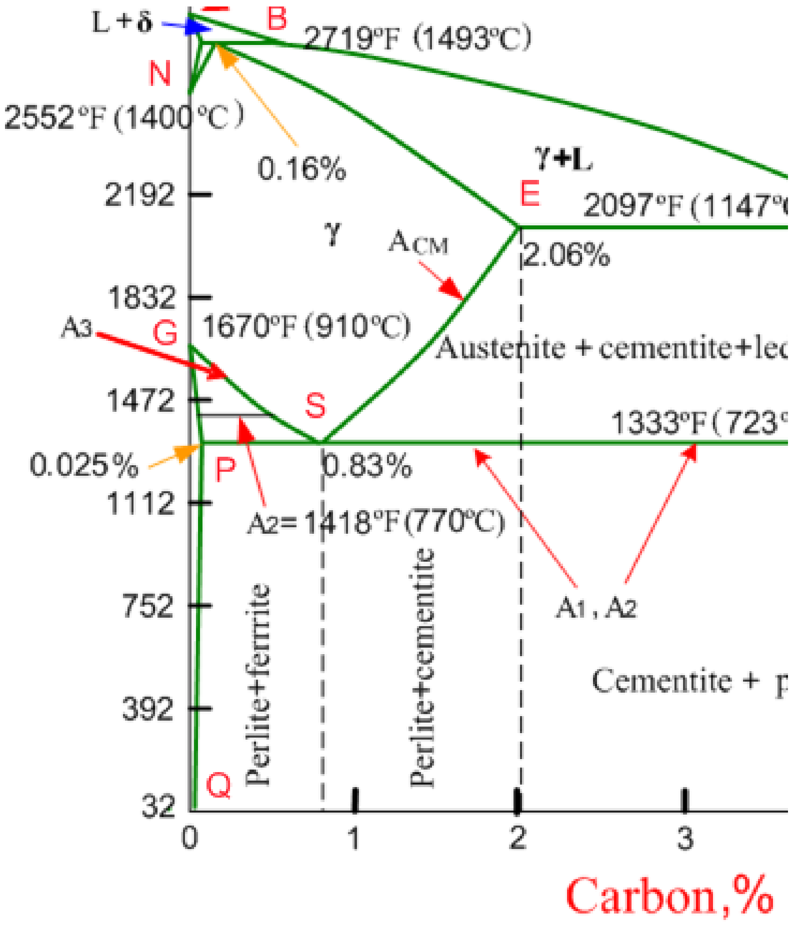
These diagrams are extensively used in the assessment of the decomposition of austenite in heat-treatable steels. We have seen that the iron-carbon phase diagram does not show time as a variable and hence the effects of different cooling rates on the structures of steels are not revealed. Moreover, equilibrium conditions are not maintained in heat treatment. Although, the iron-carbon equilibrium diagram reveals on the phases and corresponding microstructures under equilibrium conditions but several useful properties of the steels can be obtained under non-equilibrium conditions, e.g. variable rates of cooling as produced during quenching and better transformation of austenite into pearlite and martensite. The steels with different percentage of carbon, give different TTT diagrams. The diagram shows the rate at which austenite is transformed, at a given temperature, from all austenite to coarse pearlite; to fine pearlite, to upper bainite to lower bainite, martensite plus residual austenite, depending upon the carbon content.

The transformation of the austenite takes place at a constant temperature, i.e., the liquid bath temperature in which the component is cooled for the required time. Since the changes takes place at a constant temperature, it is known as Isothermal Transformation. One can determine the amount of microstructural changes by the microscopic examination of the sample. In order to construct a TTT diagram, a number of small specimens of steel are heated to a temperature at which austenite are stable and then rapidly cooled to temperatures, e.g. 650°C, 600°C, 500°C, 250°C, etc. The specimens are held isothermally at these temperatures for different periods of time until the austenite is completely decomposed. Experimentally, it is observed that at the start of the cooling shown by the points B1, B2, B3 and B4, there is no decomposition of austenite. This time period is referred as incubation period. After this, austenite starts to decompose into the ferrite-cementite mixtures. After the lapse of a certain period of time, the process of decomposition of austenite is stopped, as shown by points E1, E2, E3 and E4. Experimentally, it is observed that the rate of decomposition of austenite is not constant and initially it is rapid and slows down gradually.



Constructing TTT diagram

Pearlite-to-austenite transformation at heating

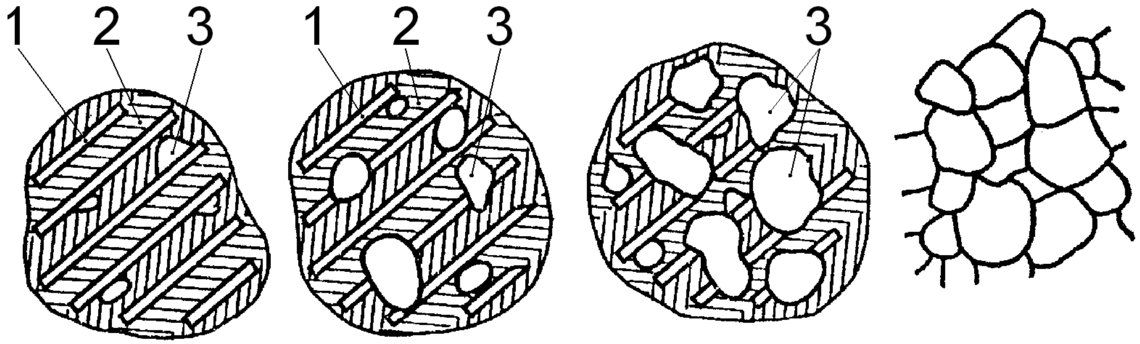


At heating of eutectoid steel above A_{c1} pearlite transforms to austenite, hypoeutectic steels – ferrite + austenite, hypereutectoid steels – austenite + cementite.

At temperature interval A_{c1}-A_{c3} the ferrite of hypoeutectoid steel gradually changes to austenite. Above A_{c3} its structure – is austenite.

For eutectoid steels at eutectoid point pearlite changes into austenite at constant temperature.

At hypereutectoid steels at temperature range A_{c1}-A_{CT} secondary cementite solves, and above A_{CT} austenite is formed.



Pearlite-to-austenite transformation at heating: 1 – cementite; 2 – ferrite; 3 – austenite.

The nuclei of austenite are formed from ferrite at the boundary with cementite. Due to diffusion, austenite grains grow and solve the carbon. Thus it changes to ferrite and cementite change to austenite. The former pearlite areas contain more carbon, then former ferrite. Thus, to get equilibrium, the material is held at appropriate temperature during a period of time. This is called soacking.

Mechanisms of austenite decomposition

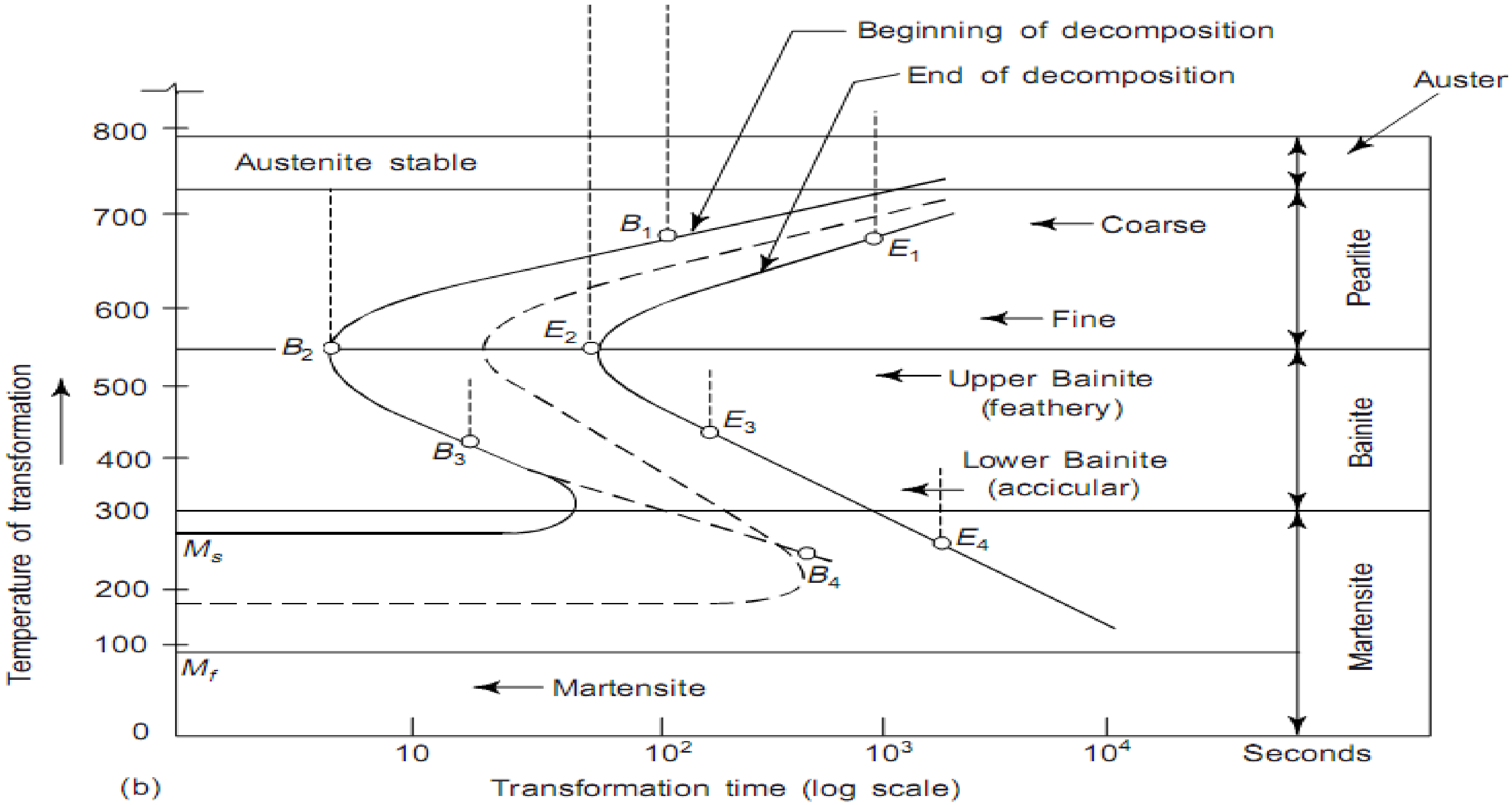
There are 2 mechanisms of phase transformation in steels at heat treatment: diffusion and diffusionless. As a result of the first ferrite+cementite structures (mixtures) are formed.Due to diffusion cementite segregates into plates.

The second – is when cooling rate is high and diffusion processes are limited. When γ-Fe rapidly changes to α-Fe the carbon remains inside the lattice and a supersaturated solid solution is formed.

Isothermal transformation of austenite

Transformation of austenite-to-pearlite – is its decomposition into ferrite and cementite. At temperature A1 austenite and pearlite are in equilibrium. Transformation will be stable only at supercooling of austenite.

Left curve corresponds to the start of decomposition, the right one – to the end. Left to the left curve austenite do not decomposes. To the right of “end line” - are the products of decomposition. Line Ms corresponds to the temperature of beginning of martensite transformation, line Mf – to the end.



Isothermal transformation of supercooled austenite

A ferrite-cementite mixture with coarse pearlite is obtained at temperatures near Ar1 (700°C). The product of austenite decomposition (a mixture of ferrite-cementite), lamellar in structure, and finer then pearlite is obtained between 700°C and 550°C, which is known as sorbite.

An evenly dispersed mixture of ferrite-cementite (troostite) is obtained, when the temperature is lowered too 550°C-500°C.

A diffusionless transformation of austenite into a hardened steel structure called martensite is observed at temperatures between 250 and 50°C. The temperatures, at which the martensite starts and finishes are marked by Ms and Mf. Ms stands for the temperature at which the formation of martensite begins and Mf stands for the temperature at which the formation of martensite (a super-saturated solid solution of carbon in α-iron.) ends

A needle-like structure known as bainite is obtained when the temperature is lowered from 500°C to 300°C. The bainite is harder, stronger and tougher than pearlite. It is formed due to mixed diffusion-diffusionless process.

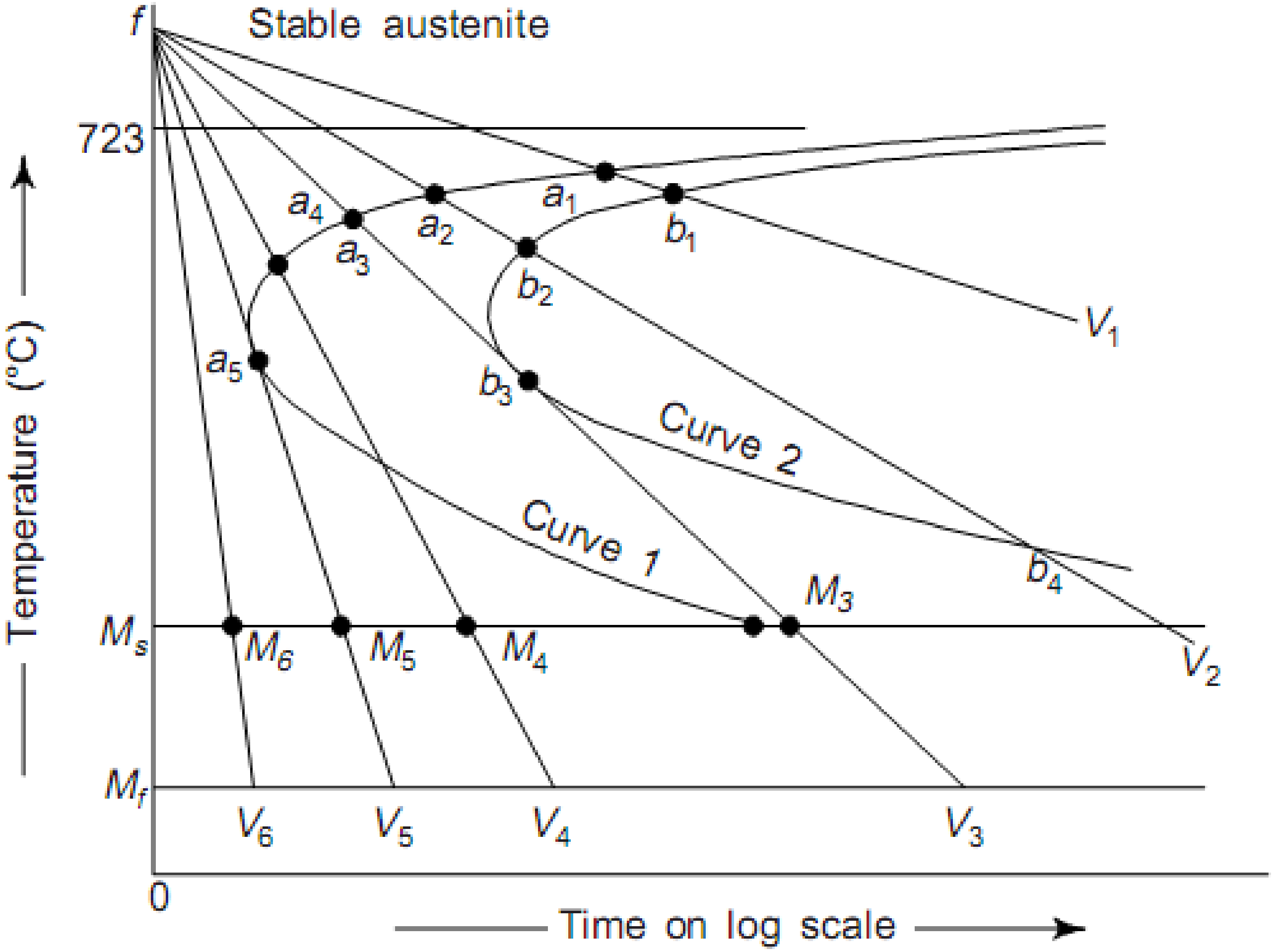
Thermokinetic transformation of austenite

Let us consider a number of specimens of eutectoid steel heated to a temperature t, above the critical points. At this temperature, the steel is present in the form of stable austenite. Let the specimen of steel is cooled continuously below the lower critical point, i.e., 723°C at various cooling rates. Let the inclined curves V1, V2, V3, on temperature-time graph represent these cooling processes.

The slowest cooling rate is represented by the curve V1. Slightly higher cooling rate is represented by the curve V 2. Still more rapid cooling rates are represented by the V3, V4 and V5. We may note that these curves are straight lines. Now, we superimpose these cooling curves (V1, V2, V3) on the time-temperature transformation diagrams.

We note that the curve V1 crosses transformation curves 1 and 2 at points a1 and b1 respectively. Obviously, on slow cooling, the austenite completely transforms into a ferrite cementite mixture. Since the transformation takes place at the highest temperature therefore the ferrite cementite mixture is pearlite. The curve V2 also intersects both the transformation curves at points a2 and b2 respectively. Austenite, at this cooling rate completely transforms into ferrite-cementite mixture.

The transformation occurs at lower temperature (as compared to V1), the resulting ferrite-cementite is sorbite. Similarly, the curve V3 also intersects both the curves at points a3 and b3 respectively. The resulting ferrite-cementite mixture is troostite. We note that the curve V4 does not cross both the transformation curves. It intersects only the curve 1 at point a4, and does not reach the stage of completion. Obviously, a part of austentic grains transform into ferrite-cementite mixture, while the other does not transform due to insufficient time. It is observed that the remaining part of austenite which has not been transformed, undergoes transformation into martensite on

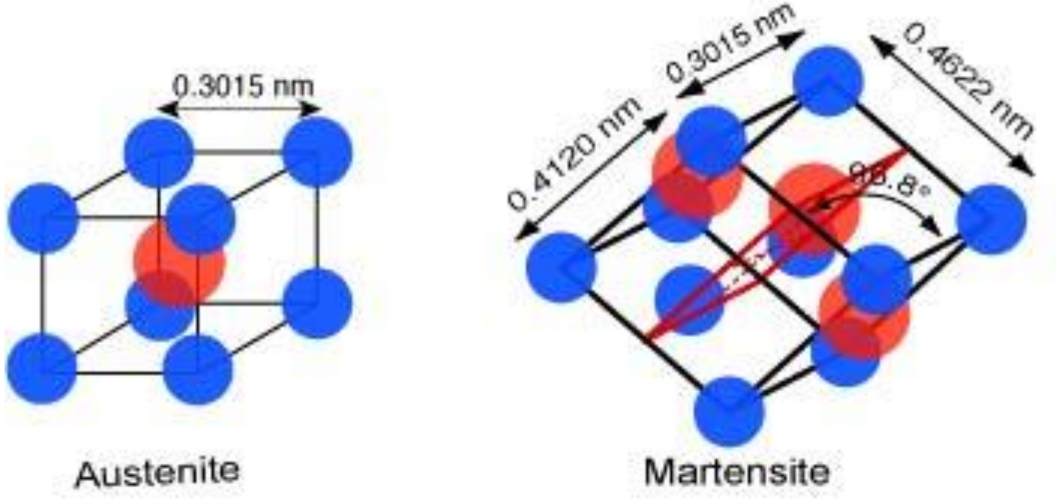


Thermokinetic decomposition of austenite Vectors correspond to cooling rate reaching the temperature Ms. It is shown by the intersection of the curve V4 and temperature Ms at the point M4 . Obviously, the structure of steel, cooled at the rate of V4, consists partly of troostite and partly of martensite. This type of structure is common to all steels, which are cooled at a rate faster than those represented by V3 and slower than by V5. This cooling rate for carbon steels is achieved by quenching in oil. We may note that at any cooling rate, higher than V5, e.g. curve V6, of austenite does not transform into ferrite-cementite mixture. However, the austenite is transformed into martensite.

Point M5 and M6. represent this transformation. This cooling rate for carbon steel corresponds to the quenching in water. We may note that the austenite is never transformed into martensite. This untransformed austenite is known as retained austenite. The minimum cooling rate, at which all the austenite is rapidly cooled to temperature Ms and is transformed into martensite is called as critical cooling rate. It is represented by straight line V5, i.e. the tangent line drawn to the curve 1. We may see that curves V2 and V3 and others between them have more slope also intersect the line Ms.

Obviously, the martensite is formed at the end of transformation. However, it has reported that martensite is never formed at such cooling rates. Perhaps, this may be due to the fact that the curves V2 and V3 and others intersect both the transformation curves. Thus the complete transformation of the austenite takes place at points b2 and b3 respectively. No austenite is left in the steel beyond these points. This means that nothing is to be transformed into martensite. This is why that point M3 has no physical sense.

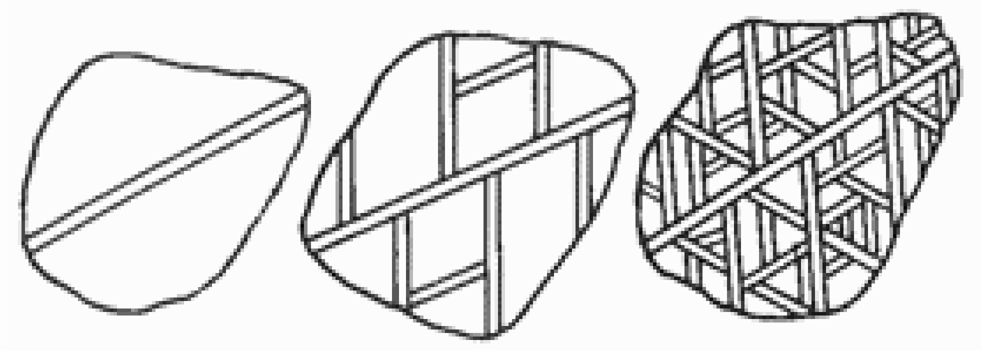
Martensite is a metastable phase of steel. In the formation of martensite, the FCC structure of austenite changes to body centered in a special way which does not involve diffusion, but results from a shearing action. The crystal structure of martensite is body centered tetragonal. Since the carbon is present in the martensite, it is hard, strong and brittle. Martensite is formed by the transformation of Carbon atom Iron atoms



Unit cell of martensite VS austenite

The hardness of martensite is much greater than that of pearlite and this enhanced hardness is of great importance. This high hardness provides an extremely high resistance to abrasion and deformation. How ever, martensite is a brittle. In order to reduce its brittleness, martensite is reheated without loss of its hardness. The process is called tempering. During tempering, metastable martensite decomposes into more stable phases of ferrite and cementite.

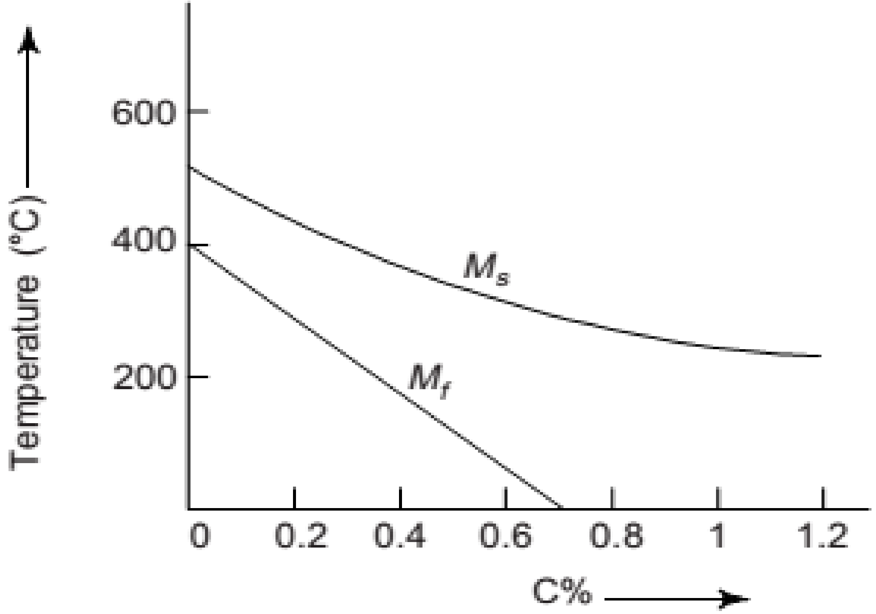
Martensite is an interstitial supersaturated solid solution in iron with a body centered tetragonal (BCT) lattice and accicular of needle like structure (Fig. below). The needles, in fact, are the plates of martensite, which appear in the microsection as long and thin needle. The rate of formation of martensite needles is very high (~ 50 milliseconds).



Formation and growth of martensite

However, the formed martensite needles do not grow in length or breadth. However, as the transformation proceeds further the subsequent needles become shorter and shorter. We may note the martensite transformation cannot proceed isothermally like the pearlite, sorbite transformation. Obviously, when the steel is held at a constant temperature (below the Ms point) the martensite transformation ceases very rapidly. However, with the further lowering of temperature, the martensite transformation begins again. The temperature at which the transformation is finally ceased, is denoted by Mf. We may note that Mf is different for each type of steel. This shows that the martensite transformation occurs over a wide range of temperatures from Ms to Mf. The martensite transformation range is determined by the percentage of carbon in steel. It is reported that higher the percentage of carbon in steel, lower is the temperature of beginning and end of the martensite transformation. Figure shows the variation of the martensite temperature range with the percentage of carbon in steel.

We note from figure that above 0.7% C, the Mf temperature is below 0°C. Obviously 100% martensite cannot be produced even if the high carbon steels are quenched in ice cold water. This means that some austenite is always left untransformed. This austenite is known as residual or retained austenite. It is observed that higher the percentage of carbon in steel, greater will be the



Temperatures of martensite transformation depending on carbon content

amount of retained austenite. Interestingly some of the retained austenite still remains in the structure of steel, even if this is cooled below the Mf temperature. The characteristic properties of martensite are its high hardness and extremely low impact strength .

Transformation of martensite and residual austenite at heating (annealing)

During annealing **martensite and residual austenite decompose.**
It runs in 3 steps.

1. At temperature below 200˚C carbon forms carbides

2. At temperature range 200-350˚C crystals of carbides start to grow. They have very different structure and properties then those of cementite.
3. At temperature 350-400˚C carbon diffuses out of martensite and an equilibrium structure is formed (ferrite + cementite).

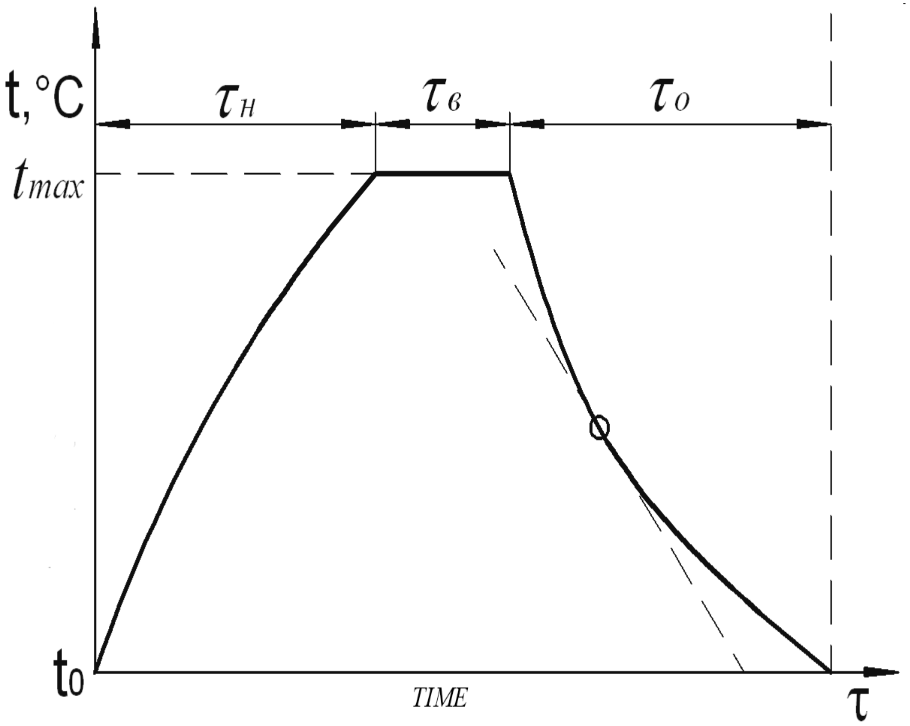
At the same time a residual austenite also decomposes. This process is very similar to bainite transformation.

The technology of heat treatment

Introduction

Heat treatment refers to the heating and cooling operations required to alter the properties of metals, alloys plastic and ceramic materials. Changes in material's properties result from changes made in microstructure of the material. Heat treatment can be applied to ingots, castings, semi-finished products, welded joints and various elements of machines and instruments.

During heat-treatment of a metal piece, when it is heated to a definite temperature followed by cooling at a suitable rate, there occur changes in the micro-constituents of the metal. These changes in the microconstituents of the metal may be in their nature, form, size and distribution in the metal piece. Obviously, temperature of heating and rate of cooling are the main controlling factors of changes in micro-constituents. These changes in micro-constituents then control the changes in physical and mechanical properties of heat treated metal specimen.



For various fabrication and manufacturing operations, heat treatment is a very important process. The purpose of heat treatment is to achieve any one or more objectives cited as follows:
(i) To remove strain hardening of a cold worked metal and to improve its ductility.
(ii) To relieve internal stresses set up during cold-working, casting, welding and hot-working treatments.

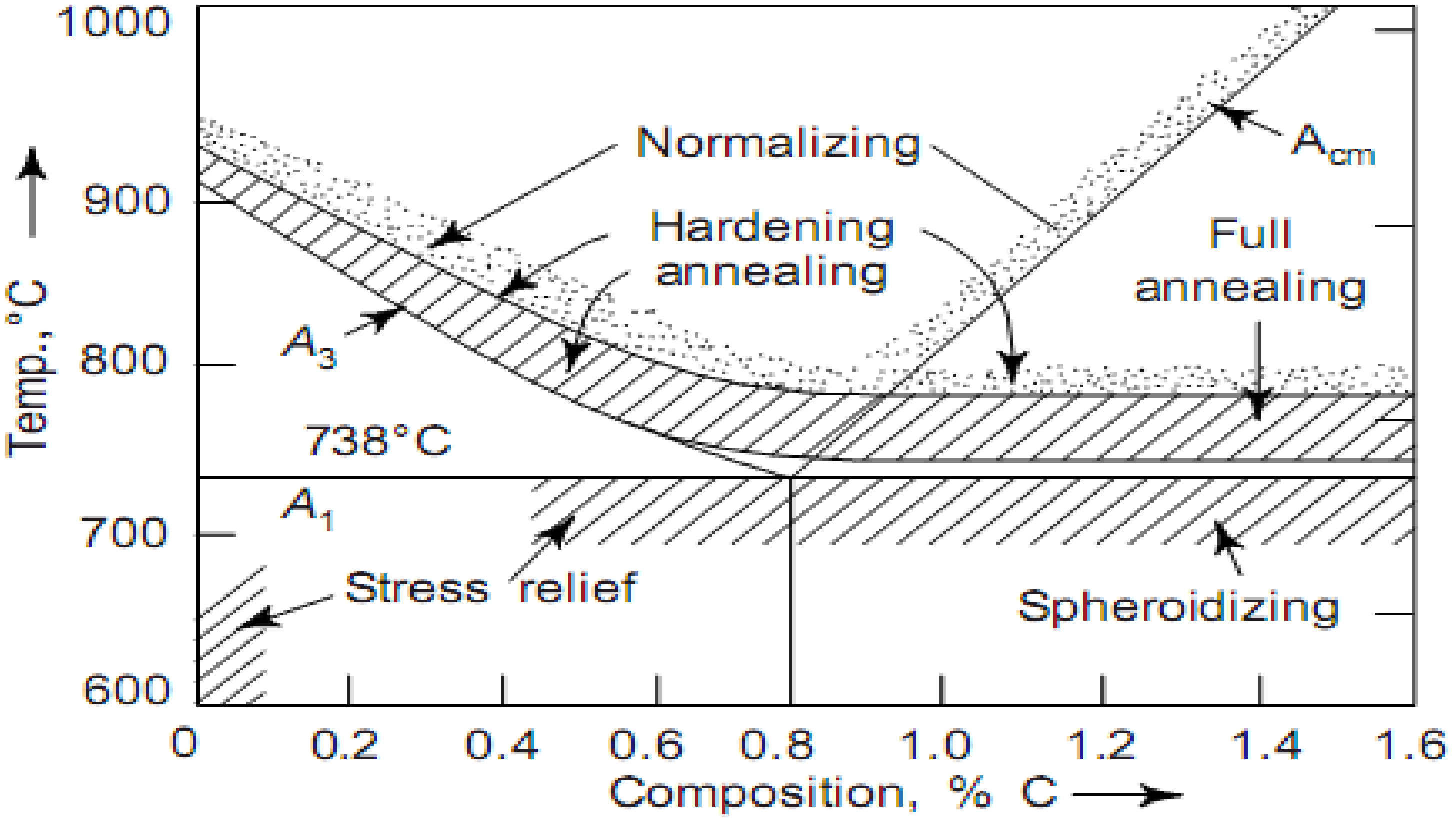
(iii) To remove gases from castings, to soften a metal to improve its machinability, and to increase the resistance to wear, heat and corrosion.
(iv) To improve the cutting ability, i.e., hardness of a steel tool, to improve grain structure after hot working a metal and to remove effects of previously performed heat-treatment operations.
(v) To improve magnetization property, especially of steels, for producing permanent magnets.
(vi) To refine grain structure after hot working a metal.
(vii) To soften and toughen a high carbon steel piece.
(viii) To produce a single phase alloy in stainless steel, and to produce a hard, wear resistant case on a tough core of a steel part.
(ix) To harden non-ferrous metals and alloys, especially aluminium alloys and to produce a single phase alloy in stainless steel.
(x) To produce a hard, wear resistant case on a tough core of a steel part and to toughen a hardened steel piece at the cost of its hardness.
The principle of the theory of heat treatment is that when an alloy has been heated above a certain temperature, it undergoes a structural adjustment or stabilization when cooled to room temperature. The cooling rate plays an important role in this operation. The structural modification is mainly based on the cooling rate.

The principal kinds of heat treatment are:
1.Annealing 2. Normalizing 3. Hardening 4. Tempering 5. Ageing.

Each of them has a number of varieties.
The properties after heat treatment depend on:
1. kind of heating: electrical or “flame” furnace, salt bath.
2. The mass of metal and its location inside of furnace.
3. Physical properties of the metal (heat capacity and heat conductivity).

The soaking is necessary for diffusion and phase transformations to run. Usually soaking time is 1/5 of heating time. During this time the core of the metal is heated enough.

Heat treatment range for carbon steels



Annealing

This is a kind of heat treatment after which a metal or alloy acquires a structure close to the equilibrium one. A material is exposed to an elevated temperature for an extended time period and then slowly cooled.

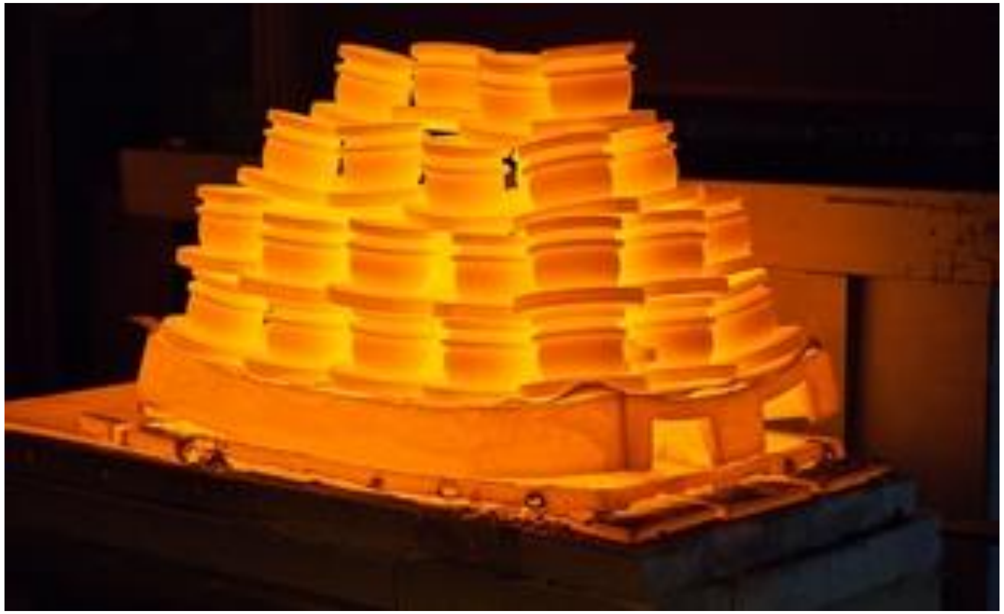
Normally, annealing is carried out to (i) relative stresses (ii) increase softness, ductility and toughness; and/or (iii) produce a specific microstructure.

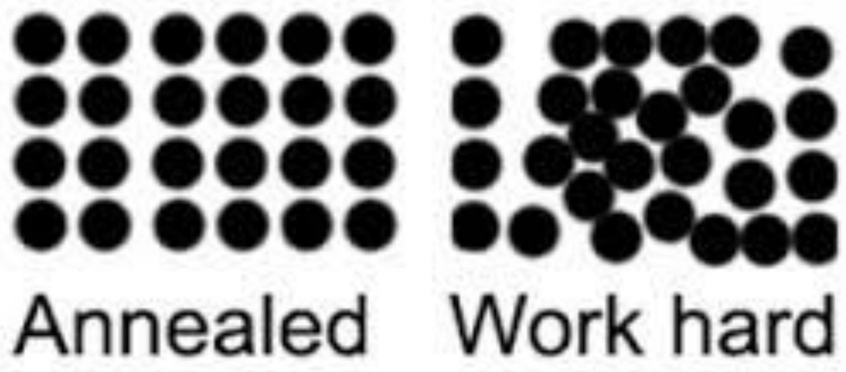
The temperature of heating in annealing depends on the composition of an alloy and the particular kind of the process; the rate of cooling from the annealing temperature is usually not high (within 30-200°C/h). There are variety of annealing heat treatments possible. These are characterized by the changes that are induced, which many times are microstructural and are responsible for the alteration of the mechanical properties.

An annealing process consists of three stages: (i) heating to the desired temperature, (ii) holding or ‘soaking’ at that temperature, and (iii) cooling, usually to room temperature. In these annealing procedures, time is an important parameter. There exist temperature gradients between the outside and interior portions of the piece during heating and cooling. The magnitudes of temperature gradients depend on the size and geometry of the piece. If the rate of temperature, change is too great, temperature gradients and internal stresses may be induced that may lead to wraping or even cracking. Moreover, the actual annealing time must be long enough to allow for any necessary transformation reactions. An annealing temperature is also an important consideration. Since diffusional processes are normally involved and therefore annealing may be accelerated by increasing the temperature. The various types of annealing operations are: (i) Full annealing, (ii) Process annealing, (iii) Spheroidise annealing and (iv) Diffusion annealing.

Full annealing.

This operation removes all structural imperfections by complete recrystallization. This operation is often utilized in low and medium carbon steels that will be machined or will experience extensive plastic deformation during a forming operation. This operation consist of: (i) Heating the hypoeutectoid steel to about 50-70°C above the upper critical temperature (for hypoeutectoid steels) and by the same temperature above the lower critical temperature for hypereutectoid steels until equilibrium is achieved. This ensures that the metal is heated thoroughly and phase transformation has taken place throughout the whole volume. (ii) The alloy is then furnace cooled; i.e., the heat-treating furnace is turned off and both furnace and steel cool to room temperature at the same rate, which takes several hours. The microstructural product of full anneal is coarse pearlite (in addition to any proeutectoid phase) that is relatively soft and ductile. The full-annealing cooling procedure is time consuming; however, a microstructure having small grains and a uniform grain structure results.





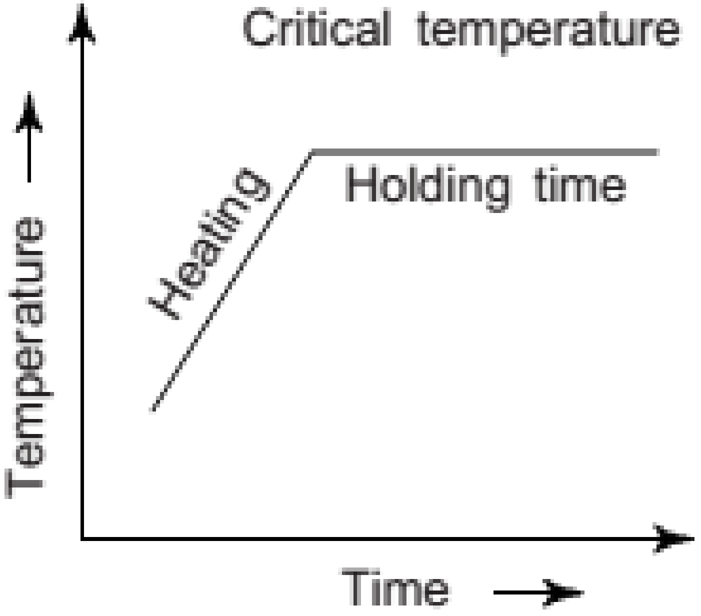
Process annealing

This is a heat treatment that is used to negotiate the effects of cold work, i.e. to soften and increase the ductility of a previously strain hardened metal. Process annealing is commonly utilized during fabrication procedures that require extensive plastic deformation, to allow a continuation of deformation without fracture or excessive energy consumption. It is the recrystallization of cold work, i.e., recovery and recrystallization processes are allowed to occur.

Ordinarily a fine grained microstructure is desired, and therefore, the heat treatment is terminated before appreciable grain growth has occurred. In other words, the exact temperature depends upon the extent of cold working, grain size, composition and time held at heat. Surface oxidation or scaling may be prevented or minimized by annealing at relatively low temperature (but above the recrystallization temperature) or in a non oxidizing atmosphere.

Process annealing is very use ful in mild steels and low carbon steels. It is done on cold-worked low carbon steel sheet, wire or tubing to relieve internal stresses and to soften the material. The process is as follows:The process is as follows:

1. The steel is heated to 550-650°C.
2. Stresses throughout the metal are relieved and recrystallization causes new grains to form and grow.



Process annealing or sub-critical annealing which is done on cold worked low carbon steel sheet, wire or tubing to relieve internal stresses and to soften the material.

The process is as follows:

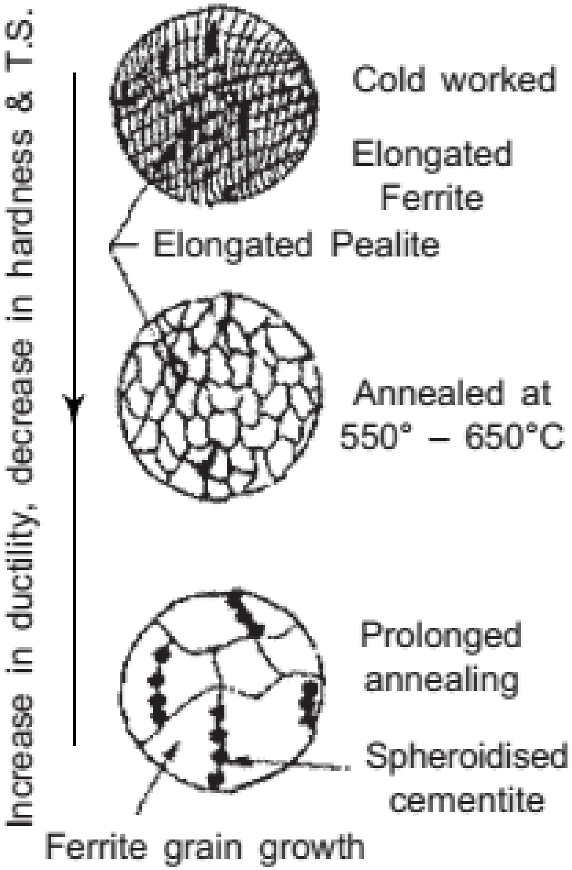
(i) The steel is heated to 550-650°C, which is just below the lower critical temperature on iron-carbon diagram for steel. (ii) Stresses throughout the metal are relieved and recrystallizationcauses new grains to form and grow.

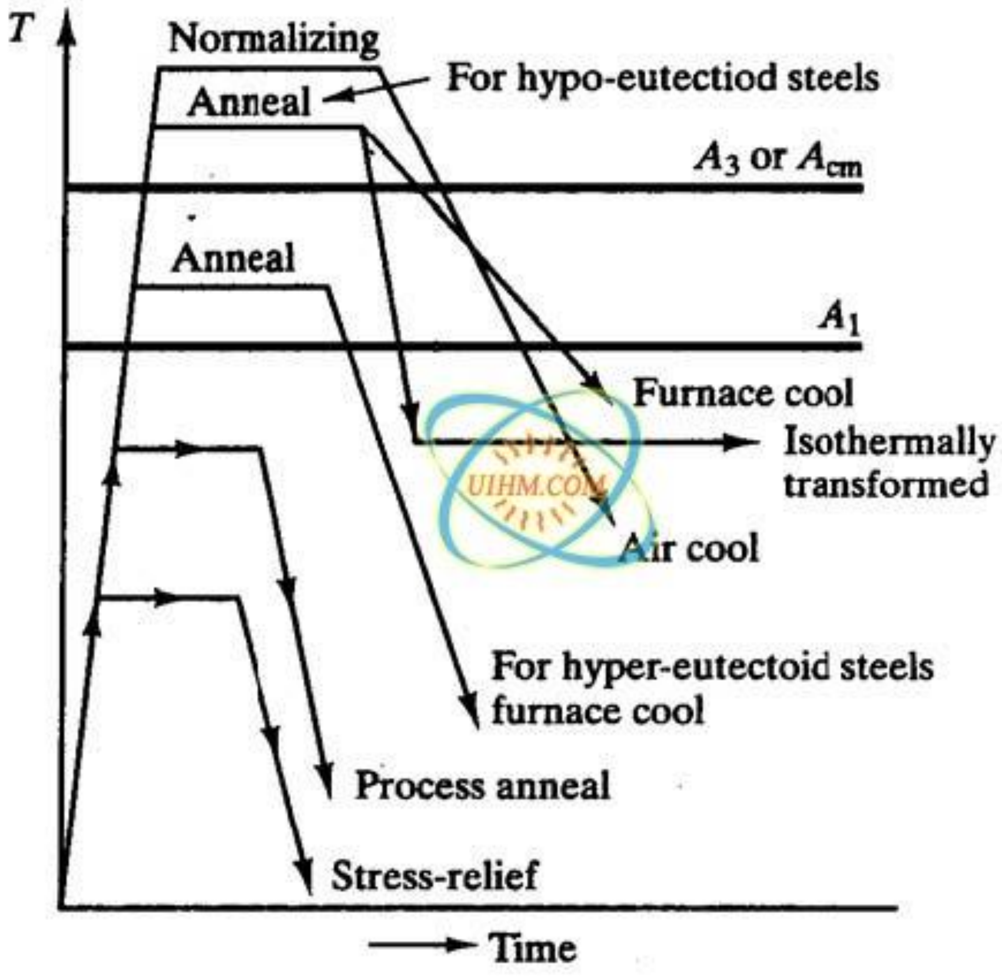
Changes taking place during process annealing are shown in Figure below.

Heating period is followed by slow cooling. Prolonged annealing causes the cementite in the pearlite to “ball up” or spheroidise. Ferrite grain growth also occurs. Obviously, annealing time and temperature control is very essential for proper process annealing.

Patening: It is mainly applied to medium to high carbon steels prior to drawing of wire or between drafts. This mainly increases ductility for wire drawing. The process is as follows:

(a) Heating to a temperature above the transformation range and (b) then cooling to a temperature below that range in air or in a bath of molten lead or salt maintained at a temperature appropriate to the carbon content of the steel and the properties required of the finished product.





Various annealing types schematic

Diffusion annealing is done for alloy steels. They are heated to 1100 – 1200 ºC and soaked. Then it is furnace cooled to 800 – 820 ºC and then air cooled. As a result big grain is formed, what is coarsed by further heat treatment

Stress-relief annealing

Internal residual stresses may develop in metal pieces due to:
(i) plastic deformation processes such as matching and grinding;
(ii) non uniform cooling of a piece that was processed or fabricated at an elevated temperature, such as a weld or a casting; and
(iii) a phase transformation that is induced upon cooling where in parent and product phases have different densities. Distortion and warpage may result in case if residual stresses are not removed.

They can be eliminated by this process-in which the piece is heated to the recommended temperature, held there long enough to attain a uniform temperature, and finally cooled to room temperature in air. We may note that the annealing temperature is ordinarily a relatively low one such that effects resulting from cold working and other heat treatments are not affected, castings, forgings, weldment and other work pieces may have residual stresses.

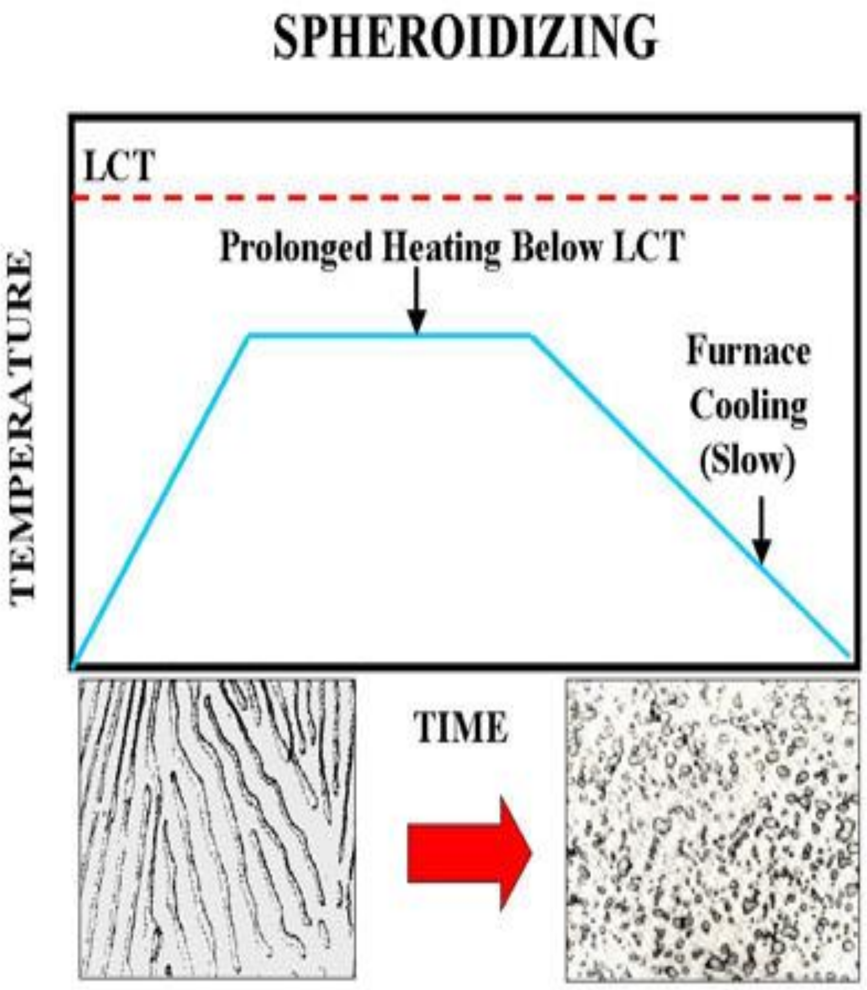
In this process, the work pieces are first heated to about their recrystallization temperature and then these are cooled slowly. Like process annealing this stress-relief may also be performed on any metal.

Double Annealing: It is quite useful for steel castings. It removes the strains. It coalesces the sulphide films (which embrittle the steel) in the ferrite and produces homogeneity by rapid diffusion. The steel is ulti mately obtained with refined grains and in soft condition. In this process, steel is heated to a temperature considerably over the A3 point, i.e. above the critical range for a time period. Then rapid cooling is performed to a temperature below the lower critical tempera ture. Now, immediately reheating is done to a point just over the upper critical temperature for a time period. Finally, slow cooling allowed to room temperature.

Spheroidizing annealing

This type of heat treatment produces carbide in the form of round or globular (spheroids) instead of plates as in pearlite. This structure gives: good machinability, high ductility and improvement in formability.

The spheroidizing heat treatment consists of heating the alloy at a temperature just below the eutectoid point (about 700°C] in the γ-Fe+ Fe3C region of the phase diagram. During this annealing there is coagulation of the Fe3C to form the spheroid particles.



Normalizing

This is used as a finishing treatment for carbon steels giving higher strength than annealing. There is no serious loss of ductility too. Heating and soaking in this process is same as in the full annealing but part is allowed to cool in air so that cooling rate is much faster.

An annealing heat treatment called normalizing is used to refine the grains (i.e., to decrease the average grain size) and produce a more uniform and desirable size distribution. Fine grained pearlite steels are tougher than coarse-grained ones. The fine grain structure increases the yield and ultimate strengths, hardness and impact strength. Normalizing is accomplished by heating at approximately 55 to 85°C above the upper critical temperature, which is, of course, dependent on composition.

Normalizing often applied to castings and forgings is stress relieving process. To some extent, it increases strength of medium carbon steel. It improves machinability, when applied to low carbon steel. Alloy steels in which the austenite a procedure termed austenizing is very stable can be normalized to produce hard martensitic structure.

Cooling in air produces high rate of cooling which can decompose the austenitic structures in such steels and martensite is produced. This increases the hardness to great extent.

The advantages of this method are:

(i) In comparison to fully annealed material, normalizing produces stronger material.

(ii) Normalizing refines the grains.

(iii) Normalizing produces homogenised structure.

(iv) Normalizing is used to improve properties of steel castings instead of hardening and tempering.

(v) Strength and hardness are increased.

(vi) Better surface finish is obtained in machining.

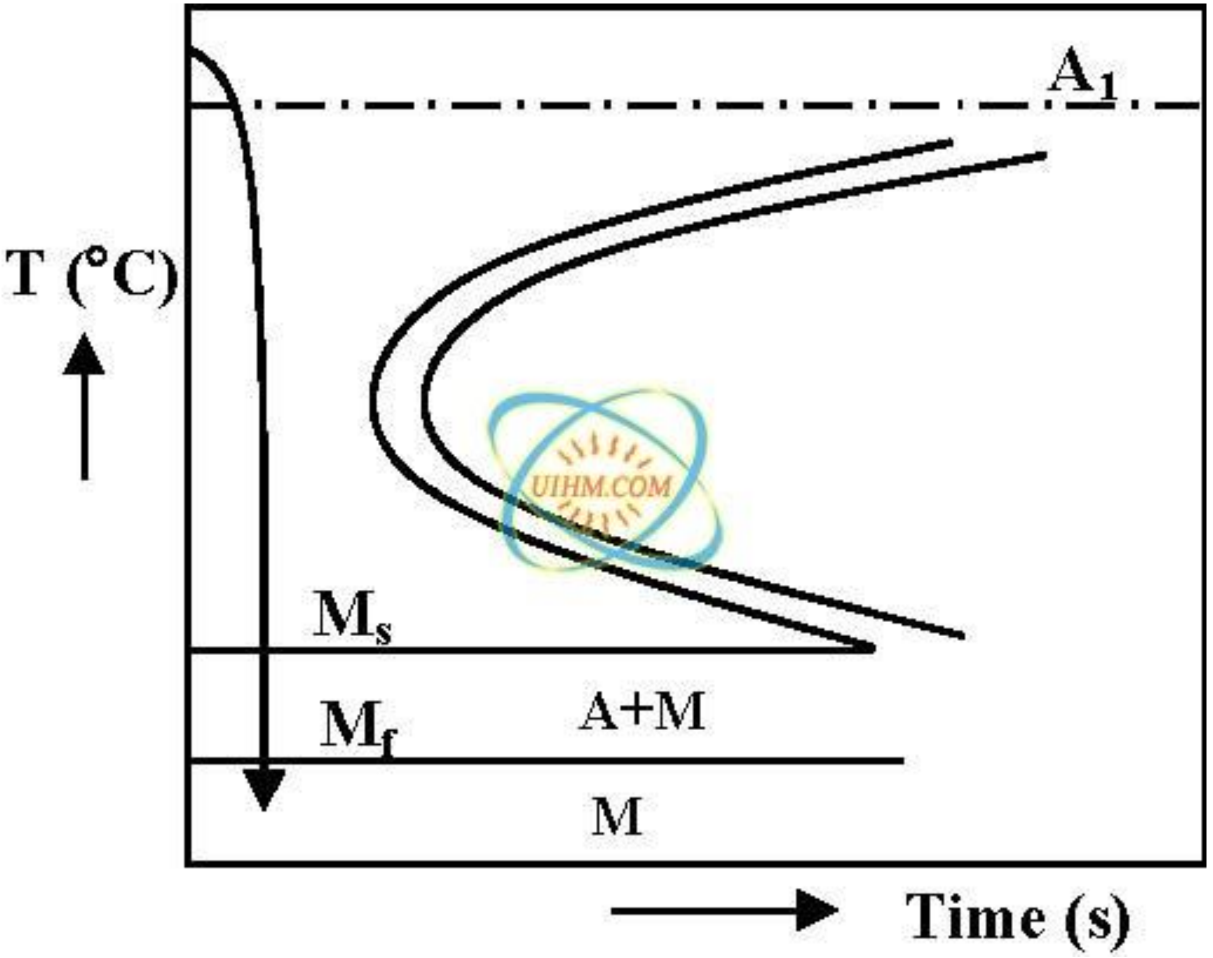
(vii) Resistance to brittle fracture is increased in hot-rolled steel.

(viii) Crack propagation is checked..

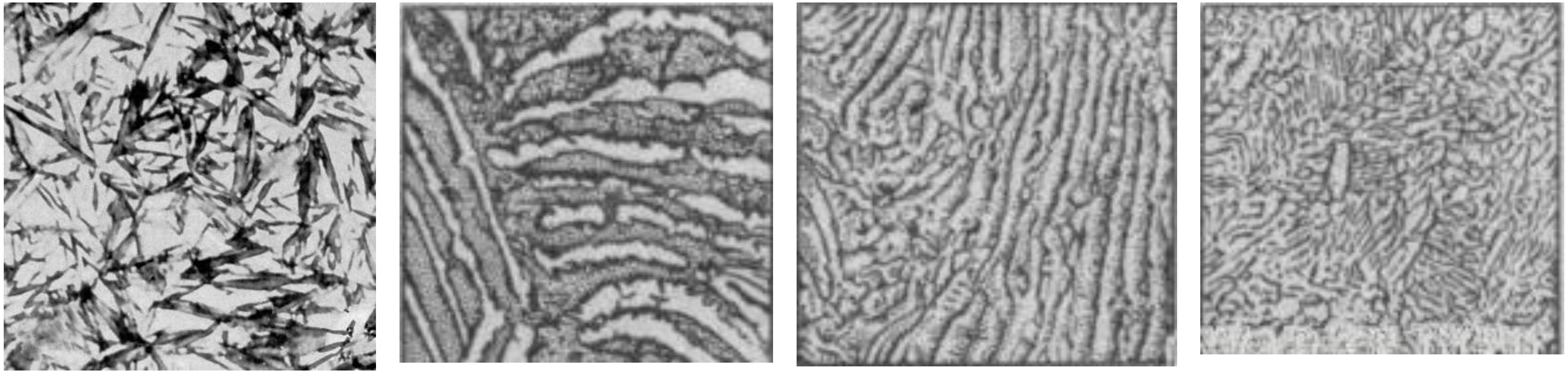
Hardening (quenching)

It is a kind of heat treatment which forms a non-equilibrium structure in an alloy. Non-equilibrium structures can be produced by heat treatment only in cases when the alloy being treated undergoes certain transformations in solid solutions, decomposition of a high-temperature solid solution by eutectoid reaction, etc. To form a non-equilibrium structure in an alloy, it is heated above the temperature of the phase transformation in the solid state and then cooled (chilled) quickly; fast cooling is essential for preventing the equilibrium transformation during cooling. Structural and tool-making alloys are hardened in order to increase their strength.

Alloys undergoing a eutectoid transformation under the equilibrium conditions can be strengthened by hardening quite substantially. Their strength increases either due to the martensitic phase change or due to a reduction of the temperature of eutectoid reaction; in both cases there forms a fine grained eutectoid mixture. If the hardening procedure has resulted in that the metal at room temperature (20-25°C) has the fixed state of hightemperature solid solution, the strengthening effect immediately after hardening is insignificant; it will be pronounced mainly on a repeated low-temperature heating or after holding at 20-25°C. In alloys possessing special properties, hardening makes it possible to change the structure-sensitive physical and chemical properties, for instance increases the electric resistance, coercive force or corrosion resistance.



Typical diagram of quenching process



a. Martensite b. Pearlite c. Sorbite d. Troostite

Microstructure of steel after various types of heat treatment

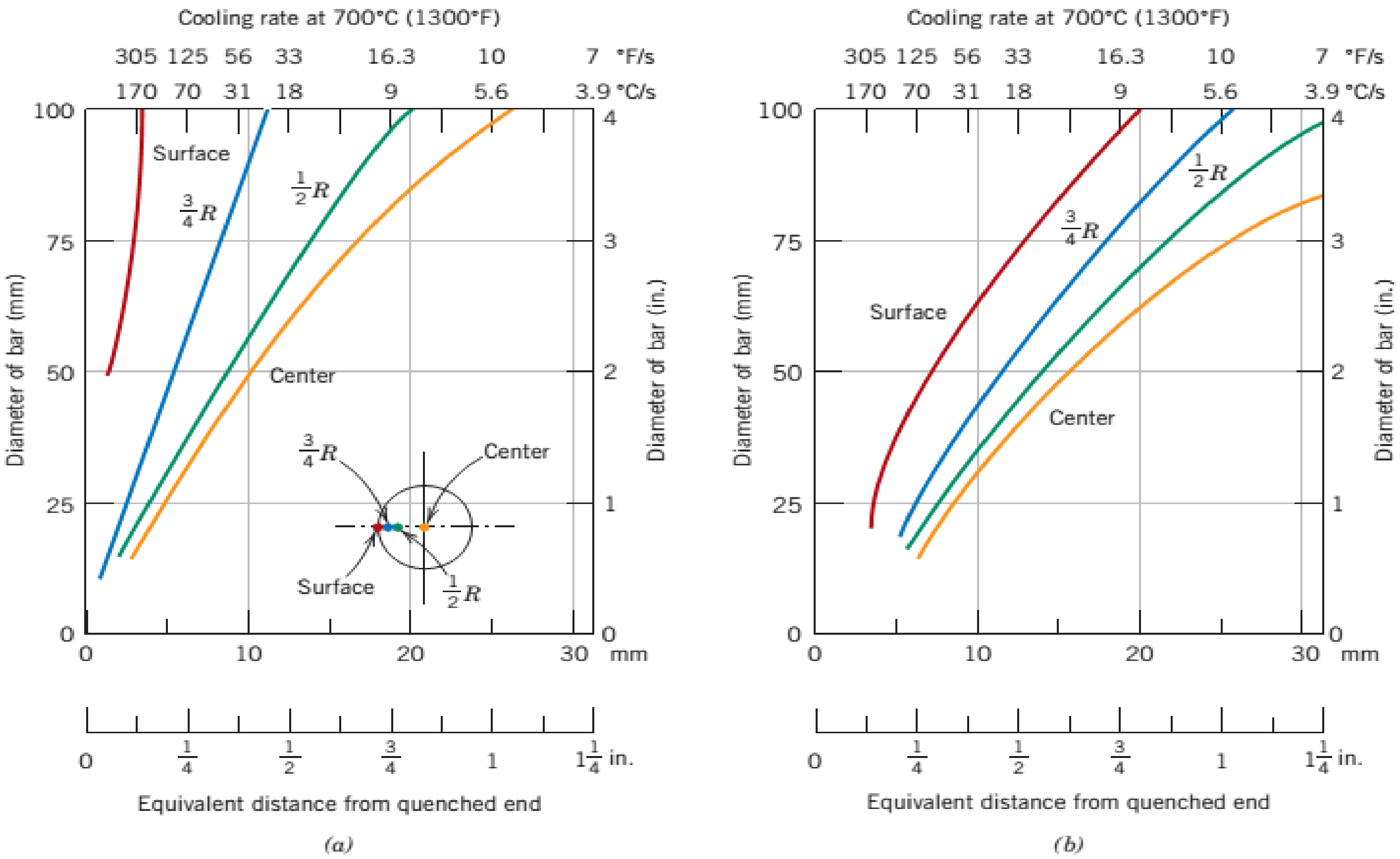
Martensite is supersaturated solid solution of carbon into α-iron and has high hardness. Sorbite is a mechanical mixture of ferrite and cementite, more dispersed and more hard than pearlite (equilibrium structure). Troostite is a mechanical mixture of ferrite and cementite, which is more dispersed and hard than sorbite.

The influence of quenching media, specimen size and geometry

The preceding treatment of hardenability discussed the influence of both alloy composition and cooling or quenching rate on the hardness. The cooling rate of a specimen depends on the rate of heat energy extraction, which is a function of the characteristics of the quenching medium in contact with the specimen surface, as well as the specimen size and geometry.

“Severity of quench” is a term often used to indicate the rate of cooling; the more rapid the quench, the more severe the quench. Of the three most common quenching media—water, oil, and air—water produces the most severe quench, followed by oil, which is more effective than air.

The degree of agitation of each medium also influences the rate of heat removal. Increasing the velocity of the quenching medium across the specimen surface enhances the quenching effectiveness. Oil quenches are suitable for the heat treating of many alloy steels. In fact, for higher-carbon steels, a water quench is too severe because cracking and warping may be produced. Air cooling of austenitized plain carbon steels ordinarily produces an almost totally pearlitic structure.



Cooling rate as a function of diameter at surface, three-quarters radius (3\4 R), midradius (1\2 R), and center positions for cylindrical bars quenched in mildly agitated (a) water and (b) oil. Equivalent Jominy positions are included along the bottom axes.

During the quenching of a steel specimen, heat energy must be transported to the surface before it can be dissipated into the quenching medium. As a consequence, the cooling rate within and throughout the interior of a steel structure varies with position and depends on the geometry and size. Figures above show the quenching rate at C (F) as a function of diameter for cylindrical bars at four radial positions (surface, three-quarters radius, midradius, and center).

Quenching is in mildly agitated water and oil; cooling rate is also expressed as equivalent Jominy distance, since these data are often used in conjunction with hardenability curves. Diagrams similar to those in Figure above have also been generated for geometries other than cylindrical (e.g., flat plates).

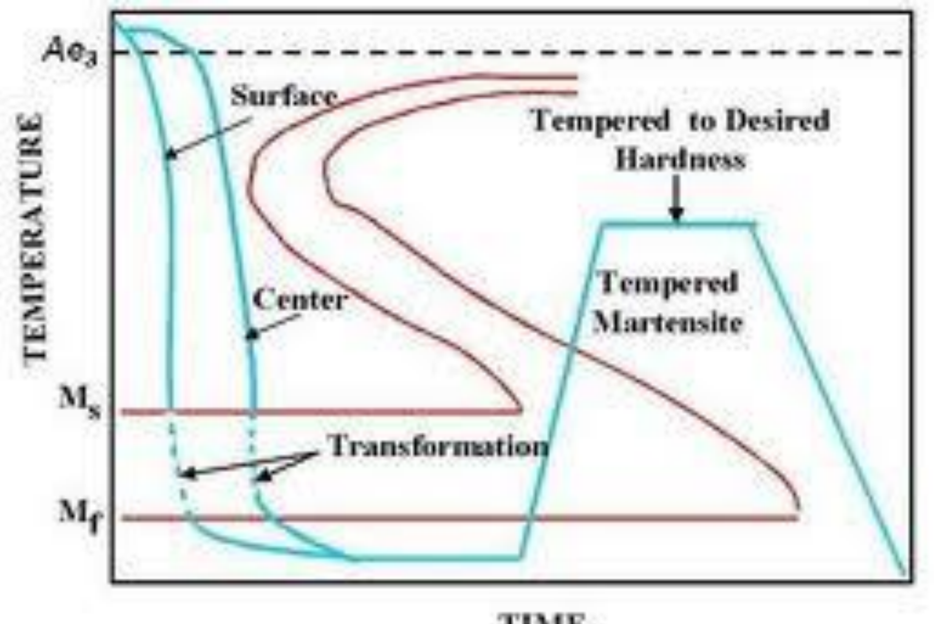
Tempering

Tempering is done after hardening. The steel is heated below Ac1, soaked and air cooled.

Tempering and ageing are the kinds of heat treatment which are applied to hardened alloys; they involve certain phase transformations which make the metal structure approach the equilibrium.

A combination of hardening and tempering or hardening and ageing is almost always aimed at obtaining higher properties (hardness, strength properties, coercive force, electric resistance, etc.) as compared to those resultant from annealing. In most alloys, hardening forms a supersaturated solid solution (or a mixture of solid solutions); in that case the main process occurring in the subsequent tempering or ageing is the decomposition of the supersaturated solid solution.
The temperature and holding time are chosen so as to avoid the formation of the equilibrium state in the alloy (as in the case of annealing). The rate of cooling from the temperature of tempering or ageing has no effect on the structure and properties of alloys (for only a few exceptions). The term ‘tempering’ is usually applied to steels and other alloys undergoing a polymorphic transformation in hardening (two-phase aluminium, bronzes, some titanium alloys) and the term ‘ageing’ to alloys which undergo no polymorphic transformations in hardening (aluminium alloys, austenitic steels, nickel alloys, etc.).

Tempering releases the stresses and reduces the brittleness. Tempering causes the transformation of the martensite into less brittle structure, i.e., a fine pearlistic structure termed as troostite. Troostitie is much tougher, although somewhat softer than martensite. Most c.s. cutting tools have this type of structure. Once the tempering temperature has been reached, it is normal to quench the steel. All structures resulting from tempering are termed tempered martensite. The changes taking place during various temperature ranges are as follows:



Conventional Quench and Tempering Method

(a) 100°C-220°C Below 200°C tempering temperature only relieves the hardening stresses and very little change occurs in the micro-structure. However, the stress relieving treatment is given when maximum hardness is desirable and brittleness is a problem. The strain is relieved due to removal of carbon atoms from their trapped positions.

(b) 240°C-400°C Above 220°C the martensite starts to change into a fine pearlistic structure termed as troostite. In the range of temperature 240°-400°C, martensite decomposes rapidly into emulsified form of pearlite called as secondary troostite. This type of material is very fine in nature and hence provides good shock resistance. The fine edge tools are usually tempered within the range 270°C-300°C.

(c) 400°C-550°C Tempering above 400°C causes the cementite particles to ball up giving a coarse structure called sorbite, which is more ductile and tougher than troostite. Within this range, the precipitate troostite begins to coalesce forming a coarser form of globular pearlite called as sorbite. We may note that both troostite and sorbite are now preferably called tempered martensite. This treated is usually preferred in such components as beams, springs and axles.

(d) 600°C-700°C Within this range, heating hardened steel causes spheroidisation, the structure being known as spherodite. This structure is formed due to further coalescence of the carbide within the alloy. Spheroidised steels exhibit fairly good machinability as the hard carbide particles are embedded in the soft ferrite matrix and consequently do not have to be cut by the cutting tool. When the shperoidized steel is heated to just above its lower critical temperature the pearlite present will alter to austenite and cooling to room temperature will yield a structure of lamellar pearlite plus pro-eutectoid ferrite or cementite depending upon carbon content. Usually the temperature of tempering is judged by colour appearance on shop floors. However, for accuracy, the exact temperature measurement are to be made.

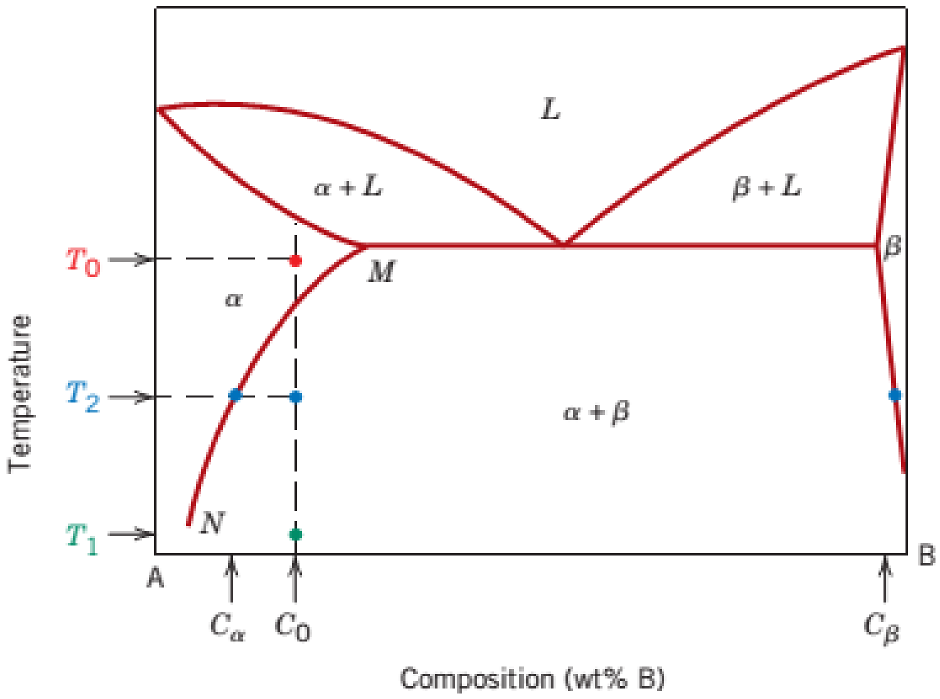
The combination of hardening and high temperature tempering is called martempering

Age hardening

The strength and hardness of some metal alloys may be enhanced by the formation of extremely small uniformly dispersed particles of a second phase within the original phase matrix; this must be accomplished by phase transformations that are induced by appropriate heat treatments. The process is called **precipitation hardening** because the small particles of the new phase are termed “precipitates.” “Age hardening” is also used to designate this procedure because the strength develops with time, or as the alloy ages. Examples of alloys that are hardened by precipitation treatments include aluminum–copper, copper–beryllium, copper–tin, and magnesium–aluminum; some ferrous alloys are also precipitation hardenable. Precipitation hardening and the treating of steel to form tempered martensite are totally different phenomena, even though the heat treatment procedures are similar; therefore, the processes should not be confused. The principal difference lies in the mechanisms by which hardening and strengthening are achieved. These should become apparent as precipitation hardening is explained.

Heat Treatments

Inasmuch as precipitation hardening results from the development of particles of a new phase, an explanation of the heat treatment procedure is facilitated by use of a phase diagram. Even though, in practice, many precipitation-hardenable alloys contain two or more alloying elements, the discussion is simplified by reference to a binary system. The phase diagram must be of the form shown for the hypothetical A–B system in Figure below. Two requisite features must be displayed by the phase diagrams of alloy sys tems for precipitation hardening: an appreciable maximum solubility of one com ponent in the other, on the order of several percent; and a solubility limit that rapidly decreases in concentration of the major component with temperature reduction. Both these conditions are satisfied by this hypothetical phase diagram. The maximum solubility corresponds to the composition at point M. In addition, the solubility limit boundary between the and phase fields dimin ishes from this maximum concentration to a very low B content in A at point N. Furthermore, the composition of a precipitation-hardenable alloy must be less than the maximum solubility. These conditions are necessary but not sufficient for precipitation hardening to occur in an alloy system. An additional requirement is discussed below.



Hypothetical phase diagram for a precipitation-hardenable alloy of composition C0.

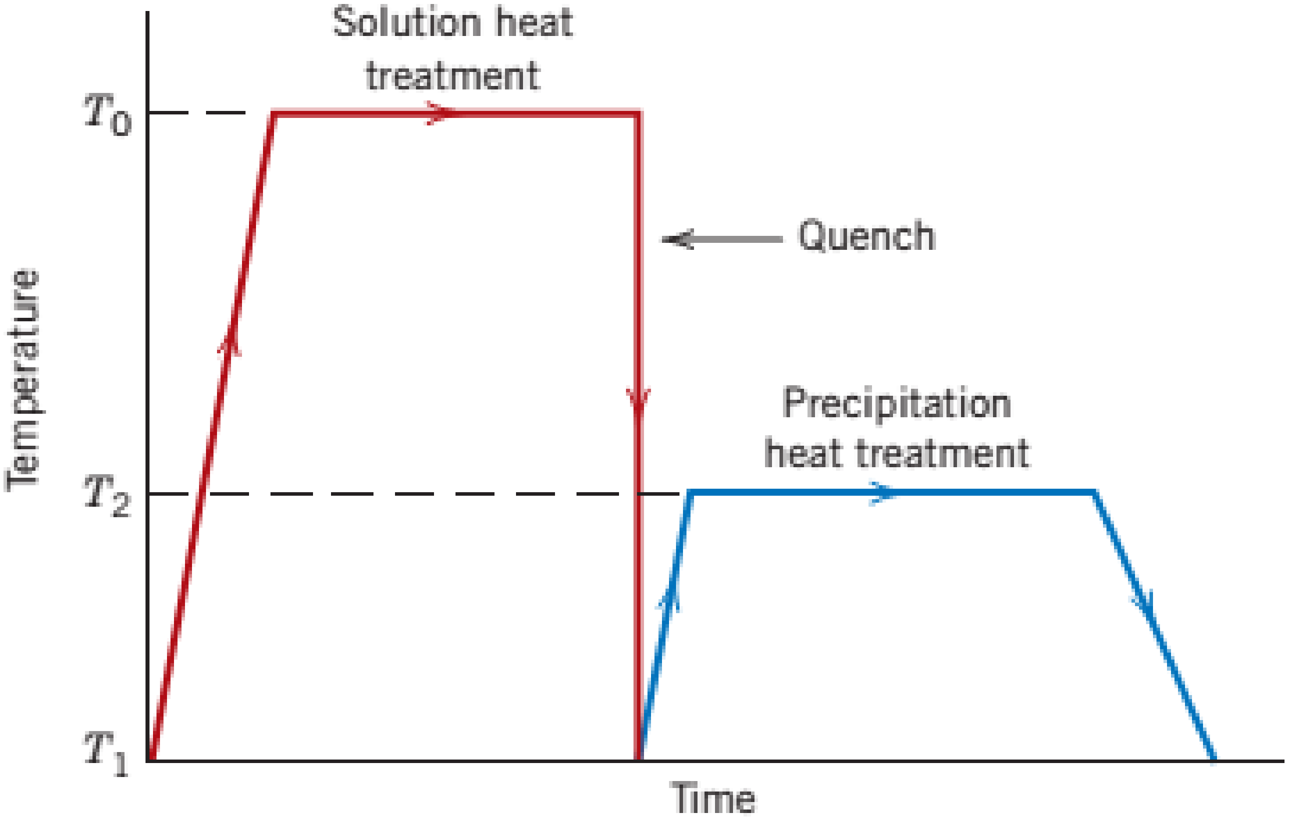
Solution Heat Treating

Precipitation hardening is accomplished by two different heat treatments. The first is a **solution heat treatment** in which all solute atoms are dissolved to form a singlephase solid solution. Consider an alloy of composition in Figure 11.21. The treatment consists of heating the alloy to a temperature within the phase field—say, T_0—and waiting until all the phase that may have been present is completely dissolved. At this point, the alloy consists only of an phase of composition This procedure is followed by rapid cooling or quenching to temperature which for many alloys is room temperature, to the extent that any diffusion and the accompanying formation of any of the phase are prevented. Thus, a nonequilibrium situation exists in which only the -phase solid solution supersaturated with B atoms is present at in this state the alloy is relatively soft and weak. Furthermore, for most alloys diffusion rates at are extremely slow, such that the single phase is retained at this temperature for relatively long periods.

Precipitation Heat Treating

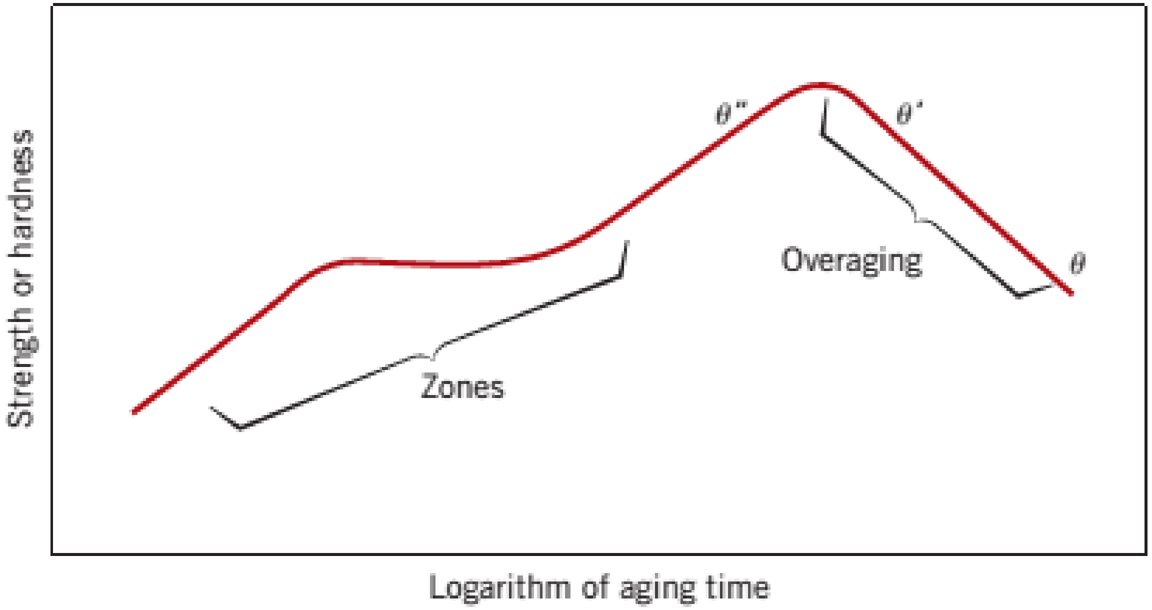
For the second or **precipitation heat treatment,** the supersaturated solid solution is ordinarily heated to an intermediate temperature (Figure above) within the two-phase region, at which temperature diffusion rates become appreciable.

The precipitate phase begins to form as finely dispersed particles of composition which process is sometimes termed “aging.” After the appropriate aging time at the alloy is cooled to room temperature; normally, this cooling rate is not an important consideration. Both solution and precipitation heat treatments are represented on the temperature-versus-time plot, Figure below. The character of these particles, and subsequently the strength and hardness of the alloy, depend on both the precipitation temperature and the aging time at this temperature. For some alloys, aging occurs spontaneously at room temperature over extended time periods.



Schematic temperature-versus-time plot showing both solution and precipitation heat treatments for precipitation hardening.

The dependence of the growth of the precipitate particles on time and temperature under isothermal heat treatment conditions may be represented by C-shaped curves for the eutectoid transformation in steels. However, it is more useful and convenient to present the data as tensile strength, yield strength, or hardness at room temperature as a function of the logarithm of aging time, at constant temperature The behavior for a typical precipitation-hardenable alloy is represented schematically in Figure below.



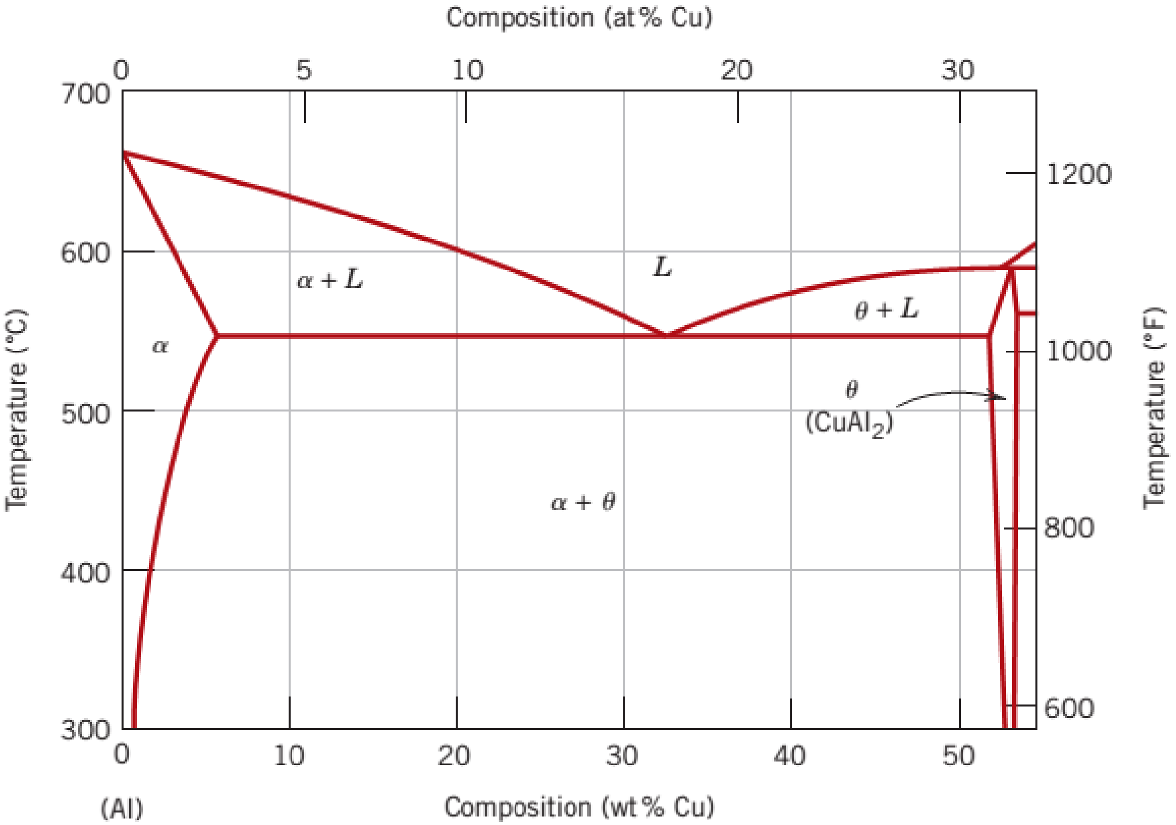
Schematic diagram showing strength and hardness as a function of the logarithm of aging time at constant temperature during the precipitation heat treatment.

With increasing time, the strength or hardness increases, reaches a maximum, and finally diminishes. This reduction in strength and hardness that occurs after long time periods is known as **overaging.** The influence of temperature is incorporated by the superposition, on a single plot, of curves at a variety of temperatures.

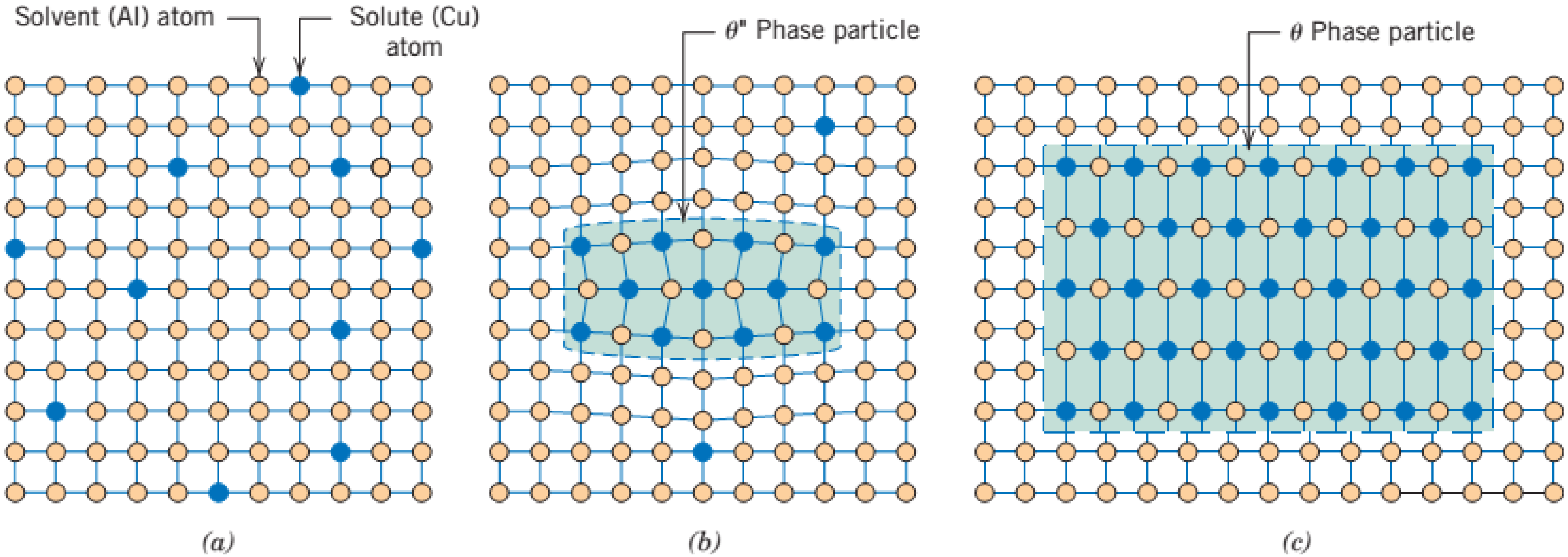
Mechanism of Hardening

Precipitation hardening is commonly employed with high-strength aluminum alloys. Although a large number of these alloys have different proportions and combinations of alloying elements, the mechanism of hardening has perhaps been studied most extensively for the aluminum–copper alloys. Figure below presents the aluminum-rich portion of the aluminum–copper phase diagram. The α phase is a substitutional solid solution of copper in aluminum, whereas the intermetallic compound CuAl2 is designated the θ phase. For an aluminum–copper alloy of, say, composition 96 wt% Al–4 wt% Cu, in the development of this equilibrium phase during the precipitation heat treatment, several transition phases are first formed

in a specific sequence. The mechanical properties are influenced by the character of the particles of these transition phases. During the initial hardening stage, copper atoms cluster together in very small and thin discs that are only one or two atoms thick and approximately 25 atoms in diameter; these form at countless positions within the phase. The clusters, sometimes called zones, are so small that they are really not regarded as distinct precipitate particles.

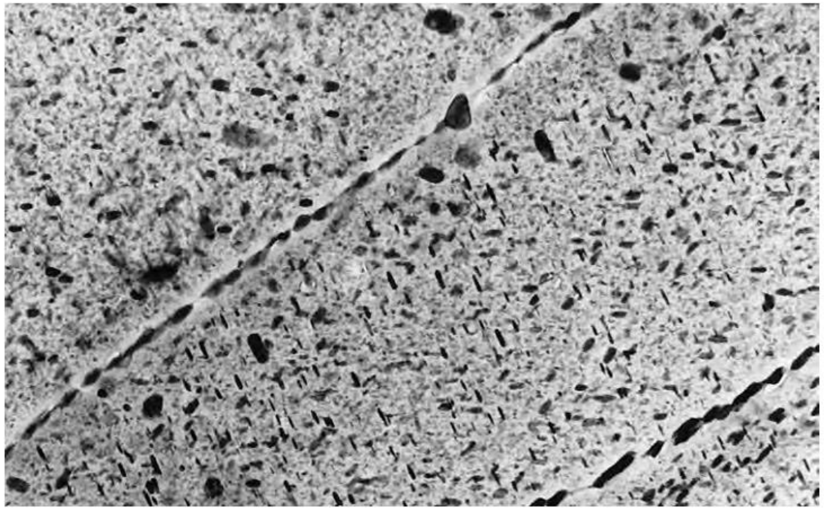


The aluminum-rich side of the aluminum–copper phase diagram



Schematic depiction of several stages in the formation of the equilibrium precipitate (θ) phase. (a) A supersaturated solid solution. (b) A transition, precipitate phase. (c) The equilibrium phase, within the -matrix phase.

However, with time and the subsequent diffusion of copper atoms, zones become particles as they increase in size. These precipitate particles then pass through two transition phases (denoted as θ’’ and θ’), before the formation of the equilibrium phase.Transition phase particles for a precipitation-hardened 7150 aluminum alloy are shown in the electron micrograph of Figure

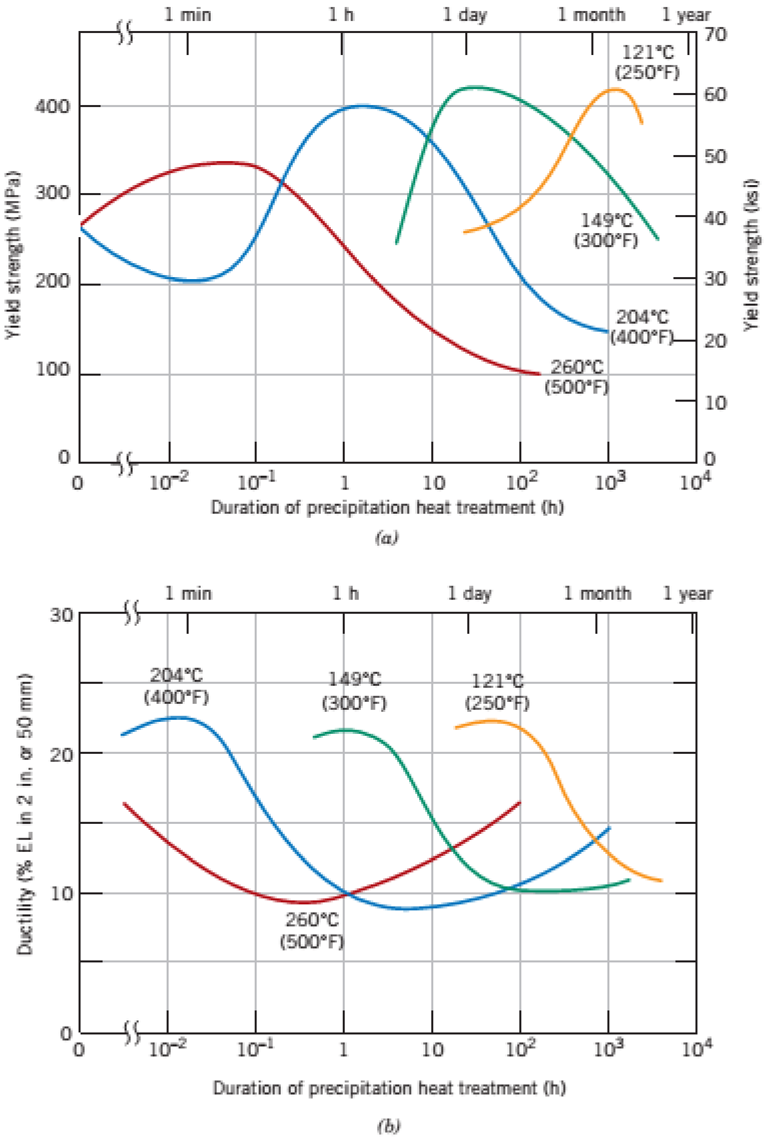


A transmission electron micrograph showing the microstructure of a 7150-T651 aluminum alloy (6.2Zn, 2.3Cu, 2.3Mg, 0.12Zr, the balance Al) that has been precipitation hardened. The light matrix phase in the micrograph is an aluminum solid solution. The majority of the small plate-shaped dark precipitate particles are a transition η-phase, the remainder being the equilibrium ($MgZn_2$) phase. Note that grain boundaries are “decorated” by some of these particles

The strengthening and hardening effects shown in Figure below result from the innumerable particles of these transition and metastable phases. As noted in the figure, maximum strength coincides with the formation of the θ’ phase, which may be preserved upon cooling the alloy to room temperature.

Overaging results from continued particle growth and the development of θ’’ and θ’ phases. The strengthening process is accelerated as the temperature is increased. This is demonstrated in Figure a, a plot of yield strength versus the logarithm of time for a 2014 aluminum alloy at several different precipitation temperatures. Ideally, temperature and time for the precipitation heat treatment should be designed to produce a hardness or strength in the vicinity of the maximum.

Associated with an increase in strength is a reduction in ductility, which is demonstrated in Figure b for the same 2014 aluminum alloy at the several temperatures. Not all alloys that satisfy the aforementioned conditions relative to composition and phase diagram configuration are amenable to precipitation hardening.



The precipitation hardening characteristics of a 2014 aluminum alloy (0.9 wt% Si, 4.4 wt% Cu, 0.8 wt% Mn, 0.5 wt% Mg) at four different aging temperatures: (a) yield strength, and (b) ductility (%EL).

Surface hardening

Introduction

A number of components require only a hard surface to resist wear and tear and a tough core to resist shock loads instead of complete component being made hard. These two properties do not exist in one steel. For toughness, one finds that the core should not exceed 0.3% carbon content, also sometimes it is not desirable to harden complete component. For example, it is undesirable to have case harden screw threads. The threads would be brittle and distortion during hardening would need expensive thread grinding operations to correct the distortions. Surface hardening is classified into two types: selective heating and chemical heat treatment.

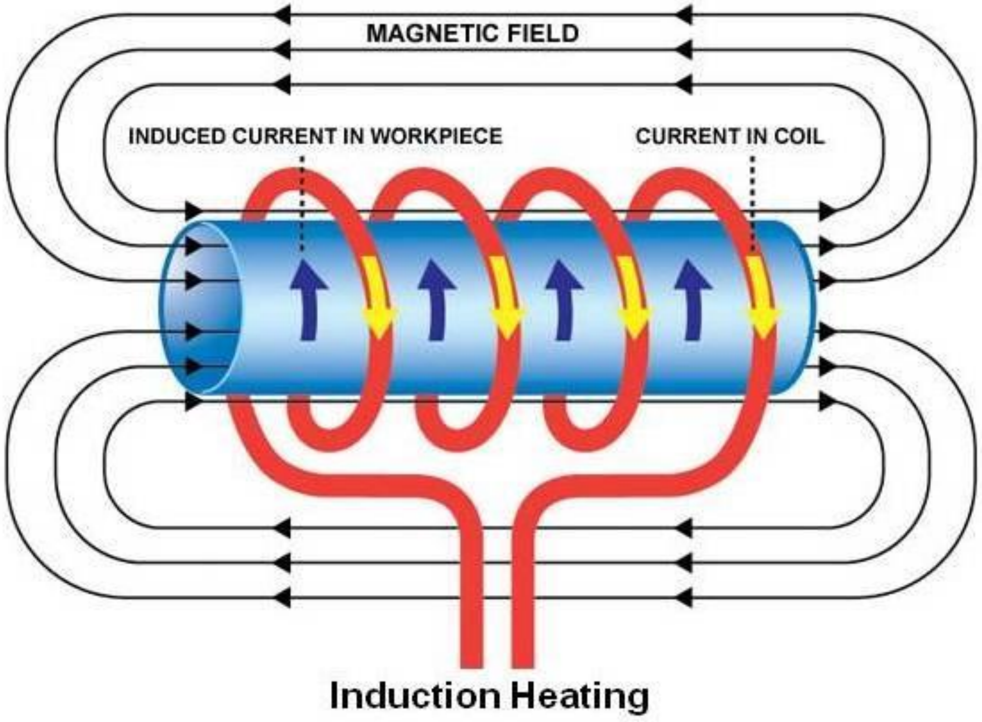
Selective heating

In this case, the time available to change the micro-structure of steel is short. Obviously, hardened and tempered steels respond well but annealed steels do not. Moreover, composition of the steel must be such that the quenching will produce martensite and so harden the steel. Clearly, carbon content to be 0.4% or more.

Flame hardening can be one of the method of selective heating. The surface of a component is heated to 850°C with an oxyacetylene flame and quenched with cold water immediately. Flame heating transforms the structure of the surface layers to austenite and quenching changes the austenite surface layers to martensite resulting into a hard surface. Depth of hardening depends on the heat supplied per unit time.

Flame hardening is mostly used in case of carbon and alloy steels having carbon content 0.4% to 0.6, e.g. shafts, gears, cylinder linears, crank shafts bearing journals, etc.

Another method of selective heating is **induction hardening.** Steel components are placed within a coil through which a high frequency is allowed to pass. Surface layers of the component are heated between 850-1000°C. Subsequently cooling transforms the austenite to martensite. The heating coil is often made of tube perforated with fine spray holes so that it can be used both for heating and quenching. The depth of heating produced by this method is related to the frequency of the alternating current. Higher the frequency of a.c. current, less will be the hardened depth, but there will be more rapid rise in temperature.



Induction hardening schematic

As a kind of selective heating, a self-tempering may be referred. In this method a steel item is quenched in water or oil. Core remains unquenched, and upper layer changes to martensite. After appropriate time of cooling steel part is removed from quenching medium and allowed to continue cooling at still air. The surface layer starts to heat due to convection of heat from the core portion. This heat is high enough to heat it to annealing temperature. This method allows precise temperature and time control.

Induction-hardened spur gear

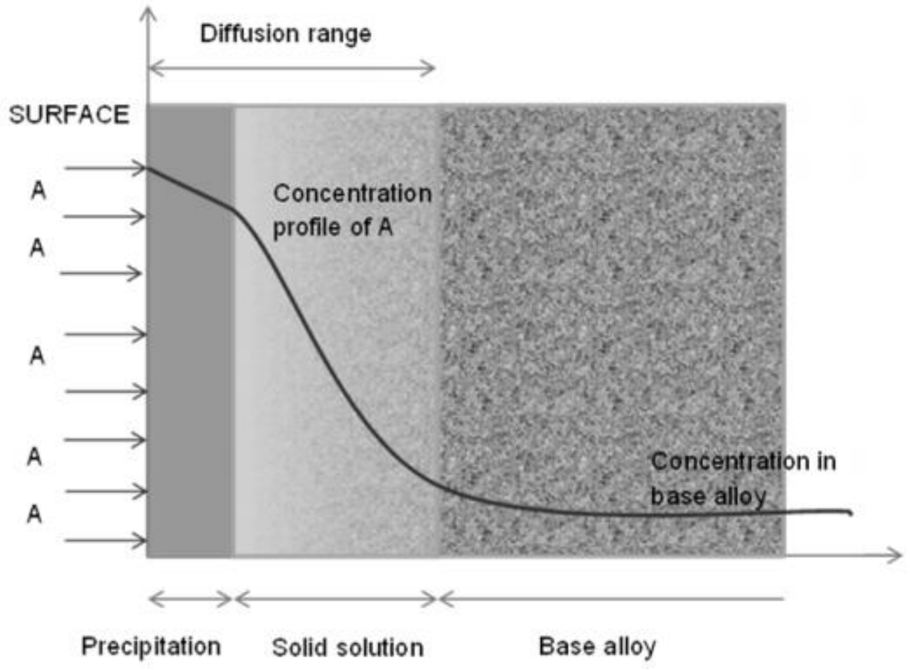
Chemical heat treatment

Introduction

Chemical heat treatment (CHT) - is the process of changing the chemical composition, microstructure and properties of the surface layer of metals by high-temperature diffusion saturation by atoms of other elements that solve in base material or form chemical compounds with it.

Surface engineering represents the technically attractive and economically viable method aimed at improving the superficial layer of materials. Since the material surface controls the service life in many applications, the objective is to develop a wide range of functional properties that are different from the base substrate including physical, chemical, electrical, electronic, magnetic or mechanical. Being a part of surface engineering, the thermochemical treatment employs thermal diffusion to incorporate non-metal or metal atoms into a material surface to modify its chemistry and microstructure. The process is conducted in solid, liquid or gaseous media with one or several simultaneously active chemical elements. For majority of thermochemical treatments the mechanism includes a decomposition of solid, liquid or gaseous species, splitting of gaseous molecules to form nascent atoms, absorption of atoms, their diffusion into a metallic lattice and reactions within the substrate structure to modify existing or form new phases. Since in industrial scale processes the entire part is subjected to high temperatures, surface diffusion is superimposed on changes within the material volume that for some treatments may involve phase transformations and this adds to the complexity. Historically, the thermochemical treatment was limited to machined parts, forgings and castings with an application in machinery, automotive, tooling, oil drilling, mining and defence. The key processes covered nitriding, carburizing and their combinations. Similarly, steel was in practice the only material subjected to the modification. To enhance the process predictability and repeatability, the conventional gas nitriding was refined and the alternative technique of ion (plasma) nitriding was introduced. In quest for the perfect process, the plasma technology is still a subject of continuous improvement and developed techniques of post discharge nitriding or active screen plasma nitriding may serve as examples. In the meantime, the thermochemical modifications included other processes such as boronizing, aluminizing, chromizing or thermo-reactive diffusion, exploring vanadium, molybdenum and other carbide-forming elements. Although they never achieved the application level of nitriding, they successfully serve many niche markets.

Strengthening the surface layers of products that are made from inexpensive and non-deficient alloy as base material followed by CHT got broad application.



Saturation of steel by the element ”A”

Main advantage of CHT – is efficient change of the properties of surface layer by changing it chemical composition and getting a sufficient combination of properties on the surface and at the core of a metal.

Diffusion coating at CHT is formed under isothermal conditions at artificial environmets which provide direct or indirect contact and chemical interaction of components.

Temperature and active environment provide:

1. Activation of surface, dissolving the films, which prevent the diffusion of saturating element.

2. Dissociation – change of saturating element to the active atomic state

3. Chemical adsorption - "capture" of atoms of saturating element by the metal surface.

4. Heterodiffusion - atoms penetrate deep into the metal surface

The rate and deepness of diffusion determines the time necessary for CHT and the thickness of deposited coating.

For active solid state diffusion it is necessary to provide:

1. differential concentration of saturating element in active medium and the in surface being saturated.

2. Atomic radius of saturating element shouldn’t be more then 15% more then atomic radius of metal being saturated.

3. Interacting elements should dissolve in each other or should propagate reactive diffusion.

4. To provide sufficient temperature

Methods of chemical heat treatment

Depending on the physical state of saturating element there are the following methods of CHT:

1) saturation by solid phase (solid-phase method);
2) saturation by liquid phase (liquid-phase method);
3) saturation by gas phase (gas-phase method);
4) saturation by vapor phase (vapor-phase method).

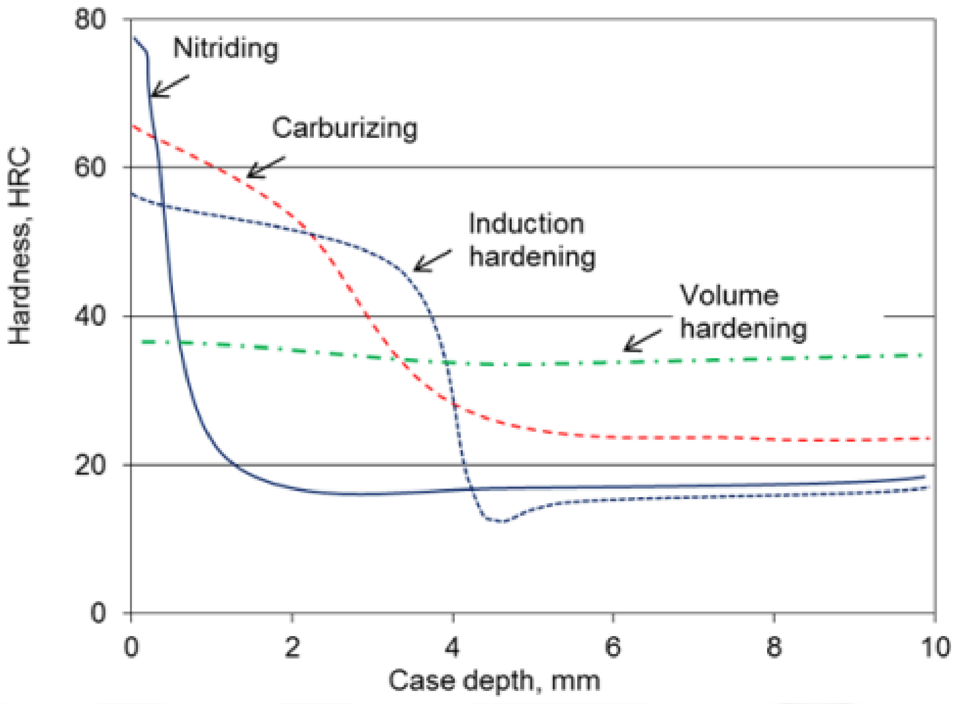
The saturation by solid phase. With this method, the saturation of products in contact with the diffusing element that is in the solid state. Preferably powders of pure metals and ferrous alloys are used. The finer the powder, the more even coating is obtained.

The saturation at liquid phase. For this type of saturation diffusing element can be in the following states:
1) in the molten state ;
2) chemical compounds (molten salts of saturating metals);
3) in molten solution with other metals that can not penetrate the surface due to diffusion (Li, Na, Rb, Ca, Bi , etc.).

Nitriding

Nitriding is the process of surface saturation with nitrogen. As a result of nitriding metal surface becomes very hard (HV 1300)

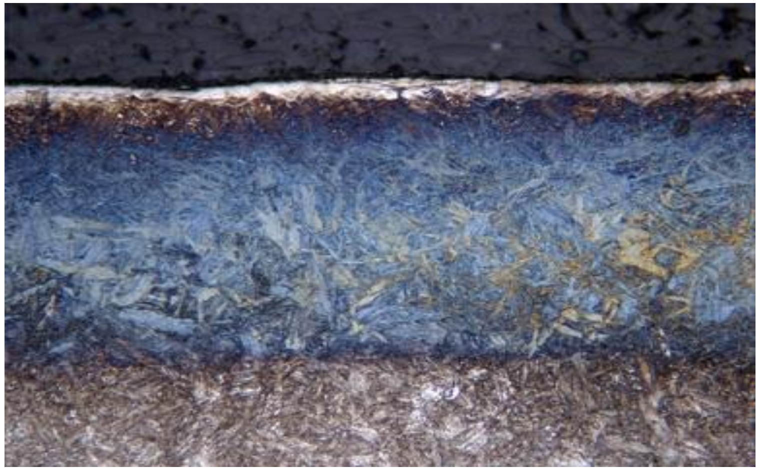
Nitriding has been and continues to be the major thermochemical treatment which along with ferritic nitrocarburizing represents the dominant volume of industrial surface modification technologies. The treatment leads to an incorporation of nitrogen into the surface of steel while it is in ferritic state. In commercial applications, the typical modified zone is up to 200-300 μm thick, rarely exceeding 600 μm. Its impact on surface hardness distribution, in terms of the maximum value and penetration depth, as compared with other heat and thermochemical treatments, is shown below. There is no additional heat treatment required following nitriding and the component surface experiences an increase in hardness, wear resistance, improved corrosion resistance and fatigue life.



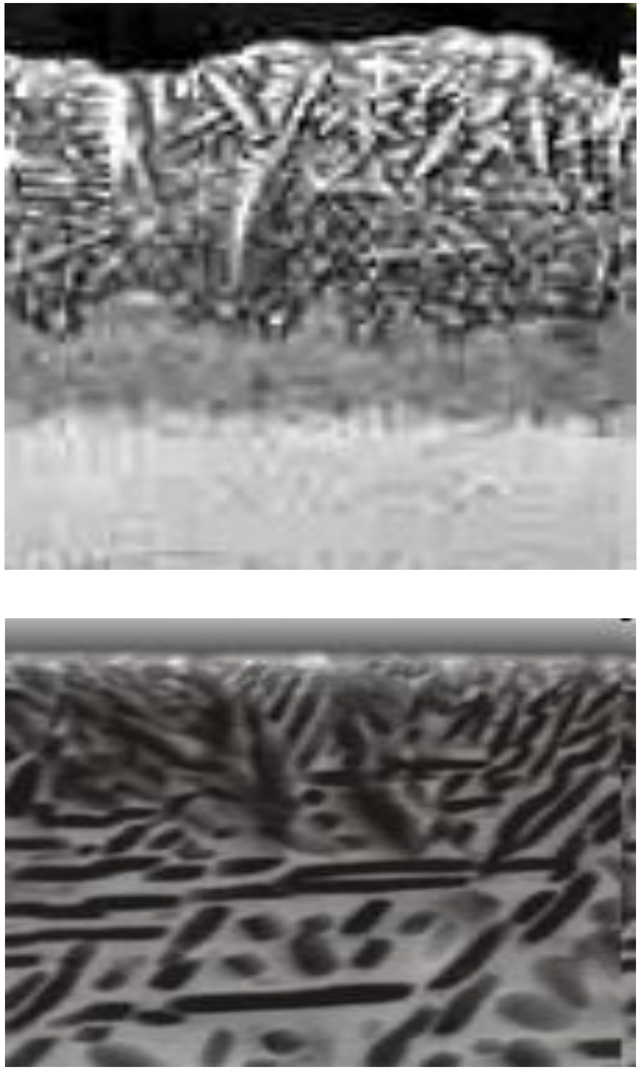
Hardness depth profiles for selected thermal and thermochemical treatments, emphasizing differences in the maximum hardness and penetration depth

There are two types of nitriding :
Low temperature nitriding is carried out at a temperature below 600 ° C. As a result , regardless of the environment , mainly nitrogen diffuses to the surface.

High temperature nitriding is carried out at temperatures above the eutectoid transformation temperature (700-1200 ° C). This type is used for nitriding ferritic and austenitic steels, refractory metals



Nitrided steel



Nitrided titanium alloy

Nitriding is carried out on finished products after the final heat treatment . The optimal structure for nitriding is sorbite, so the details are subjected to martempering before nitriding.

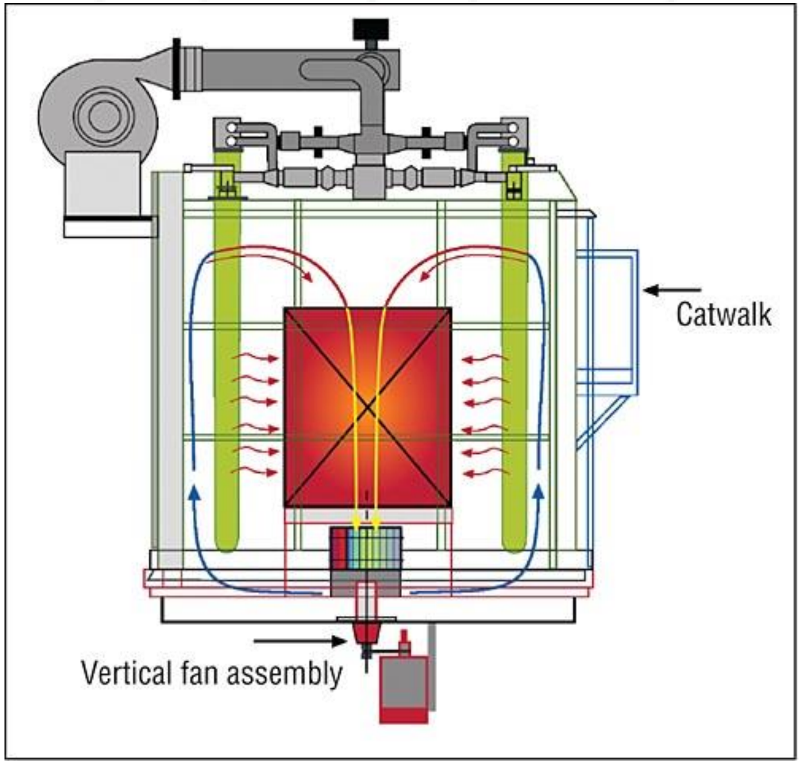
The disadvantages of the nitriding process should be considered as a very long process duration, reduced corrosion resistance and heat resistance of stainless, acid and heat resistant steels. The thickness of the nitrided layer ranges from 0.1-0.2 mm. Nitriding rate - 0.01 mm / hour

To implement nitriding, several technologies, exploring different sources of nitrogen, were commercialized.

Gas nitriding

Gas nitriding was patented in 1913 and 1921, and is carried out usually at temperatures of 550-580 oC in a box furnace or fluidized bed in an atmosphere filled with partially dissociated ammonia. The advantages of the fluidized bed are the near-ideal temperature uniformity through the entire gas-particle volume and fast heating rate. For gas nitriding the fundamental reaction is the catalytic decomposition of ammonia to form the nascent (elemental) nitrogen:

$$NH_3 = [N] + 3/2H_2$$



The control parameters include time, temperature and gas dissociation rate. In production environment, the latter is periodically measured and adjusted. The inherent feature of conventional gas nitriding is that the superficial concentration of nitrogen cannot be precisely monitored. As a result the structure of nitrided layer and the entire process are often missing predictability and repeatability.

Liquid salt nitriding Liquid nitriding, developed in 1940's, is conducted in the fused salt bath containing either cyanides or cyanates. A typical commercial bath is composed of a mixture of 60-70% sodium salts {96.5% NaCN, 2.5% Na_2CO_3, 0.5% NaCNO} and 30-40% potassium salts {96%KCN, 0.6%K2CO3, 0.75% KCNO, 0.5% KCl}. The commercial equipment for salt nitriding, along with gas and plasma technologies is shown in Figure below. The major advantage is the short cycle time due to intense heating and the high reactivity of the medium. Several methods exist to accelerate further the nitriding rate, such as bath additions of sulphur or melt pressurizing. Typically, for low-alloy steel the cycle time lasting 1.5 h at the operating temperature of 565 °C produces a case of 0.3 mm thick. The salt-bath technology has also a number of negative features, such as the bath toxicity and poor quality of the nitrided surface

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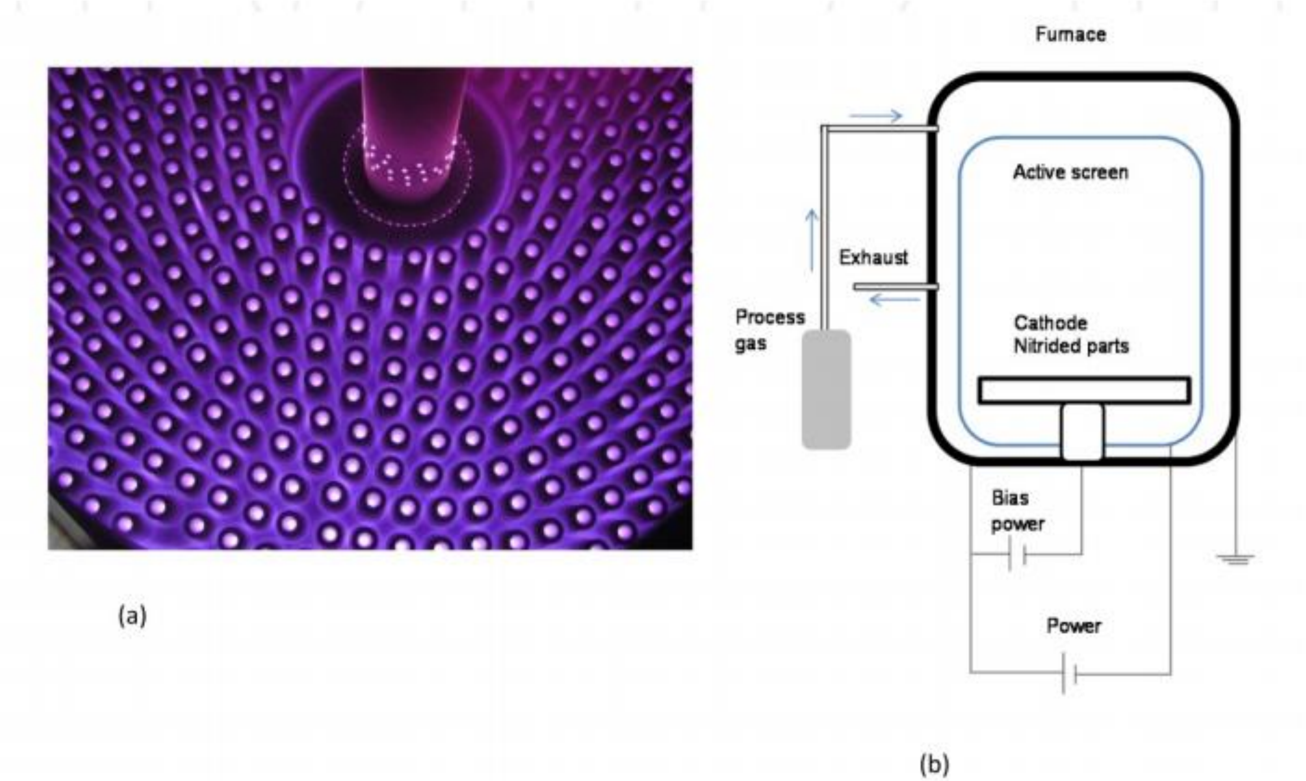
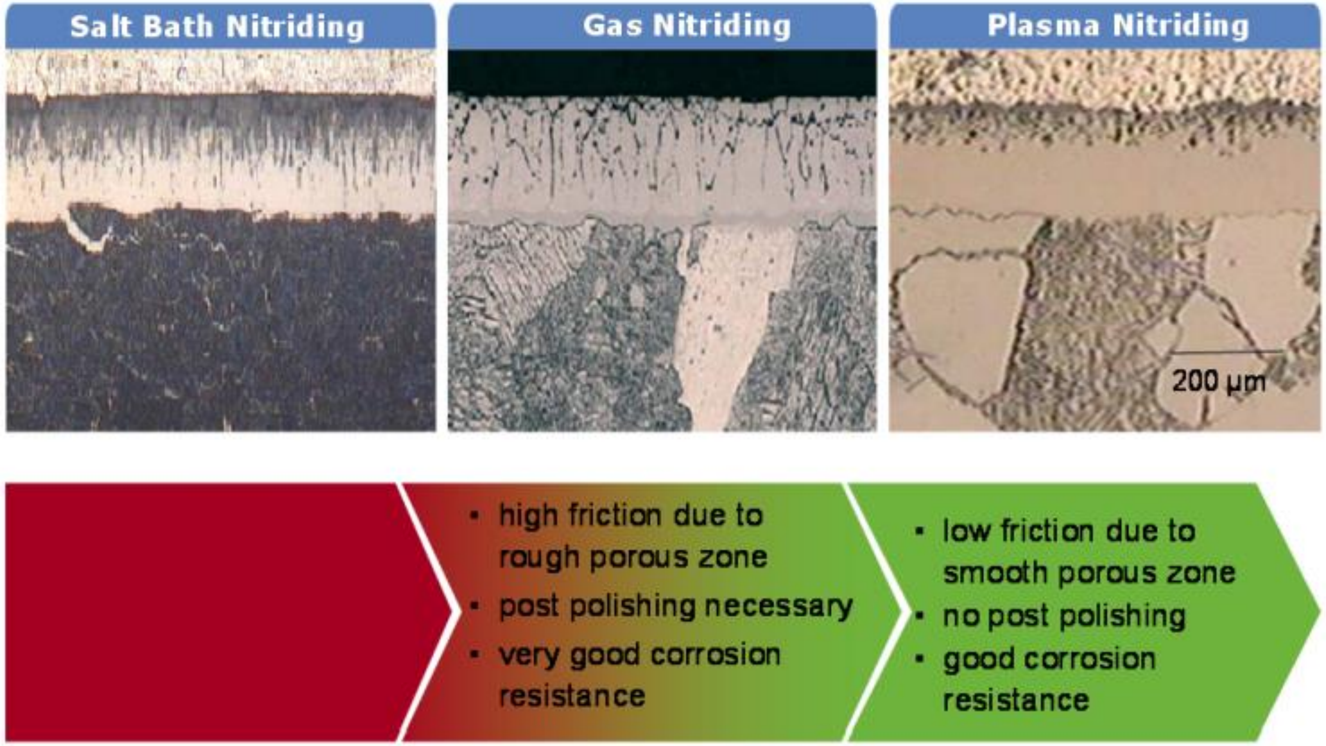
Salt bath nitriding process

Plasma (ion) nitriding

Plasma nitriding, called also ion nitriding, was invented by Wehnheldt and Berghause in 1932 but became commercially viable as late as in 1970's. It uses the glow discharge phenomenon to introduce nascent nitrogen to the surface of an alloy and its subsequent diffusion into subsurface layers. Plasma is formed in a vacuum using a high-voltage electrical energy to accelerate nitrogen ions which bombard the alloy surface. The advantages of ion nitriding include the low temperature, short saturation time and simple mechanical masking. The unique advantage is surface-activation sputtering. Due to the sputtering effect of positive ions in the glow discharge, the protective oxide, inherent for surfaces of stainless steels, aluminum or titanium alloys, is removed. Thus, nitrogen atoms can be moved from the plasma to the material sub-surface. In the conventional direct-current system the nitrided component is subjected to the high cathode potential and plasma forms directly on the component surface. This may create disadvantages such as the temperature non-uniformity with a possibility of overheating, sensitivity to the part geometry, causing edge effect and a possibility of surface damage due to arcing.



Plasma nitriding: (a) view of components during Ultraglow® process. (b) schematics showing a concept of active screen plasma nitriding



- high friction due to rough porous zone
- post polishing necessary
- very good corrosion resistance

- low friction due to smooth porous zone
- no post polishing
- good corrosion resistance

Microstructures of steel after liquid salt, gas and plasma nitriding along with some characteristic features aligned in a direction of improvement

Steels applicable to nitriding

Steels applicable to nitriding In general, nitriding is applicable to a wide variety of carbon steels, low alloy steels, tool steels, stainless steels and cast irons. For optimum properties after nitriding, however, there are steels with chemistries, particularly designed for this purpose. They contain strong nitride-forming elements such as Al, Cr, Mn, Mo and V. There is a limitation on carbon content which should not exceed 0.5%, as most nitride-forming elements also form stable carbides which limit binding of nitrogen. When differences in hardness depth profiles for carbon and alloyed steels are essential, there are also substantial differences between individual grades, designed for nitriding. The especially high surface hardening is achieved with steels containing Al, forming AlN nitrides. However, additions of Al, typically in the range of 1%, cause steel brittleness. The nickel nitriding steels containing aluminum develop higher core strengths than do nickel-free nitriding grades. Nickel also increases the toughness of the nitrided case. The base steel properties are of importance to provide the support for nitrided case, especially in applications where components carry high compressive and bending stresses.

Carburizing (cementation)

It is a process of saturation of metals and alloys by carbon for high surface hardness, wear resistance, fatigue strength. The most common methods of carburizing: 1) saturation at the gas environment , 2) saturation by solid carburizer 3) carburization by pastes.

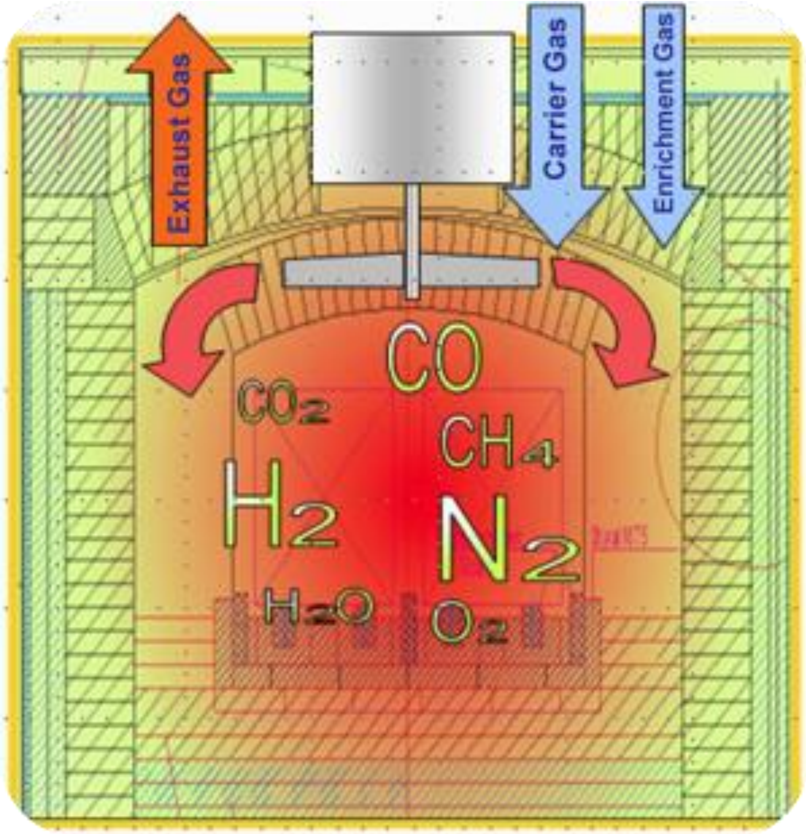
The objective of carburizing is to enrich surface layers of steel or other alloys with carbon. To achieve the sufficient carbon solubility and penetration depth the treatment is carried out at relatively high temperatures of 900-950°C. As a result, steels, which do not have the sufficient carbon content within their volume, obtain the hard surface. The reduced carbon content is deliberately selected to retain the core toughness. The endothermic carburizing atmospheres consist of a mixture of carburizing ingredients such as CO and CH_4 and decarburizing ones such as CO_2 and H_2O. To control the process, the carburizing potential of the furnace atmosphere requires the measurement of all the gas constituents CO, CO_2, CH_4 and H_2O. The driving force for carburizing is determined by the gradient between potentials of carbon in the furnace atmosphere and carbon at the steel surface. The key reactions of carburizing involve

$$2CO \rightarrow C_{(g-Fe)} + CO_2$$

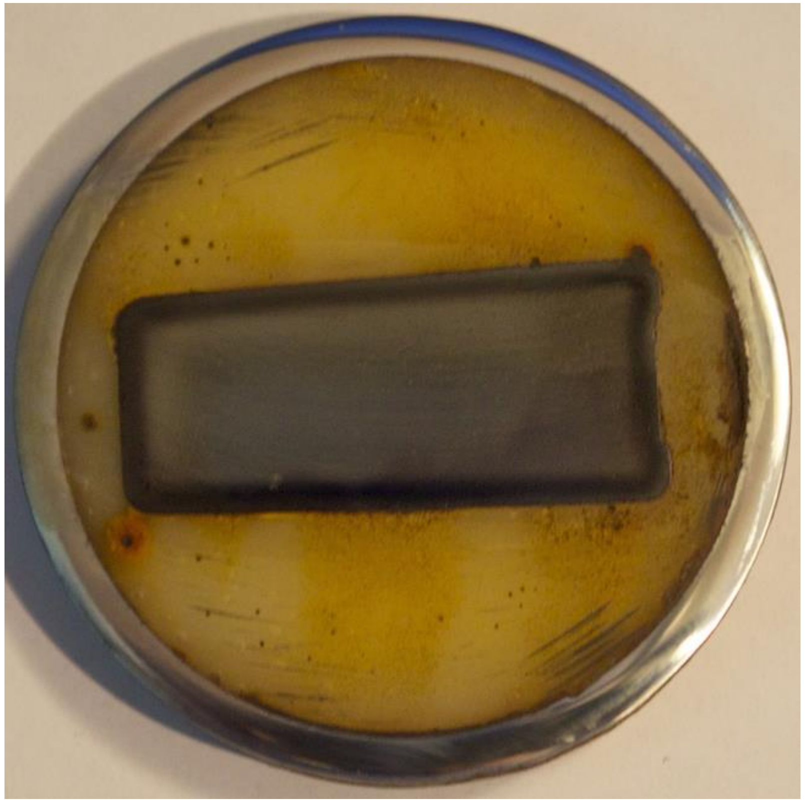
$$CH_4 \rightarrow C_{(g-Fe)} + 2H_2$$

$$CO + H_2 \leftrightarrow C_{(g-Fe)} + H_2O$$

A variety of applications of steel carburizing were explored for decades with typical examples of automotive gears. This includes also stainless steels, in particular the ferritic and austenitic stainless grades. Recently, the carburizing process creates a growing attention in area of martensitic stainless steels.



Furnace for gas carburizing

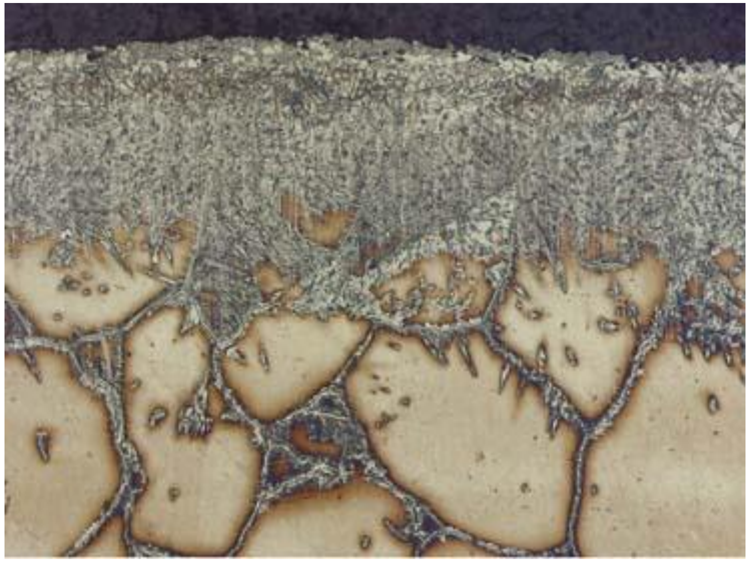


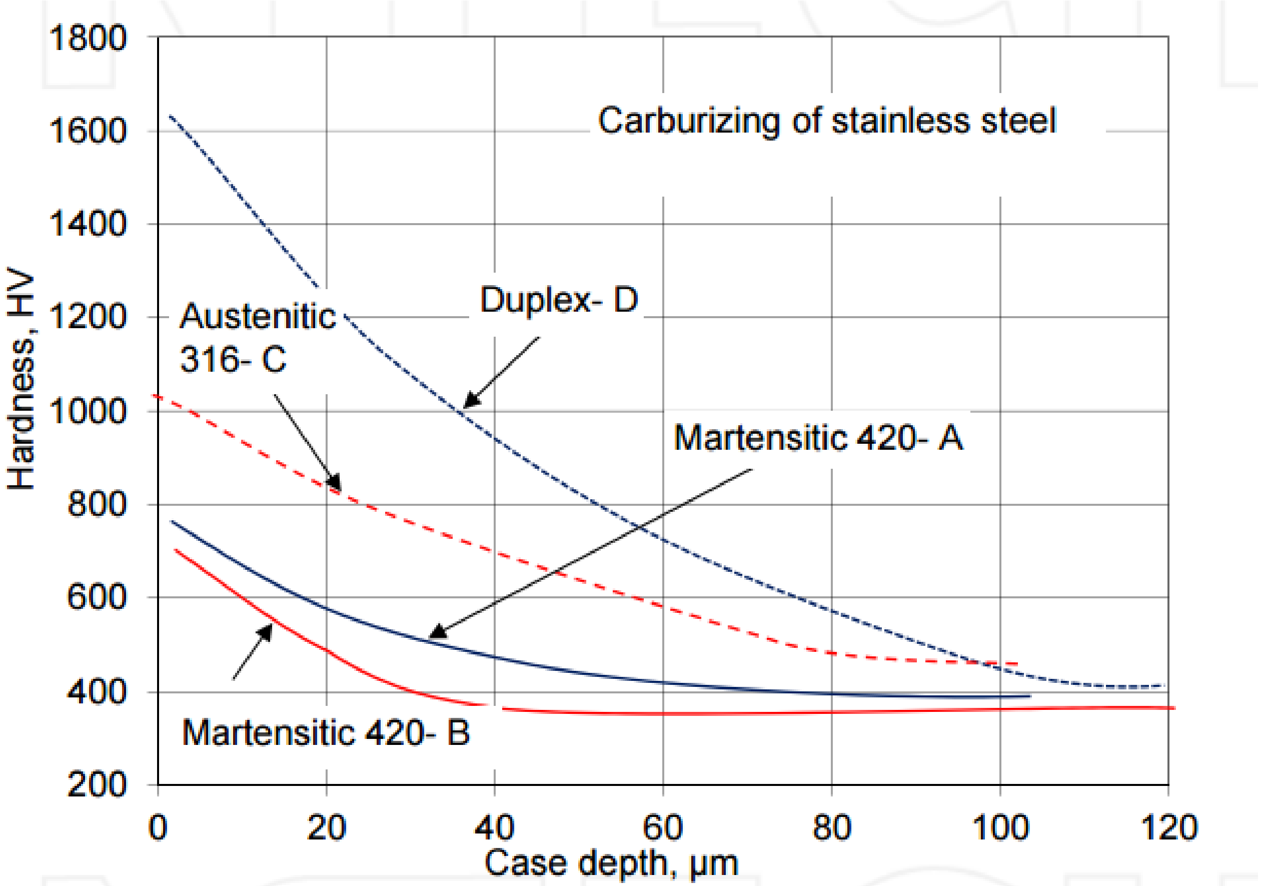
Carburized steel-made taper roller. Carburised layer forms a “casing” on the surface. This process is also called a “case hardening”

A comparison of hardness depth profiles for all three families of stainless steels is shown in Figure below. A relatively novel, low temperature gas carburizing at 470°C increases the surface hardness of AISI 316 austenitic stainless steel from 200 HV to 1000 HV through extreme supersaturation of up to 12 at.% carbon in the solid solution.

After treatment, two types of carbides M_5C_2 and M_7C_3 form with long needles or laths morphology, exhibiting the special orientation relationship with the austenitic matrix.

The plasma carburizing of AISI 410 stainless steel in a gas mixture of 80% H2 + 20% Ar with 0.5- 1% of CH4 by volume, leads to surface hardness of 600-800 HV with no evidence of reduced corrosion resistance.





Hardness depth profiles for carburized stainless steel of different grades: A – AISI 420 martensitic stainless steel, carburized in low temperature plasma at 450 ºC for 4 h in 1% CH4; B – as A but CH_4 concentration of 0.5%; C – AISI 316 austenitic stainless steel, gas carburized at 470 ºC for 246 h; D –JIS SUS329J1 duplex stainless steel, superplastically deformed and carburized in powder at 950 oC for 8 h

Process temperature varies depending on method (880 ... 1000 ° C.)

Gas carburizing. Active gas consists of CO- CO2 and contains small amounts of CH4, H2 and H2O.
Carburizing by solid phase (carburizing by powdered or granular mixtures). The basis of all solid Carburizers is coal.
Charcoal less active, but contains a minimal amount of harmful impurities.
Coal (coke) is less suitable because it contains sulfur and other contaminants

Carburizing by paste. The paste (suspended carburizer) is applied to the surface, dried and then heated.

The thickness of paste layer should be 6-8 times greater than the desired thickness cemented layer. Carburizing temperature set within 910-1050° C.
Frequently used pastes for carburizing: potash or soda (Na_2CO_3, K_2CO_3), barium carbonate , fine-grained coke.

TITLE: 1215 Steel
Lab No.: 102519
Camera: Leitz MM5 VI BF_DF
Objective: Pl16x_0.30 569184
Alloy: 1215
Etchant: 2% Nital
Specification: n/a
Technician: AMC
Comments: case depth

Iron, Fe	98.42 - 98.95
Manganese, Mn	0.75 - 1.05
Sulfur, S	0.260 - 0.35
Carbon, C	0.090
Phosphorous, P	0.040 - 0.090

Thickness of the coating, composition and type of carburizer are determined mainly by steel grade, its heat treatment, precision of product etc.

Structure of carburised layer of carbon steels consists of three zones: hypereutecoid (perlite + secondary cementite) eutectoid (pearlite) and hypoeutectoid(perlite + ferrite). The concentration of carbon in the surface layer is 0,8-1,1 %

Nitrocarburization

This is the process of saturation by both nitrogen and carbon simultaneously.

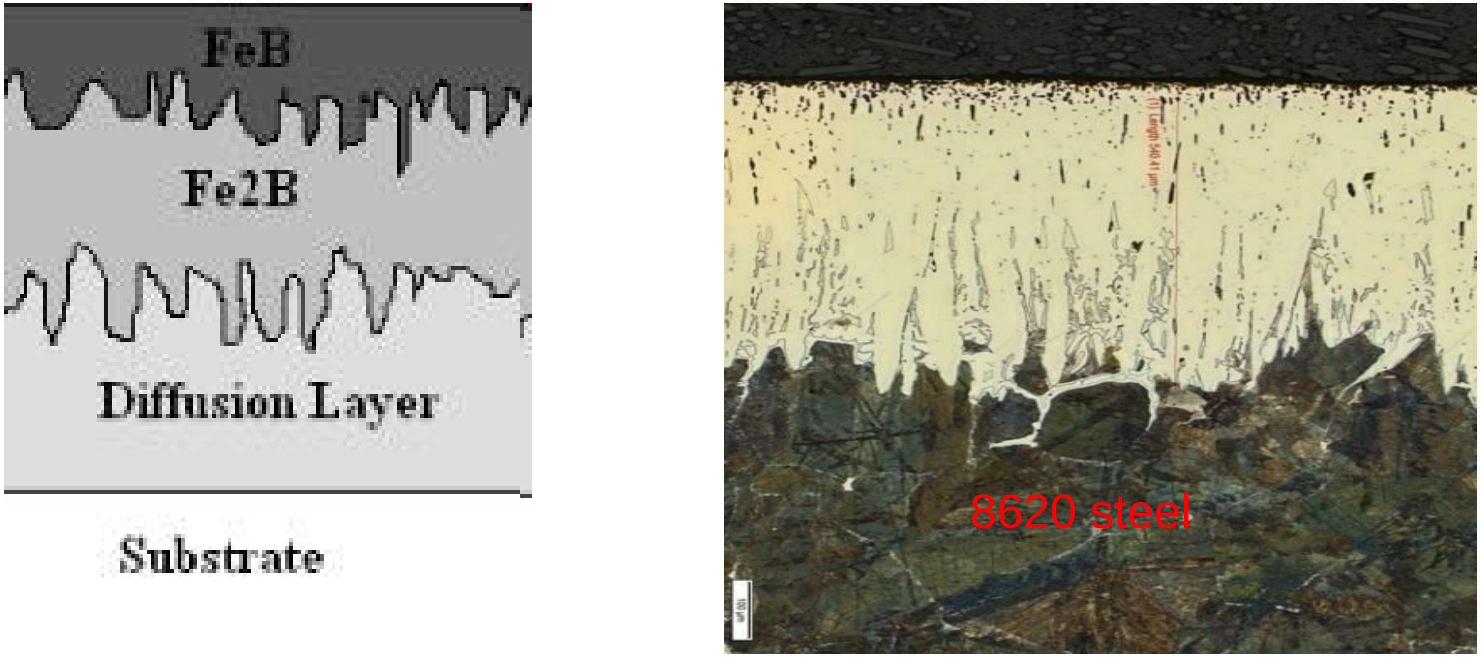
Depending on the temperature of the nitrocarburization process is divided into three types: low temperature (at 520-700 °C), Medium (for 760-860 °C) and high-temperature (at 860-1050 °C).

Borating

This is a process of saturation of the surface by boron. Borating is used to increase durability of dies for castingi. It increases the durability of dies twice, molds for ceramics – in 3 times, cutting tools for processing of insulators in 3-5 times.

An important feature of borated layer is conserving the hardness when heated to T = 950 ° C.

During boronizing, called also boriding, the surface layer of material is saturated with boron. The process is performed in solid, liquid or gaseous medium and is applicable to any ferrous material as well as to alloys of Ni, Co or Ti. In case of steel it is carried out at temperatures between 840 and 1050 ^{o}C for up to 10 h creating borides FeB and Fe_2B, which have a needle-like structure and hardness reaching 2000 HV. In addition to improving wear resistance, boronizing enhances also the corrosion resistance and oxidation resistance at temperatures of up to 850 ^{o}C. The main disadvantage of boronizing is the brittleness of the compound layer, especially the FeB phase

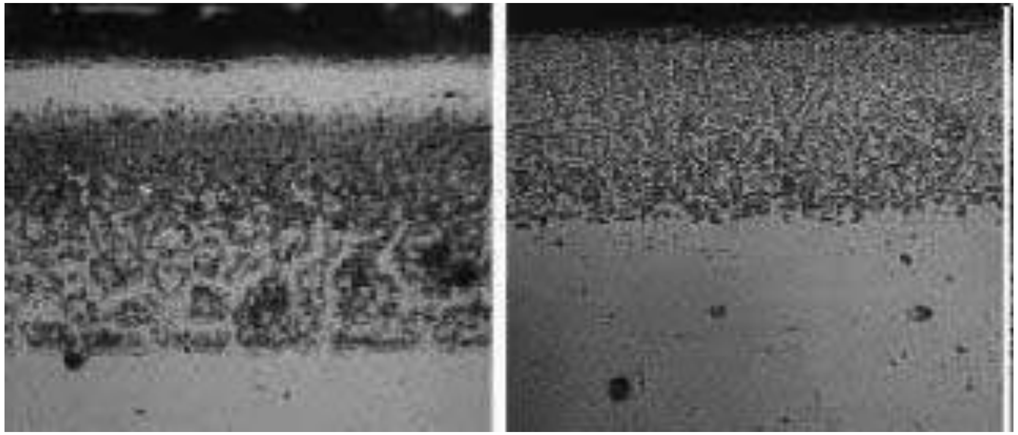


The schematic and microstructure of boronised AISA 8620 alloy steel

Chromizing

chromizing allows to obtain materials with special physical and mechanical properties and simultaneously reduce the cost of expensive alloy steels.
After chromizing the steel is resistant to corrosion in aqueous solutions of nitric acid, moist atmosphere in the presence of sulfur dioxide etc. is increased.
Parts made of low carbon steel after chromizing can be used in various industries instead of parts made of high-alloy steels.

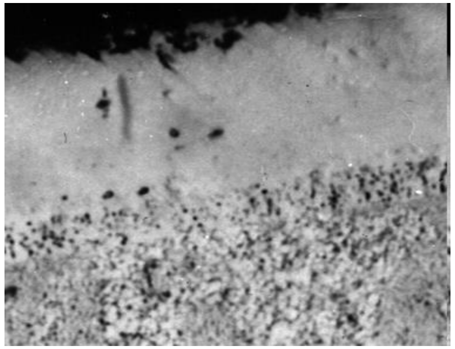
The purpose of diffusion chromizing is to enrich surface layers of an alloy with chromium. As other diffusion processes it may be carried out by powder pack, salt bath or fluidized bed. The compound surface layer is formed by a reaction between the carbide former, such 100 Heat Treatment – Conventional and Novel Applications as Cr deposited on the surface and carbon in the substrate. The outcome shows similar properties to coatings produced by CVD and PVD. In some sources, the process is divided into soft chromizing, when carbon content in a substrate is below 0.1% and hard chromizing for the carbon content in a substrate exceeding 0.3%. As negative features of chromizing, the shallow penetration depth and the distinct interface with the substrate are often quoted. Both features are caused by the diffusion kinetics of chromium in steel.

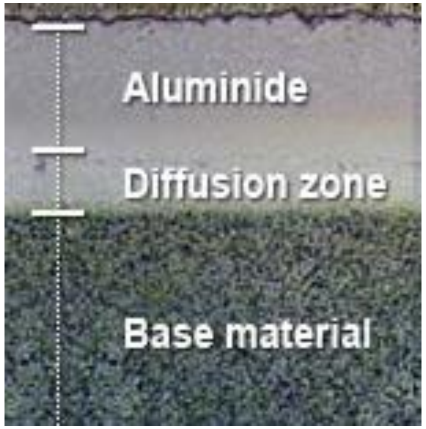


Aluminizing – is a diffusion saturation of the surface of metals and alloys by aluminum to improve heat resistance, corrosion and erosion resistance.

Carbon and alloy alloys, cast iron, heat-resistant steels and alloys , refractory metals and their alloys , titanium , copper and other materials are subjected to aluminizing

Main methods: aluminizing in powder mixtures, in a bath of molten aluminium or its alloys and metallization of the surface of metals and alloys by aluminium followed by diffusion annealing.

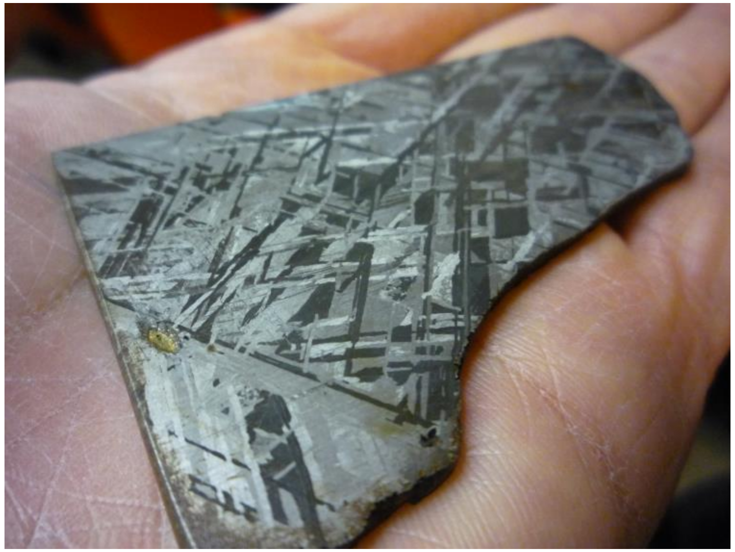




THE DEFECTS AND FAULTY HEAT TREATMENT

The faulty heat treatment may cause following major defects in a metal or a alloy:

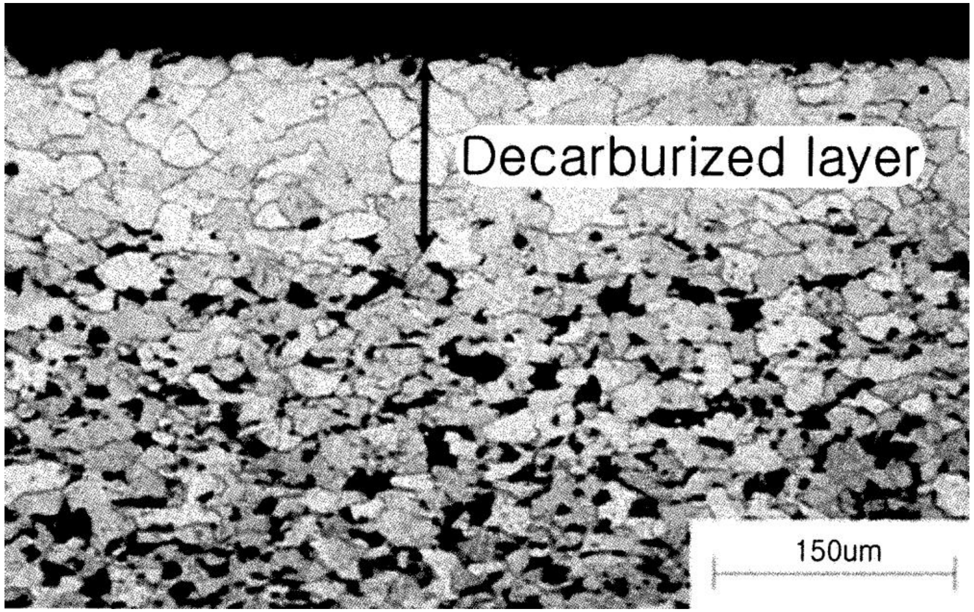
(i) Overheating: Prolonged heating of a metal or a alloy above a temperature marked by A3 line. leads to the formation of very large actual grains. It is usually termed as overheating. On cooling a metal, this yields a structure containing crystalline martensite (usually called as Widmanstatten structure). Such a structure has reduced ductility and toughness. By means of usual annealing, it is possible to retrieve an overheated metal or alloy. One may use double annealing for considerable heating.



(ii) Burning: Heating a metal or an alloy near melting point for a longer duration may lead to burning. This leads to the formation of iron oxide inclusions along the grain boundaries. Burnt metal or alloy has a stoney fracture and such a metal or alloy is irremediable and such metals are rejected.

(iii) Oxidation: Sometimes a metal or alloy gets oxidized due to oxidizing atmosphere inside the furnace. It is usually characterized by a thick layer of scale on the surface of a metal or alloy. One can prevent it by making use of controlled atmosphere in the furnace or using molten salt baths.

(iv) Decarburization: Decarburization is the loss of carbon in the surface layers of metals or alloys. It is caused by the oxidizing furnace atmosphere. In order to prevent it, the metal or alloy should be heated in a natural or reducing atmosphere or inside boxes with cast iron chips or in molten salts baths.

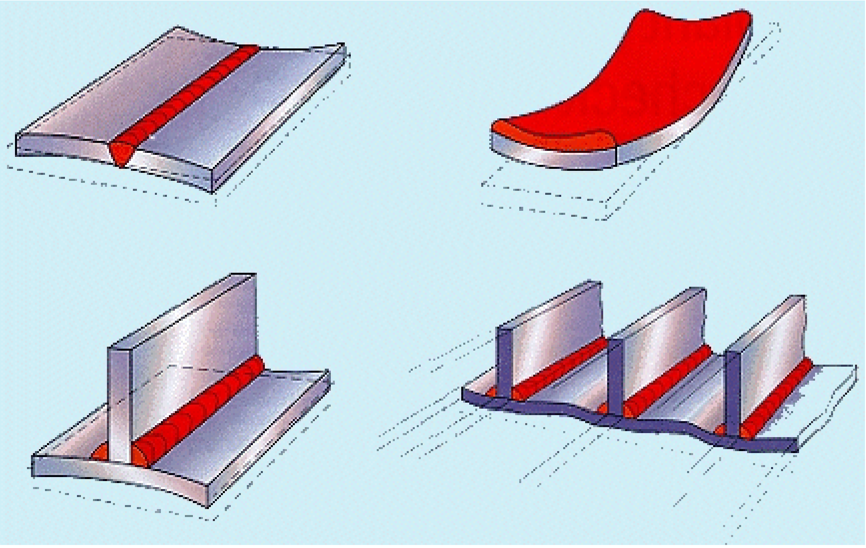


(v) Cracks: These occurs in quenching when the internal tensile stress exceed the resistance of metal or alloy to separation. The tendency of a metal or alloy to crack formation increases with carbon content, hardening temperature and cooling rate in the temperature interval of martensite transformation.

Quench-cracked blade

Cracks also increases with the hardenability of metal or alloy. Concentration of local stresses is the another reason for the formation of cracks. We may note that the cracks are irremediable defects. In order to prevent the formation of cracks, it is advisable to (1) avoid stress concentrations, e.g. sharp corners on projections, acute angles, abrupt changes from thicker to thinner cross-sections, etc. in component design, (2) conduct quenching from the lowest possible temperature, (3) cool the metal or alloy slowly in the martensite interval of temperatures by quenching in two media and stepped quenching (i.e., martempering), and (4) apply isothermal quenching.

(vi) Distortion and Wraping: This is consisting in changes in the size and shape of heat-treated work and is mainly due to thermal and structural stresses. Asymmetrical distortion of work is often called wraping in heat-treating practice. Usually, it is observed in case of overheating or non-uniform heating for hardening, when the work is quenched in the wrong position and when the cooling rate is too high in the temperature interval of martensite transformation. By eliminating these causes, one may substantially reduce warping.



Wraping after welding

4. FERROUS ALLOYS

Introduction

Accounting for 60% of the world's total output of crude steel, the Basic Oxygen Steelmaking (BOS) process is the dominant steelmaking technology. In the U.S., that figure is 54% and slowly declining due primarily to the advent of the "Greenfield" electric arc furnace (EAF) flat-rolled mills. However, elsewhere its use is growing.

Classification of carbon steels

During steel-manufacturing processes, combination of carbon and oxygen takes place to form a gas. If the oxygen is not removed before or during casting (by adding silicon or other deoxidizer) the gaseous products continue to evolve during solidification. The type of steel produced is determined by the control of the amount of gas evolved during solidification. If no gas is evolved, the steel is called "killed" because it lies quietly in moulds. Increasing degree of gas evolution results in semi-killed, capped or rimmed steels.

Some carbon steels and high strength low-alloy steels can be supplied in all four types. Alloy steels and stainless and heat resisting steels are normally manufactured as killed steel.

Killed steel:

Killed steel is a form of steel which has been treated to fully deoxidize it when it is processed during the casting phase. Deoxidation of steel ensures a more even consistency in the finished product while increasing density and durability. There are a number of applications for killed steel, and certain grades of steel must be killed in order to meet materials standards. Materials testing can be used to determine whether or not steel has been deoxidized if there are doubts about the integrity of a steel product.

When steel is heated for casting, it interacts with the oxygen in the air. Typically, some oxygen becomes dissolved in the molten steel, and travels with it into the mold. Some of the oxygen bubbles out as the steel settles in the mold, but some of it becomes trapped, where it interacts with the carbon in the steel to create carbon monoxide.

The carbon monoxide, in turn, creates small bubbles inside the finished product. These bubbles compromise the integrity of the steel, creating weak points which could break or fracture, especially under strain. The bubbles also disrupt the texture of the steel, and make it less dense. In some cases, this may not be viewed as a problem, but in others, it can become an issue. Steel used in the manufacture of a bridge, for example, needs to be able to withstand stress without developing cracks.

When killed steel is made, a material such as aluminum, silicon, or manganese is added to the steel before it is poured into the molds. This deoxidizes the steel, forcing the oxygen out of the steel so that by the time it hits the mold, most if not all of the oxygen is gone. Some people say that the “killed” is a reference to the fact that the steel does not bubble in the mold once it is poured.

Killed steel has a very even grain and texture as a result of the absence of carbon monoxide bubbles. It is also very dense, lacking the small holes found in steel which has not been killed, which makes it heavier than pieces of steel of the same size which have not been subjected to this process. Killed steel is sometimes subject to shrinkage because of the density, which can be a concern in certain casting applications. This steel product's strength and durability are increased by deoxidation, although factors can influence the qualities of a finished steel product.

Semi Killed steel:

It has characteristics intermediate those of killed or rimmed steels.

Structural steels containing 0.15 to 0.25% carbon are generally semi-killed.

In semi-killed steel, the aim is to produce metal free from surface blowhole and pipe.

The surface should have a sound kin of considerable thickness.

They are used for general structural applications.

During solidification of semi-killed steel, gas is evolved in the body of the ingot, tending to compensate in part of entirely for the shrinkage accompanying solidification.

Since pipe cavities are minimized, semi-killed steels are usually cast in big-end -down molds without hot-tops.

This type of steel is suitable for drawing operation (except severe drawing).

Capped Steel:

It has characteristics similar to those of rimmed steels but to a degree intermediate between those of rimmed and semi-killed steels.

A deoxidizer may be added to effect a controlled running action when the steel is cast. the gas entrapped during solidification is in excess of that needed to counteract normal shrinkage, resulting in a tendency for the steel to rise in the mould.

The capping operation caused the steel to solidify faster, thereby limiting the time of gas evolution, and prevents the formation of an excessive number of gas voids within the ingot.

Capped steel is generally cast in bottle-top moulds using a heavy metal cap.

Capped steel may also be cast in open-top moulds, by adding aluminum or ferro-silicon on the top of molten steel, to cause the steel on the surface to lie quietly and solidify rapidly.

Rimmed Steel:

In rimmed steel, the aim is to produce a clean surface low in carbon content. Rimmed steel is also known as drawing quality steel.

The typical structure results for a marked gas evolution during solidification of outer rim.

They exhibit greatest difference in chemical composition across sections and from top to bottom of the ingot.

They have an outer rim that is lower in carbon, phosphorus, and sulphur than the average composition of the whole ingot and an inner portion or core that is higher the average in those elements.

In rimming, the steel is partially deoxidized. Carbon content is less than 0.25% and manganese content is less than 0.6%.

They do not retain any significant percentage of highly oxidizable elements such as Aluminum, silicon or titanium.

A wide variety of steels for deep drawing is made by the rimming process, especially where ease of forming and surface finish are major considerations.

These steel are, therefore ideal for rolling, large number of applications, and is adapted to cold-bending, cold-forming and cold header applications.

Structural steels

Steels used for the manufacture of machine parts, structures and buildings are called structural steels. Structural steels are both carbon and alloy steels. The carbon content of these steels does not exceed 0.5-0.6 %. They must have high strength, ductility, toughness, high technological properties. Structural carbon steels are divided into steel of ordinary quality and Qualitative steels.

All structural steels are essentially weldable. However,welding involves locally melting the steel, which subsequently cools. The cooling can be quite fast because the surrounding material, e.g. the beam, offers a large 'heat sink' and the weld (and the heat introduced) is usually relatively small. This can lead to hardening of the 'heat affected zone' (HAZ) and to reduced toughness. The greater the thickness of material, the greater the reduction of toughness.
The susceptibility to embrittlement also depends on the alloying elements principally, but not exclusively, the carbon content. This susceptibility can be expressed as the 'Carbon Equivalent Value' (CEV), and the various product standards for carbon steels standard give expressions for determining this value

Carbon steels of ordinary quality.

In the process of fusion they are less purified from phosphorus, sulfur, oxygen and nitrogen. Ordinary quality steels are used for hot-rolled products - beams , rods , channels, corners, as well as sheets, tubes , forgings. Depending on the guaranteed properties they are divided into three groups.

Group A – steels with guaranteed mechanical properties without specifying chemical composition. They are denoted by the letters Ст and numbers 1, 2 , 3 ... 6 (Ст1, ... Ст6). The higher the number , the higher strength and lower ductility.

Group Б - steel with guaranteed chemical composition. Their grades are marked by letter Б – БСт1, БСт2 ... БСт6 . The higher the number , the higher carbon content.

Group В - high quality steel . They are supplied with guaranteed chemical composition and mechanical properties. Steel denoted by the letter В (ВСт1 , ВСт2 ... ВСт6). Steel composition corresponds to a similar grade of group Б, and mechanical properties - of group A.

Due to the nature of steel deoxidation they are divided into calm, semicalm and boiling steels.

Killed Calm steel (сп) are deoxidized by manganese, silicon and aluminum. They contain little of oxygen and solidify with no gas bubbles. (boiling")

Rimm Boiling steel (кп) are deoxidized by manganese only, oxygen content is increased. As a result of interaction with carbon, oxygen forms bubbles of CO, which are released during crystallization, creating the effect of a boiling. Semikilled Semicalm steel (нс) are deoxidized by manganese and silicon. They occupy an intermediate position between calm and boiling steels.

Qualitative carbon steels. During manufacture of quality steels precise melting and pouring techniques are followed, the requirements for chemical composition are much higher: sulfur content of < 0.04 % phosphorus < 0.035-0.04 %, and lower content of other non-metallic impurities.

- High-quality steels are mark as followed by numbers 08, 10 , 15 and so on up to 85, which show the carbon content in hundredths of a percent.

Low carbon steels 05кп, 08, 10, 10кп have low strength and high ductility. These steels are used without heat treatment.

The largest category of this class of steel is flat-rolled products (sheet or strip), usually in the cold-rolled and annealed condition. The carbon content for these high-formability steels is very low, less than 0.10% C, with up to 0.4% Mn. Typical uses are in automobile body panels, tin plate, and wire products.

For rolled steel structural plates and sections, the carbon content may be increased to approximately 0.30%, with higher manganese content up to 1.5%. These materials may be used for stampings, forgings, seamless tubes, and boiler plate.

Steel 15, 20, 25 are used without heat treatment or after normalization for welded structures, after carburizing.

Medium carbon steels 30, 35, 40, 45, 50 are used after normalizing, martempering and surface hardening for various engineering products.

These steels are similar to low-carbon steels except that the carbon ranges from 0.30 to 0.60% and the manganese from 0.60 to 1.65%. Increasing the carbon content to approximately 0.5% with an accompanying increase in manganese allows medium carbon steels to be used in the quenched and tempered condition.

The uses of medium carbon-manganese steels include shafts, axles, gears, crankshafts, couplings and forgings. Steels in the 0.40 to 0.60% C range are also used for rails, railway wheels and rail axles.

High carbon steel 60, 65, 70, 75, 80, 85 have high strength, wear resistance. They are used after quenching and tempering , normalizing and tempering , surface hardening for parts operating under conditions of friction at high vibration loads.

High carbon steels are those with carbon contents between 0.60% and 1.4% of the overall weight. The alloys in this particular category constitute the strongest and hardest within the three groups, but they are also the least ductile. These steels are used in a range of different mechanical, cutting and bearing applications as it can be hardened through heat treating and tempering.

Ultrahigh-carbon steels are experimental alloys containing 1.25 to 2.0% C. These steels are thermomechanically processed to produce microstructures that consist of ultrafine, equiaxed grains of spherical, discontinuous proeutectoid carbide particles.

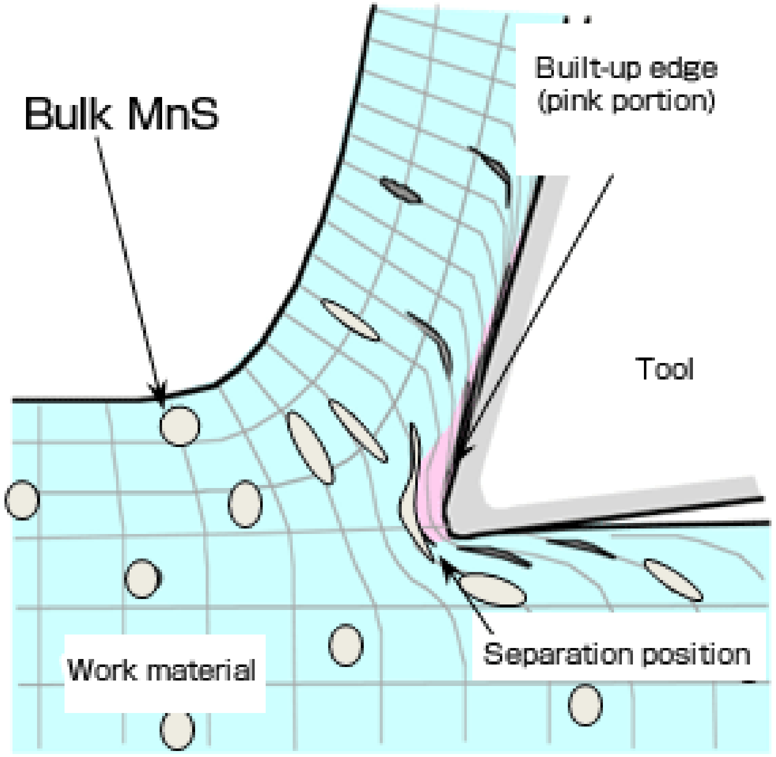
Free machining steels

Free machining steel is steel that forms small chips when machined. This increases the machinability of the material by breaking the chips into small pieces, thus avoiding entanglement in the machinery. This enables automatic equipment to run without human interaction. Free machining steel with lead also allow for higher machining rates. Free machining steel costs 15 to 20% more than a standard steel, but this is made up by increased machining speeds, larger cuts, and longer tool life.

The disadvantages of free machining steel are: ductility is decreased; impact resistance is reduced; copper-basedbrazed joints suffer from embrittlement with bismuth free machining grades; shrink fits are not as strong

There are four main types of free machining steel: leaded, resulfurized, rephosphorized and super. Super free-machining steels are alloyed with tellurium, selenium, and bismuth.

They are carbon steels with high content of sulfur and phosphorus. When machining these steels high quality surface is obtained. This property is achieved due to the sulfur content (0.12-0.3 %) and phosphorus (0.05-0.15 %).



Cutting edge build-up

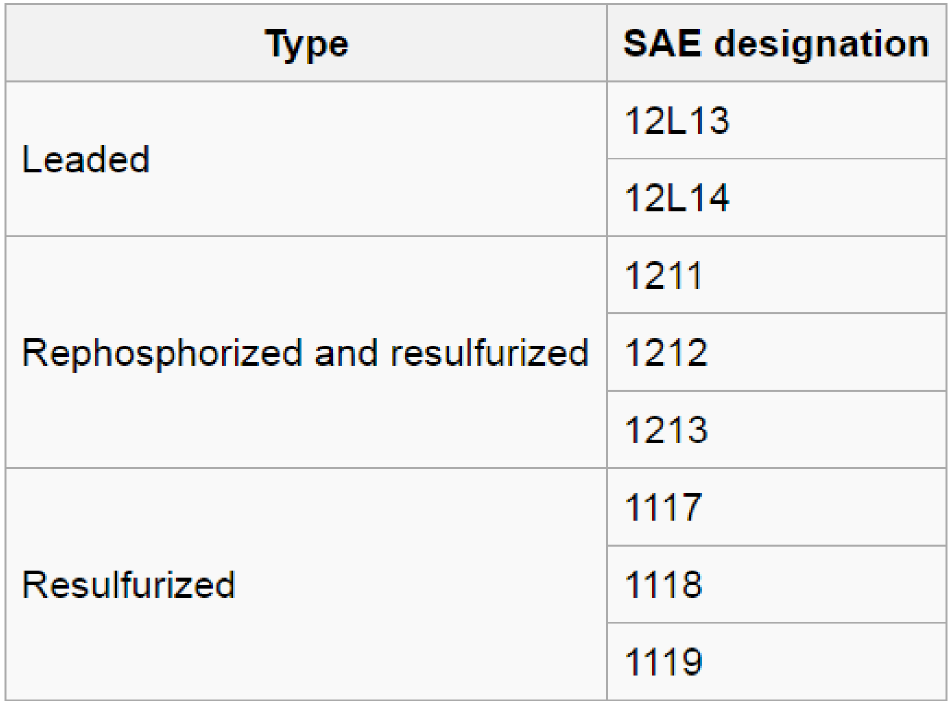
Sulfur in steels is in the form of sulphides, which form inclusions elongated in the direction of treatment and promote the formation of short and brittle chips. In turn brittle chips quickly remove heat from the workpiece, thereby increases the resistance of the cutting tool and the cutting speed increases.

Phosphorus increases the hardness and strength, reduces flexibility, thus contributing to the formation of a smooth surface after machining

Free machining steels are marked by the letter A, followed by a number that indicates the average carbon content in hundredths of a percent.

Steel, A12, A20 , A30 , A40H (modified by manganese) is used for manufacture of screws, bolts and various small parts of complex configuration for high-speed automatic machines

Some SAE steel grades for free machining steels



Type	SAE designation
Leaded	12L13
	12L14
Rephosphorized and resulfurized	1211
	1212
	1213
Resulfurized	1117
	1118
	1119

Lead acts as a chip-breaking discontinuity. It also acts as a dry lubricant to prevent a built up edge on the cutting tool. Lead works in a similar way to sulfur.

Bismuth achieves a free machining steel by melting into a thin film of liquid for a fraction of a microsecond to lubricate the cut. Other advantages to bismuth include: more uniformly distributed because of its similar density to iron; more environmentally friendly, as compared to lead; still weldable

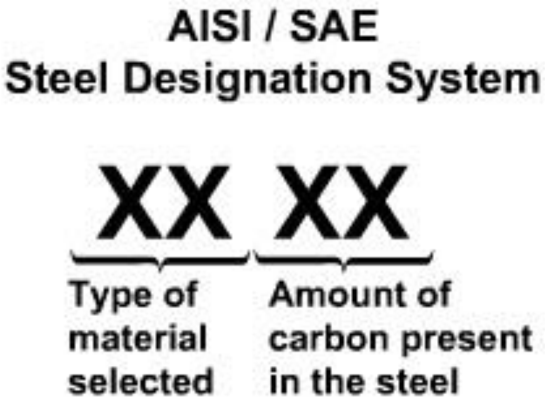
Tool carbon steels

Steels which are used for cutting tools after quenching and low tempering should have high hardness, wear resistance cutting edge of adequate strength and heat resistance.

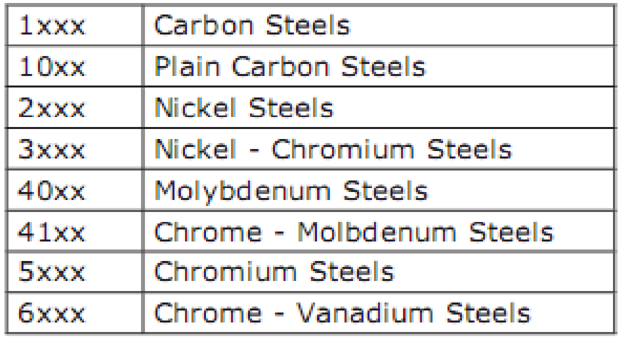
Tool carbon steel with are mark by letter Y and numbers indicating carbon content in tenth of percent - Y8 (Y8A), Y10 (Y10A), Y11 (Y11A) and others. The letter “A” indicates increased quality of steel.

SAE classification system

The (American) Society of Automotive Engineers (SAE) has classified steel alloys with a four - digit numerical index system. Example, that one common steel alloy is identified by the designation SAE 1030. The first digit identifies it as a carbon steel, while the second digit shows that it is a plain carbon steel. The last two digits denote the percentage of carbon in the steel (0.30%).



A small extract from the SAE classification system



1xxx	Carbon Steels
10xx	Plain Carbon Steels
2xxx	Nickel Steels
3xxx	Nickel - Chromium Steels
40xx	Molybdenum Steels
41xx	Chrome - Molbdenum Steels
5xxx	Chromium Steels
6xxx	Chrome - Vanadium Steels

Alloy steels

Alloy Steel - an alloy of iron and carbon , which contains special (alloying) elements . The need for alloy steels is due to the requirements for technical devices operating at various conditions : temperature from - 269 to 1200ºC, high specific loads, corrosive environments etc.
Carbon steel even after heat treatment can not meet industrial demands.

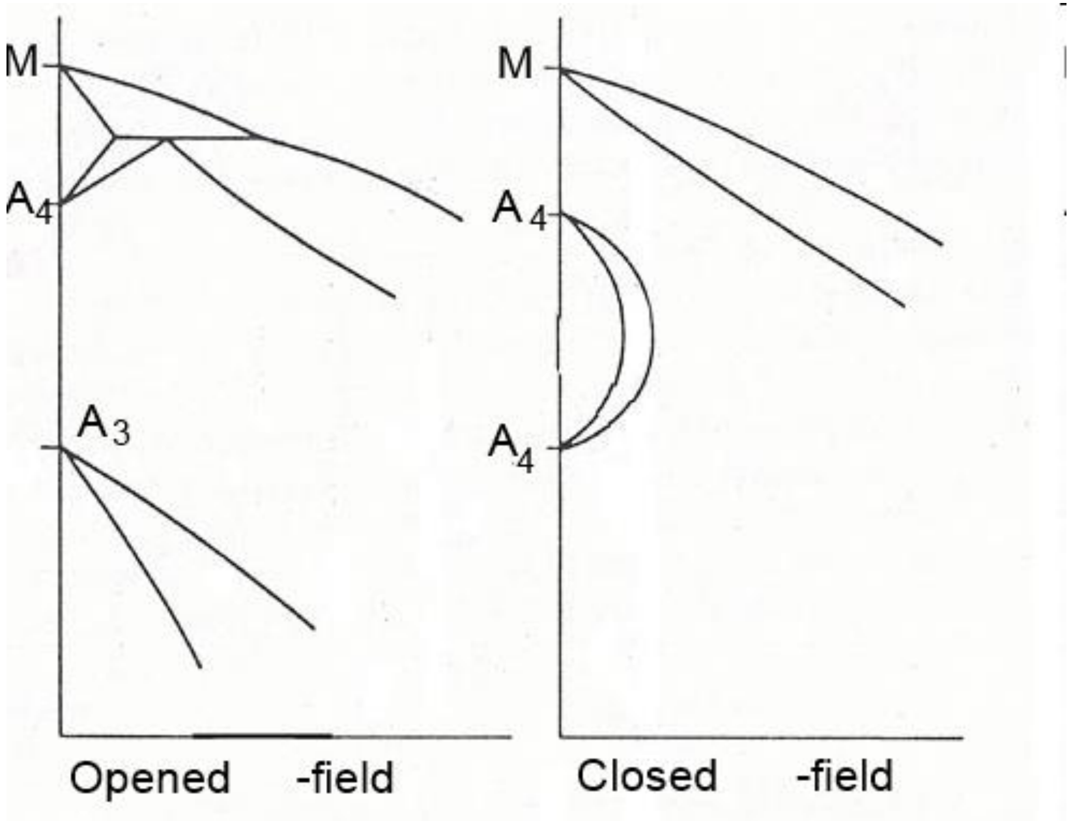
Alloying elements in steels. The introduction of alloying elements in steel can create the following phases: solid solutions , doped cementite (or special carbides) and intermetallic compounds.

Effect of alloying elements on the polymorphic transformation of iron. All elements except carbon, nitrogen , hydrogen form with iron substitutional solid solutions . They are soluble in iron and affect the position of the points A3 and A4.

They may do one of two: they close or widen the γ-field of phase diagram.

Taking this into account we may divide all alloying elements into 2 groups: γ-stabilizers and α-stabilizers.

The first group – Nickel and manganese. They lower point A3 and raise point A4. This leads opening of γ-field of the phase diagram.



Effect of alloying elements on polymorphic transformation

The region of α-phase is shortened. At appropriate concentration of alloying element point A4 is raised to solidus line, and point A3 is lowered to room temperature.

All the alloys do not have phase transformations α↔γ. In all the range of temperatures these alloys are single-phase γ-steels – solid solution of alloying elements in austenite.

These steels also non-magnetic and called austenitic steels

The elements as Copper, Nitrogen only slightly increase the γ-field.

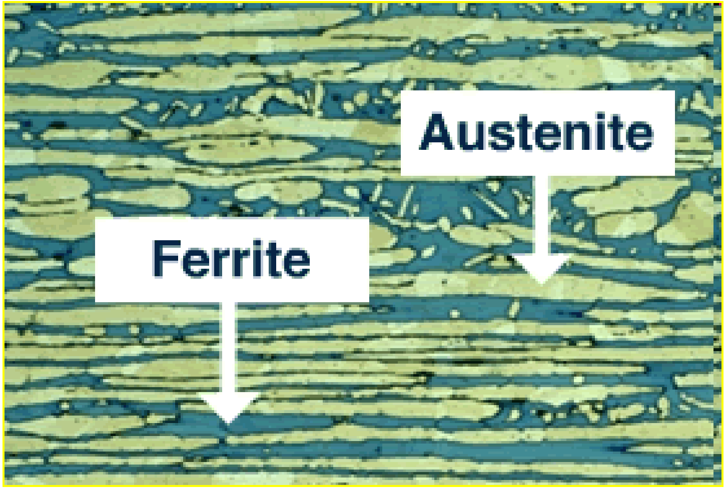
The elements of the second group are Cr, W, Mo, V, Si, Al and others. They lower the A4 point and raise A3 point.

As a result the α-region expands and γ-region is closed to very short field.

The α↔γ phase transformation in these alloys (at appropriate concentration) is not observed.

At all the temperatures the alloys exhist in a form of α-solid solution of alloying elements in iron. These steels are called feritic steels.

The steels which have both ferrite and austenite in their structure are called Duplex steels. They have higher strength and toughness, then single-phase alloys, have good corrosion resistance and are not so expensive as austenitic stainless steels due to lower content of alloying elements



The function of alloying elements

Each element that is added to the basic constituent of iron has some effect on the end properties of the material and how that material reacts to fabrication processes. The alloying additions are responsible for many of

the differences between the various types or grades of carbon steels. Following is a list of the elements commonly added to iron and their effects on the material:

Carbon. Carbon is the most important alloying element in steel and can be present up to 2% (although most welded steels have less than 0.5%). The carbon can exist either dissolved in the iron or in a combined form, such as iron carbide (Fe_3C). Increased amounts of carbon increase hardness and tensile strength as well as response to heat treatment (hardenability). On the other hand, increased amounts of carbon reduce weldability. •

Manganese. Steels usually contain at least 0.3% manganese, which acts in a three-fold manner: it assists in deoxidation of the steel, prevents the formation of iron sulfide inclusions, and promotes greater strength by increasing the hardenability of the steel. Amounts up to 1.5% are commonly found in carbon steels.

Silicon. Usually, only small amounts (0.2%, for example) are present in rolled steel when silicon is used as a deoxidizer. However, in steel castings, 0.35–1.0% is common. Silicon dissolves in iron and tends to strengthen it. Weld metal usually contains approximately 0.5% silicon as a deoxidizer. Some filler metals can contain up to 1.0% to provide enhanced cleaning and deoxidation for welding on contaminated surfaces. When these filler metals are used for welding of clean surfaces, the resulting weld metal strength will be markedly increased. The resulting decrease in ductility could present cracking problems in some situations.

Sulfur. This is an undesirable impurity in steel rather than an alloying element. Special effort is made to eliminate or minimize sulfur during steelmaking. In amounts exceeding 0.05%, it tends to cause brittleness and reduce weldability. Additions of sulfur in amounts from 0.1% to 0.3% will tend to improve the machinability of steel but impair weldability. These types of steel can be referred to as freemachining.

Phosphorus. Phosphorus is also considered to be an undesirable impurity in steels. It is normally found in amounts up to 0.04% in most carbon steels. In hardened steels, it tends to cause embrittlement. In low-alloy, high-strength steels, phosphorus can be added in amounts up to 0.10% to improve both strength and corrosion resistance, although it is not generally added for this reason in carbon steels.

Chromium. Chromium is a powerful alloying element in steel. It is added for two principal reasons: first, it greatly increases the hardenability of steel; second, it markedly improves the corrosion resistance of iron and steel in oxidizing types of media. Its presence in some steels could cause excessive hardness and cracking in and adjacent to the weld. Stainless steels contain chromium in amounts exceeding 12%.

Molybdenum. This element is a strong carbide former and is usually present in alloy steels in amounts less than 1.0%. It is added to increase hardenability and to elevate temperature strength.

Nickel. Nickel is added to steels to increase their hardenability. It performs well in this function because it often improves the toughness and ductility of the steel, even with the increased strength and hardness. Nickel is frequently used to improve steel toughness at low temperatures.

Vanadium. The addition of vanadium will result in an increase in the hardenability of steel. It is very effective in this role, so it is generally added in minute amounts. In amounts greater than 0.05%, there can be a tendency for the steel to become embrittled during thermal stress relief treatments.

Columbium. Columbium (also called niobium), like vanadium, is generally considered to increase the hardenability of steel. However, due to its strong affinity for carbon, it can combine with carbon in the steel to result in an overall decrease in hardenability.

Copper. Copper enhances corrosion resistance to certain acids and promotes an austenitic microstructure. It can also be added to decrease work hardening in grades designed for improved machinability. It may also be added to improve formability.

Nitrogen. Nitrogen is a very strong austenite former that also significantly increases mechanical strength. It also increases resistance to localized corrosion, especially in combination with molybdenum. In ferritic stainless steels nitrogen strongly reduces toughness and corrosion resistance. In martensitic grades nitrogen increases both hardness and strength but reduces toughness.

Titanium. Titanium is a strong ferrite and carbide former, lowering the effective carbon content and promoting a ferritic structure in two ways. In austenitic steels with increased carbon content it is added to increase the resistance to intergranular corrosion (stabilized grades), but it also increases mechanical properties at high temperatures. In ferritic grades titanium is added to improve toughness, formability, and corrosion resistance. In martensitic steels titanium lowers the martensite hardness by combining with carbon and increases tempering resistance. In precipitation hardening steels, titanium is used to form the intermetallic compounds that are used to increase strength.

Niobium. Niobium is a strong ferrite and carbide former. Like titanium, it promotes a ferritic structure. In austenitic steels it is added to improve the resistance to intergranular corrosion (stabilized grades), but it also enhances mechanical properties at high temperatures. In ferritic grades niobium and/or titanium is sometimes added to improve toughness and to minimize the risk for intergranular corrosion. In martensitic steels niobium lowers hardness and increases tempering resistance. In the US it is designated Columbium (Cb).

Aluminium. If added in substantial amounts aluminum improves oxidation resistance and is used in certain heat-resistant grades for this purpose. In precipitation hardening steels, aluminum is used to form the intermetallic compounds that increase the strength in the aged condition.

Cobalt. Cobalt is used in martensitic steels, where it increases hardness and tempering resistance, especially at higher temperatures.

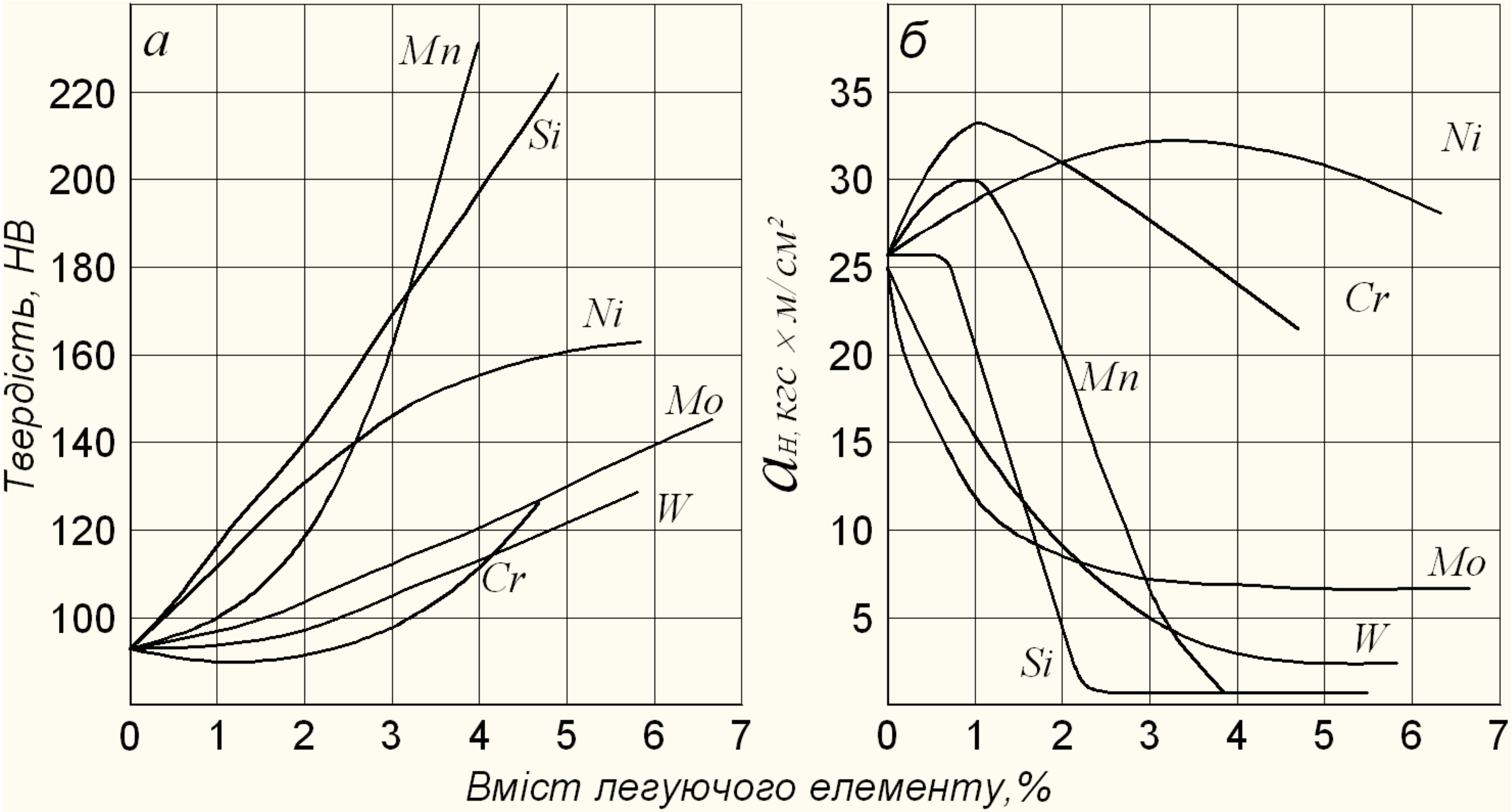
Tungsten is present as an impurity in most stainless steels, although it is added to some special grades, for example the superduplex grade 4501, to improve pitting corrosion resistance.

Phosphorus increases strength and hardness, but at the expense of ductility and impact to toughness.

As such its content in most steel is limited to a maximum of 0.05%. It lowers the melting point of steels and promotes corrosion at high temperature. In terms of welding, phosphorus content of over 0.04% makes weld brittle and increases the tendency to crack.

Phosphorus is unwanted element in alloy steels.
Sulphur improves machinability but lowers transverse ductility. Its content is limited to 0.05% in steels. For welding, weldability decreases with increasing sulphur content. The same as phosphorus, it lowers the melting point and promotes corrosion at high temperatures.

For high temperature alloy steels the content of these elements is limited by 0,02%

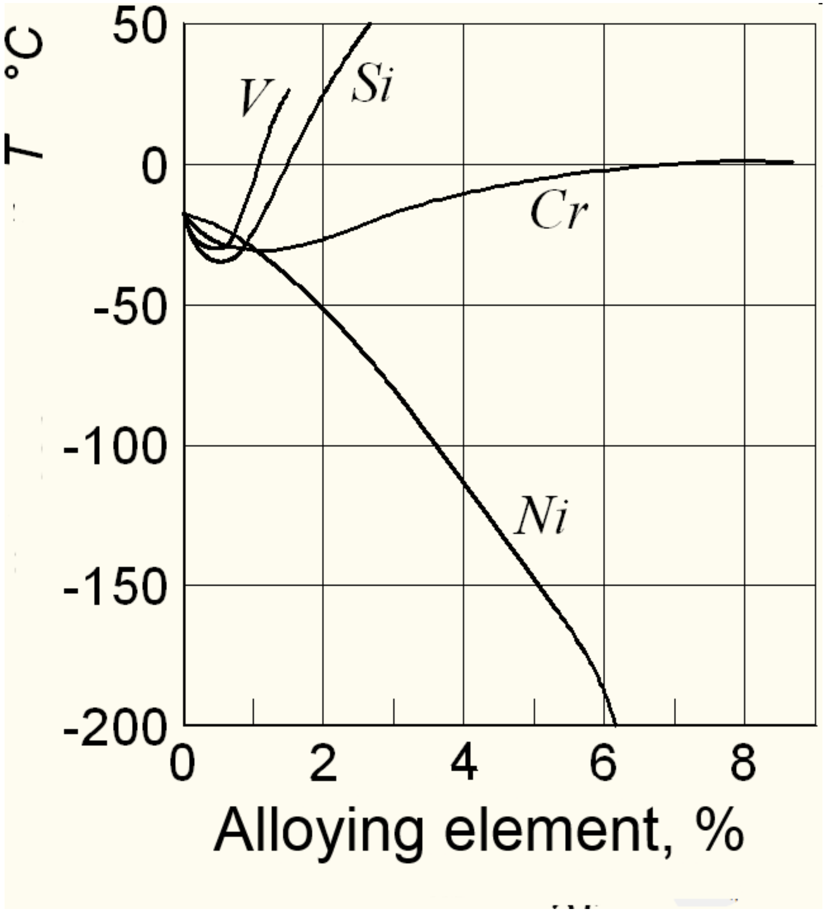


Effect of alloying elements on mechanical properties of steels

Alloying elements are also capable to change mechanical properties of steels.

Depending on their quantity and combination they may decrease the glass transition point, increase operating temperature, ductility, hardness, corrosion resistance.

The figure below illustrates the influence of alloying elements on strength and toughness

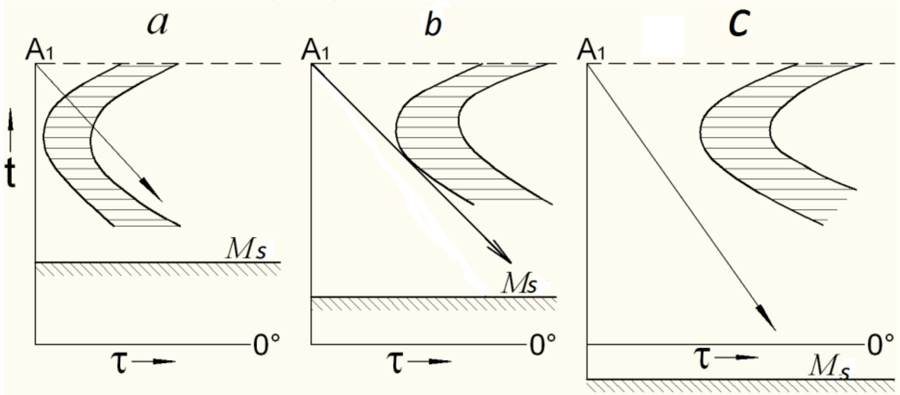


The influence of alloying elements on low temperature brittleness

Classification

Due to the structure after air cooling:
pearlitic ;
martensitic ;
austenitic .

Pearlitic steels are characterized by a low content of alloying elements, martensitic – have a significant content, austenitic - high content of alloying elements.



Due to quality:
normal quality, high quality, especially high quality steels (sulfur and phosphorus % 0,055-0,015 0,045-0,025 %).

Due to the structure in equilibrium :
hypoeutectoid, eutectoid, hypereutectoid, ledeburite steels.

Due to the content of alloying elements:
1. Low alloy - 2.5 ... 5 ... 5 %;
2 Mid alloy - up to 10 %;
3. High alloy - more than 10 %.

Dou to the number of alloying elements:
1.Three component (iron , carbon, alloying element); 2. Four component (iron , carbon , two alloying elements) and others.

By application:
1. Structural steels; 2. Tool steels; 3. Steels and alloys with special properties (heat-resistant, wear-resistant , with special magnetic and electrical properties)

Marking of alloy steels

Russian system

It is carried out as follows . The first one, two, three figures at the beginning of grade denote the carbon content (18Х2Н2МФА , 9ХВНСА). In structural steels carbon is in hundredths of a percent, in tool - tenths of a percent. The letters to the right side of the carbon denotes alloying elements : А - nitrogen, Б - niobium , В - Tungsten Г - manganese, Д - copper, К - cobalt, Н - Nickel , М - Molibdenium, П - phosphorus, С - silicon, Т - Ti , Ф - vanadium , Х - chromium , Ц - Zinc, Ч – rare earth elements, Ю - aluminum.
Lets describe several designations.
18Х2Н2МФА
18 – this means 0,18% of carbon content;
Х2 – 2% of chromium;
Н2 – 2% of Nickel;
М and Ф stand for 1% of molybdenum and vanadium;
А – stands for high quality steel with reduced content of sulfur and phosphorus.

03Х13АГ19
03 - stands for 0,03% of carbon;
Х13 – means 13 % chromium;
А - 0,2—0,3 % of nitrogen;
Г19 – 19% % of manganese.

German system of marking alloy steels

Low alloy steels. The content at any alloying element is below 5%. The carbon content multiplied by 100 is indicated by a number at the beginning, followed by the alloying element symbols and a numbers, indicating their average content multiplied by a coefficient

Alloying element	Coefficient
Cr, Co, Mn, Ni, Si, W	4
Al, Cu, Mo, Ti, V	10
P, S, N	100

11CrMo 5-5 – steel containing C 0.09-0.14%, Cr 1.05-1.25%, Mo 0.48-0.62%;
14NiCr 4 – steel containing C 0.14-0.20%, Ni 3.0-3.5%, Cr 0.6-0.9% (as far as its quantity is less then 1%, the digit is not used

High alloy steels. The content of at least one alloying element is above 5%. The designation starts from letter “X”. The carbon content multiplied by 100 is indicated by a number at the beginning, followed by the alloying element symbols (in decreasing order) and a numbers, indicating their average content (no coefficient is used)

X 2 CrNiMo 10 10 5 – steel containing C < 0.03%, Cr 8.5-10.5%, Ni 8.5-11.0%, Mo 4.5-5.5%;
X 5 CrNiCuNb 17-4-4 – steel containing C < 0.07%, Cr 15.0-17.5%, Ni 3.0-5.0%, Cu 3.0-5.0%, Nb 0.15-0.45% (below 1%, no digit).

European (EN 10027-2 standard) steel designation

According to this system, which is based on German system, the steel is designated by a series of numbers as follows: 1.XXXX. 1 indicates steel (0 – cast iron, 2 – cobalt alloy, 3 – color metals). Two next digits indicate the group of steel (00, 90 – ordinary quality steel, 07, 97 – steels with high carbon content, 15, 16, 17, 18 – tool steels etc). The last two digits indicate the number of steel in the group. This should be referred to special tables

SAE Classification

Steel	Description
10xx	Non-resulfurized carbon steel grades (plain carbon steel)
11xx	Resulfurized carbon steel grades (free cutting carbon steel)
13xx	Manganese (1.75%)
20xx	Nickel steels
23xx	Nickel (3.50%)
25xx	Nickel (5.00%)
30xx	Nickel-chromium steels
31xx	Nickel (1.25%); Chromium (0.65 or 0.80%)
33xx	Nickel (3.5%); Chromium(1.55%)
40xx	Molybdenum (0.25%)
41xx	Chromium (0.50-0.95%);Molybdenum (0.12 or 0.20%)
43xx	Nickel (1.80%); Chromium (0.50 or 0.80%); Molybdenum (0.25%)
46xx	Nickel (1.55 or 1.80%); molybdenum (0.20 or 0.25%)
47xx	Nickel (1.05%); Chromium (0.45%);Molybdenum (0.25%)
48xx	Nickel (3.50%); Molybdenum (0.25%)
50xx	Chromium (0.28 or 0.40%)
51xx	Chromium (0.80, 0.90, 0.95, 1.00 or 1.05%) Spring Steel
5xxxx	Carbon (1.00%); Chromium (0.50, 1.00, or 1.45%)
60xx	Chromium-vanadium steels
61xx	Chromium (0.80 or 0.95%); Vanadium(0.10 or 0.15% min)

70xx	Heat resisting casting alloy
80xx	Nickel-chromium-molybdenum steels
86xx	Nickel (0.55%); Chromium (0.50 or 0.65%); Molybdenum (0.20%)
87xx	Nickel (0.55%); Chromium (0.50%); Molybdenum (0.25%)
90xx	Silicon-manganese steels
92xx	Manganese (0.85%); Silicon (2.00%) â€“ Spring Steel
93xx	Nickel (3.25%); Chromium (1.20%); Molybdenum (0.12%)
94xx	Manganese (1.00%); Nickel (0.45%); Chromium (0.40%); Molybdenum (0.12%)
97xx	Nickel (0.55%); Chromium (0.17%); Molybdenum(0.20%)
98xx	Nickel (1.00%); Chromium (0.80%); Molybdenum(0.25%)

Alloy Structural Steels.

Chromium steel. Chromium steel 40X , 45X , 50X are cheap construction materials. With the increase of carbon content strength increases but ductility and toughness reduce. Chromium steel can become brittle after tempering.

Chromium - is the main alloying element of chromium steel. It provides the corrosion resistance of the metal, especially in oxidizing environments. In addition, this element is able to increase the hardness, resistance to corrosion and wear resistance of the steel.

Typically, if steel contains about 1-2% of chromium, its strength is increased by 1.5-2 times. If contains 12% chromium, it will become stainless, well, if 25% of chromium, it is scale resistant and heat-resistant.

These steels are not desirable to hold in furnace temperature of forging because the additive of chromium after prolonged heating promotes the grain growth. In addition, it is the most cost-effective steel alloying relationship. Its corrosion resistance of the steel takes after quenching and subsequent polishing, but its useful mechanical properties are obtained after quenching and tempering.

Only in the atmosphere steels can be heat-resistant up to 700 ° C. In the sea water, due to the development of localized corrosion, its resistance is quite small.
If chromium steel is heat treated, it serves well in fresh water and atmospheric conditions. Chromium steels are used in various technical fields as molding, sheet, rod and tube

Steels 50X, 45X and 40X are used for the production of gears and rollers, which have a high resistance to wear;

Steels of grades 20X, and 15X for the manufacture of rollers, piston pins and pinions; steel grades 35X, and 30X for the manufacture of gears, rollers and axles.

Chromium heat-resistant stainless steel, in fact, turns out to be the most promising in the production of equipment for all kinds of areas of processing and food industry: confectionery, fat, alcohol, baking, alcoholic beverage, beer and soft drinks, etc.

Cr-Mn steel. They are steels 40XΓ , 30XΓ. They have higher strength than the chromium steel, however, they have reduced ductility, increased brittleness when cooled well below zero. They have a tendency to embrittlement after tempering

Chromium and manganese are two of the most potent additions to steel for improving hardenability. These elements have traditionally been avoided in standard alloys due to the increased difficulty in reducing their oxides compared to molybdenum, nickel, and copper. The availability of dry hydrogen and nitrogen atmospheres and high temperature sintering, coupled with the need for reducing alloying costs, makes these newer chromium-manganese alloys ideal for many high performance applications. The alloys provide a good balance of strength, toughness, ductility, and machinability.

Cr-Ni steel.

Chromium-nickel steel 12XH3A , 20XH3A , 12X2H4A , 20X2H4A are used for large parts of responsible use. After quenching in oil they have the structure of martensite in a mixture with bainite, providing high strength and toughness. An important feature is the chrome-nickel steel - heat resistance, which characterizes, at high temperatures, as the metal can resist the oxidation process. This property provides a chromium steel because he has more affinity to oxygen than that of iron. Therefore with incandescent surface of the alloy film is formed from emissions of oxides, which protects it from corrosion. The higher the chromium in the steel, the lower the temperature needed to form a given film.

Marking of chromium-nickel steels characterizes its properties and composition. Letters - are the main elements in the alloy composition (in this case - and X is H). The numbers after the letters - the percentage content of the element. That is the type of steel XH32 - a chromium-nickel steel with approximately 32% nickel content. Accordingly XH78 -

chrome-nickel steel with a nickel content of about 78%.

Chromium-nickel steel are two basic classes - austenitic and ferritic-austenitic. They are characterized by their heat resistance and methods of application. Since the austenitic-ferritic steel grade can withstand a temperature up to 900 - 1000 ° C, austenite steel - to 1000 - 1100 ° C.

It is important to note that, in spite of the heat resistance, ХН45Ю grade steel, has the ability to deform. Therefore, its use for the production of parts which will work under certain conditions: first, if the working fluid provides for chemically active substances, the temperature should not exceed 1300° C; secondly, if the items are loaded, the temperature should not exceed 1000 ° C. Nevertheless, the properties of this alloy is much better than that of steel ХН78Т.

Cr-Ni-Mo steel. Chromium-nickel steel may be additionally alloyed by molybdenium (40ХНМА , 40ХН2МА) or tungsten (18ХНВА , 18Х2Н4ВА). These steels have martensitic structure after any, even very slow cooling. These steels are a group of high-strength steels. They work well with dynamic loads and at low temperatures .

Cr-Mn-Si steel - is the main steel in aircraft. 30ХГСА steel containing 0.3 % carbon, up to 1.0% chromium , manganese and silicon. It has good weldability, high mechanical properties, satisfactory workability by cutting tool and high ductility in the annealed condition.

30ХГСА steel is used for the manufacture of landing gears, spars, bolts, nuts.

Low carbon alloy steels

This group includes steel containing carbon in an amount of 0.07 to 0.32%. After carburizing, quenching and low tempering hardness of the surface layer is up to 60 HRC and of a core is about HRC 15-30. For carburizing only alloy steels of this group are used.

Steels for bearings

Bearings operate under difficult operating conditions (high speed sliding and rolling, high specific loads , the presence of vibration, etc.). In this connection it is presented to them a number of requirements to be met by bearing materials.

Rolling-contact bearings consist of inner and outer rings and balls or rollers located between the rings. For the manufacture of bearings currently the following steels are used: ШХ15, ШХ15СГ, 20Х2Н4А, 18ХГТ, ШХ4

The most common are steels ШХ15 (0,95-1,05 % C ; 1,3-1,65% Cr) for small bearings and ШХ15СГ (0,95-1,05 % C ; 1,3-1,65% Cr ; 0,4-0,65% Si; 0,9-1,2% Mn) for larger bearings . These steels have high wear resistance, hardness and resistance to contact fatigue.

Stainless steels

Corrosion it is a process of fracture of metals under the influence of the environment. In this case, the mechanical properties of metals sharply deteriorate.

- To neutralize the oxidative processes in steel alloying elements are introduced and corrosion decreases sharply, and, this decrease is of abrupt character. Thus, alloys containing less than 12 % Cr are much the same as iron.

Alloys containing more than 12 % Cr behave like noble metals: having a positive potential, they do not rust or oxidize in air, in water, in a number of acids, alkalis and salts.

Chromium stainless steels are divided into 3 groups : I - with 13 % Cr; II - with 17 % Cr; III - with 25-28% Cr.
•Main grades : I group – 0X13 , 2X13 , 3X13 , 4X13 ,. Group II – 12H17 ; 08X17T ; III group – 15X25T ; 15X28 .
The first group - Martensitic and the second and third – ferritic steels.
Steel of second and third groups are used at temperatures 1050 - 1150° C, (for parts of flame furnaces).

Chromium-nickel stainless steel. The introduction of Ni to the steel containing 18 % Cr, is enough for it to become austenitic. This improves the mechanical properties, reduces susceptibility to grain growth and increases corrosion resistance.

The most widespread steel containing 18 % Cr and 10 % Ni. They are used not only in engineering but also in architecture and for other consumer products.

Typical representatives of this group of steels : 12X18H8, 17X18H9, 12X18H9T, 04X18H10

The **stainless steels** are highly resistant to corrosion (rusting) in a variety of environments, especially the ambient atmosphere. Their predominant alloying element is chromium; a concentration of at least 11 wt% Cr is required. Corrosion resistance may also be enhanced by nickel and molybdenum additions. Stainless steels are divided into three classes on the basis of the predominant phase constituent of the microstructure—martensitic, ferritic, or austenitic.Table lists several stainless steels, by class, along with composition, typical mechanical properties, and applications.

A wide range of mechanical properties combined with excellent resistance to corrosion make stainless steels very versatile in their applicability. Martensitic stainless steels are capable of being heat treated in such a way that martensite is the prime microconstituent. Additions of alloying elements in significant concentrations produce dramatic alterations in the iron–iron carbide phase diagram. For austenitic stainless steels, the austenite or phase field is extended to room temperature. Ferritic stainless steels are composed of the ferrite (BCC) phase. Austenitic and ferritic stainless steels are hardened and strengthened by cold work because they are not heat treatable.The austenitic stainless steels are the most corrosion resistant because of the high chromium contents and also the nickel additions; and they are produced in the largest quantities. Both martensitic and ferritic stainless steels are magnetic; the austenitic stainlesses are not. Some stainless steels are frequently used at elevated temperatures and in severe environments because they resist oxidation and maintain their mechanical integrity under such conditions; the upper temperature limit in oxidizing atmospheres is about 1000C. Equipment employing these steels includes gas turbines, high-temperature steam boilers, heat-treating furnaces, aircraft, missiles, and nuclear power generating units.