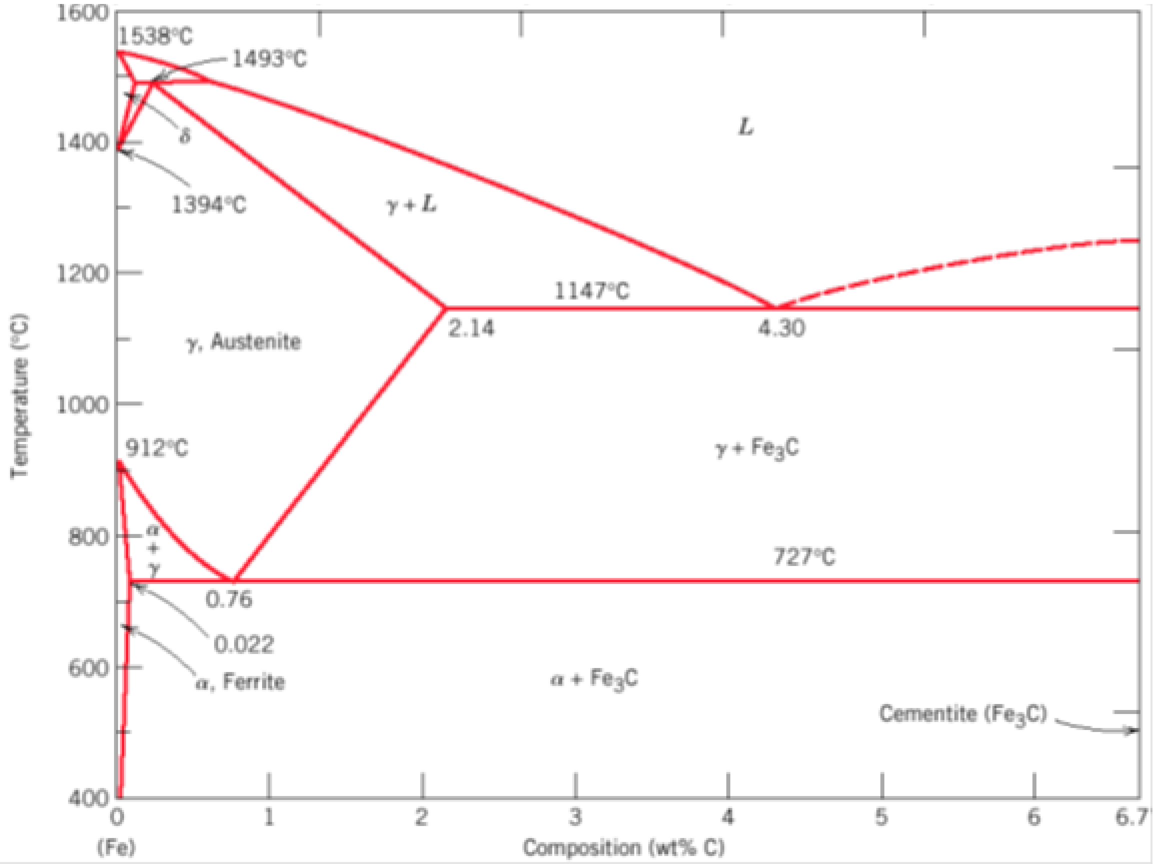
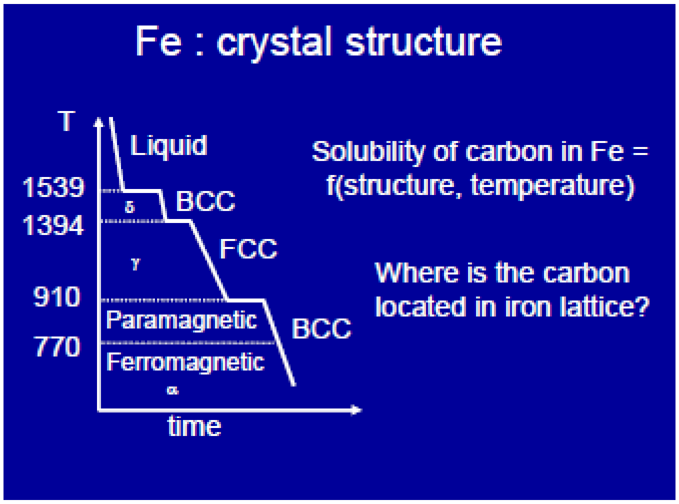
UNIT – II

The Iron–Iron Carbide (Fe–Fe3C) Phase Diagram





Fe : crystal structure

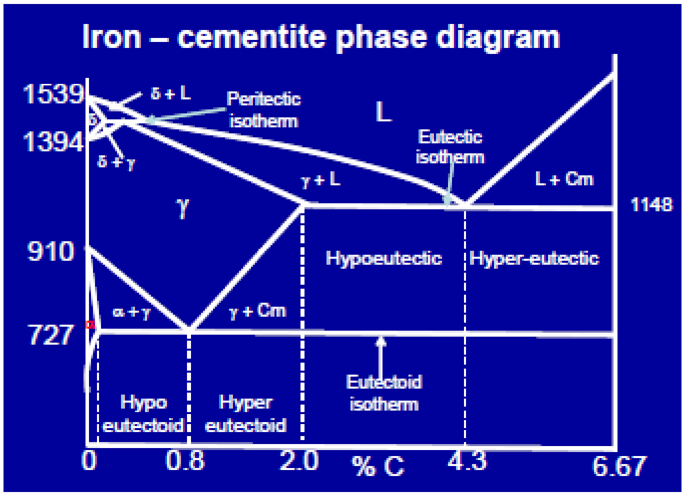
Solubility of carbon in Fe = f(structure, temperature)

Where is the carbon located in iron lattice?

The sketch in slide 1 is a typical cooling curve of pure iron. Solidification begins with nucleation and growth of crystals of iron at 1539°C. It is BCC (body centered cubic). At 1394°C it transforms into FCC (face centered cubic) structure. This is stable till 910°C where it again transforms into BCC. Each of these transformations appears as steps on the cooling curve. Apart from this there is another transformation which may not get detected by thermal analysis. This is the transformation from paramagnetic to ferromagnetic state. It occurs at 770°C. This is known as its Curie temperature. The property which is most sensitive to detect it, is magnetic permeability. The three different forms of iron are known as ferrite, stable until 910°C, austenite, stable from 910°-1394°C and ferrite, stable from1394°– 1539°C. Note that the BCC form of iron is known as ferrite. Therefore in order to distinguish between the two, the high temperature form is termed as delta ferrite. If carbon atoms are introduced into iron these are likely to occupy the interstitial sites because the atoms carbon are much smaller than those of iron atoms. The solubility of carbon in iron is a function of temperature and crystal structure.

Phases in iron – carbon binary system:

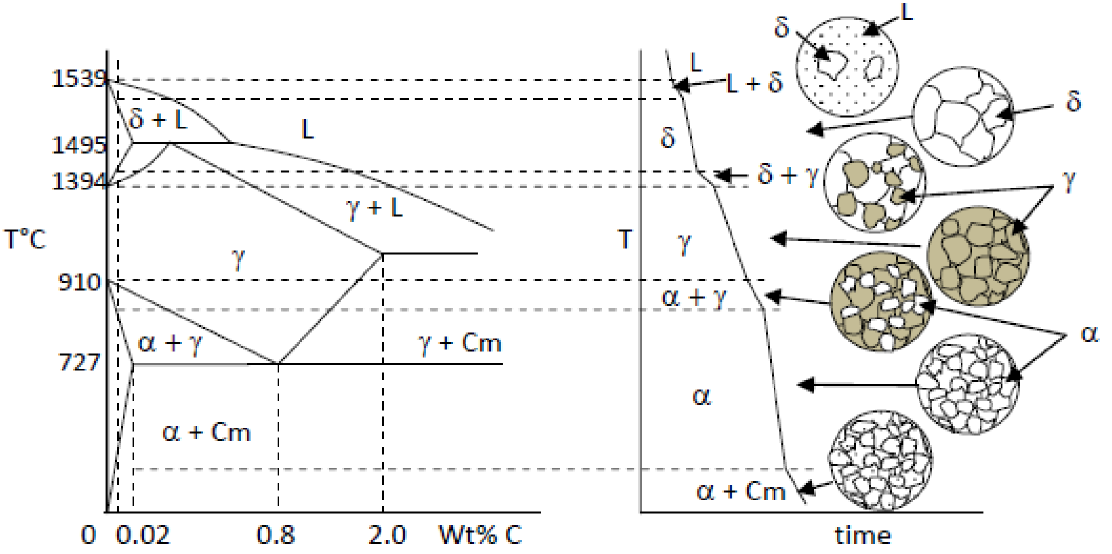
Iron can exist in three different crystalline forms each having limited solubility of carbon. The stability of these depends on temperature and composition. The two high temperature forms of iron are ferrite which is BCC (stable above 1394°C) and austenite (stable above 910°C) which is FCC. The room temperature form of iron is □ ferrite which is BCC. The solubility of carbon in ferrite is limited. The maximum solubility is around 0.025wt% as against this the solubility of carbon in austenite is a little more. It is about 2wt%. Apart from this iron carbon system may have iron carbide (Fe3C) called cementite. It has 6.67% carbon. It is considered as an inter-metallic compound having relatively more complex crystal structure than those of ferrite and austenite. It is a meta-stable phase. It may exist for indefinite periods of time at room temperature. However on prolonged thermal exposure at 600°C or beyond it transforms into ferrite and graphite. Therefore iron carbon alloys of commercial importance may be considered as a binary alloy of iron and cementite. Let us first look at its phase diagram. It is also known as iron cementite meta-stable phase diagram. Although it is a binary system there are five different phases including the liquid. This is likely to have more than one invariant reaction involving three phases.



The above figure gives a schematic Fe-Fe3C phase diagram. It has 3 invariant reactions (transformation). These are given in slide 4. The one occurring at 1495°C is the peritectic reaction. The delta ferrite reacts with liquid to form austenite. The one at 1148°C is known as the eutectic reaction where the liquid transforms into a mixture of austenite and cementite. The eutectic is known as Ledeburite. The one at 727°C is known as eutectoid transformation where austenite decomposes into a mixture of ferrite and cementite. This is known as Pearlite. On the basis of this diagram iron – carbon alloys having less than 2.0% carbon are known as steel, whereas those having more than 2.0% carbon are known as cast iron. This classification is based on their ability to undergo large plastic deformation. Steel is ductile but cast iron is brittle.

Steel:

It is an iron carbon alloy where most of the carbon is present as meta-stable iron carbide called cementite. The upper limit of carbon content is 2%. Phase diagram helps us guess the structure of alloys and their properties. Let us look at what kinds of structure steel could have depending on its composition. We would only consider the structure that develops under equilibrium rate of cooling. The steel on solidification is expected to have fully austenitic structure. It may be assumed to be homogeneous since the rate of cooling is considered to be slow. Depending on its composition we may have three types of structures. (i) % carbon < 0.02 (ii) 0.02 < % carbon < 0.8 (iii) 0.8 < % Carbon < 2.0.



The above figure explains the solidification behavior of steel having less than 0.02% carbon with the help of schematic diagrams. The sketch on the left shows a part of the equilibrium diagram (Fe-Fe3C) with the location of the alloy by a vertical dotted line. It intersects the liquidus, solidus, and a set of solvus curves. These are projected on to the cooling curve shown on the right with the help of a set of horizontal lines. The cooling curve exhibits inflection points at each of these intersections. Solidification begins with precipitation of a few grains of δ ferrite. The top most microstructure corresponds to this stage. The solidification takes place by nucleation and growth. The composition of the liquid and the solid keeps changing during this stage. When solidification is complete the entire liquid is replaced by δ ferrite having the same composition as that of the alloy. This is shown by the second schematic structure from the top Figure. The structure remains unchanged until the temperature crosses the boundary between δ /δ + γ phase fields. Thereafter austenite precipitates from δ ferrite. The grain corners and boundaries are the preferred sites where grains of austenite nucleate. The third microstructure from the top in Figure represents its main features. It consists of grains of δ (white) and a few grains of γ (grey). There is partition of carbon between these two phases. Bulk of the carbon goes into austenite. The composition of the two keeps changing as the temperature drops. The volume fraction of γ increases at the cost of δ. When the %carbon in austenite becomes equal to that of the steel δ ferrite disappears. The structure now consists of 100% austenite. Note the main features of the fourth microstructure from the top in Figure. The grain size is finer than that of 100% δ ferrite. The structure remains as 100% austenite until the temperature drops below the line representing the boundary between γ and α + γ phase fields of the equilibrium diagram. This is where α ferrite starts precipitating from austenite. The grain boundaries and the grain corners are the preferred sites for precipitation. The fifth sketch from the top of Figure is a typical representation of its microstructure at this stage. Ferrite grains are shown as white and austenite grains are shown as grey. This continues through nucleation of new grains and growth of the existing ones until the temperature drops below the line between $\alpha + \gamma$ and α phase fields of the phase diagram. At this stage the structure is 100% ferrite (α). The 6th sketch in Figure is a typical representation of the microstructure. This remains unchanged till the temperature drops below the solvus. At this stage excess carbon precipitates as cementite. The last sketch in Fig 2 is a typical representation of its microstructure. The amount of cementite keeps increasing as the room temperature drops. It can be estimated by lever rule. From the phase diagram it is evident that the steel at room temperature would consist of ferrite with a few specks of cementite. If % carbon in the steel is 0.01 the amount of cementite is given by (0.01/6.67)x100 = 0.15%. The grains are relatively finer than that after solidification.

Cast Iron (C.I):

Cast Iron is the name applied to a family of high-carbon content Fe-C alloys, specifically, those containing more than 2.14 wt. % C. Generally, most cast irons fall within the 3.0 to 4.2 wt. % range. Many contain silicon. Many cast irons are strong, but also brittle. As such, they find uses as small cylinder blocks, cylinder heads, pistons, clutch plates, transmission cases, diesel engine casting.. There are four types of cast irons: gray, nodular, white, and malleable. Cast irons melt between ~ 1150^{o}C and 1300^{o}C; since this range is lower than for steels, they are easier to melt and cast than steels

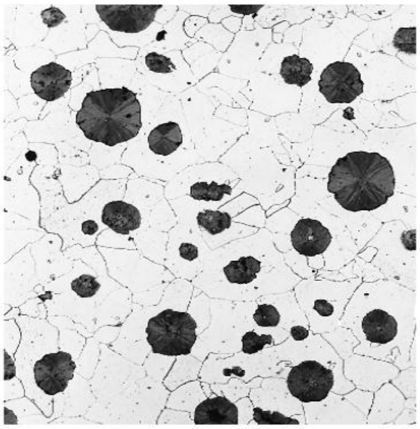
Constituents of Cast iron:

Cast irons consists of varying amounts of ferrite, cementite (Fe3C), and graphite (C). In most cast irons, the carbon-rich phase is graphite, not cementite.

Gray Cast iron:

Gray Cast iron contains 2.5 to 4.0 wt. % C and also 1.0 to 3.0 wt. % silicon. The Si promotes formation of *graphite* instead of cementite. Graphite is dispersed throughout a ferrite or pearlite matrix in the form of *flakes*. The graphite flakes have sharp edges and tips. Consequently, the flakes act as *stress raisers* which can induce fracture near their tips. For this reason, gray iron is brittle in tension. It is also good at damping vibrations. Gray iron is inexpensive and relatively easy to cast with minimal shrinkage.

Nodular Cast iron:

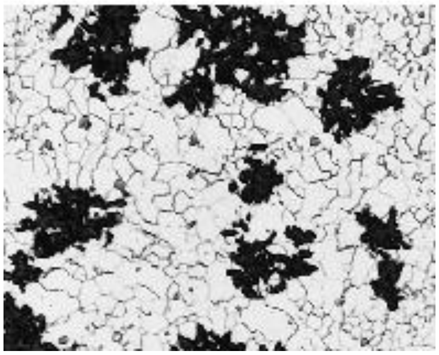


The nodular cast iron contains 2.5 to 4.0 wt. % C, 1.0 to 3.0 wt. % Si, plus Mg &/or Ce. The Mg &/or Ce cause the flakes to spherodize (hence nodular). Graphite is dispersed throughout a ferrite or pearlite matrix in the form of *spheres* or *nodules*. The graphite nodules have no sharp features; therefore, the resulting material is much more ductile than gray iron. The mechanical properties of nodular iron are similar to steel. Nodular iron is frequently used in valves, crankshafts, gears, and other automotive components.

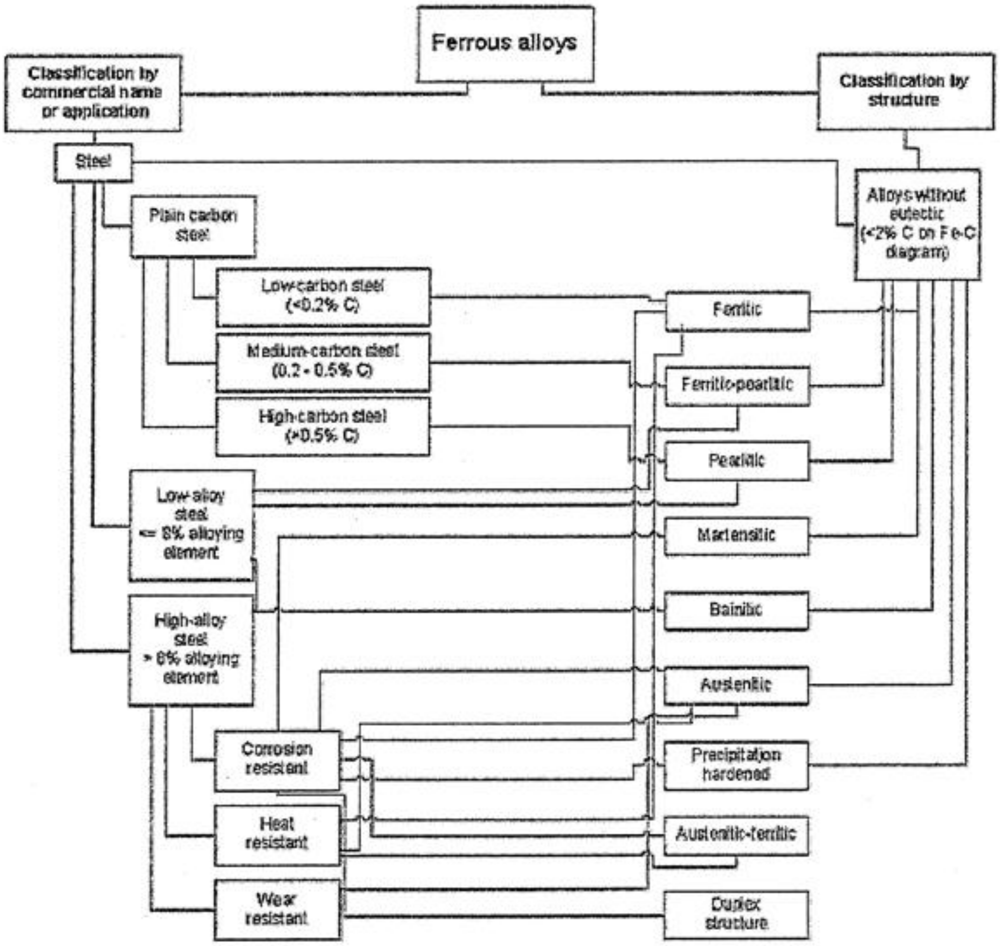
White Cast Iron:

White iron contains 2.5 to 4.0 wt. % C and *less than 1.0 wt. % Si*. Because of the low Si content, the carbon forms *Fe3C* instead of graphite. Cementite is dispersed throughout pearlite (ferrite + cementite) matrix. White iron contains a considerable volume fraction of cementite (Fe3C), a hard and brittle compound. Because of the amount of cementite, white iron is extremely hard and extremely brittle. Limited usage - mainly applications requiring hardness and wear resistance (such a rollers in rolling mills). Also used as a precursor to *malleable iron*.

Malleable Cast Iron:



Malleable iron (just like white iron) contains 2.5 to 4.0 wt. % C and *less than 1.0 wt. % Si*. Unlike white iron, the C exists in the form of *graphite* instead of cementite. Graphite rosettes are dispersed throughout a *ferrite (or pearlite)* matrix. Malleable iron is produced by *heating white iron in order to decompose the cementite into graphite*. The graphite forms clusters, similar to nodular iron. Reduction in the amount of cementite causes the material to become relatively ductile (or malleable). Used in connecting rods, transmission gears, differential cases, flanges, pipe fittings.



Steel:

The term steel is used for many different alloys of iron. These alloys vary both in the way they are made and in the proportions of the materials added to the iron. All steels, however, contain small amounts of carbon and manganese. In other words, it can be said that steel is a crystalline alloy of iron, carbon and several other elements, which hardens above its critical temperature. Like stated above, there do exist several types of steels which are (among others) plain carbon, stainless steel, alloyed steel and tool steel.

Plain carbon steel.

Carbon steel is by far the most widely used kind of steel. The properties of carbon steel depend primarily on the amount of carbon it contains. Most carbon steel has a carbon content of less than 1%. Carbon steel is made into a wide range of products, including structural beams, car bodies, kitchen appliances, and cans. In fact, there are three types of plain carbon steel and they are low carbon steel, medium carbon steel, high carbon steel, and as their names suggests all these types of plain carbon steel differs in the amount of carbon they contain. Indeed, it is good to precise that plain carbon steel is a type of steel having a maximum carbon content of 1.5% along with small percentages of silica, sulphur, phosphorus and manganese.

General properties of plain carbon steel.

Generally, with an increase in the carbon content from 0.01 to 1.5% in the alloy, its strength and hardness increases but still such an increase beyond 1.5% causes appreciable reduction in the ductility and malleability of the steel.

Low carbon steel or mild steel, containing carbon up to 0.25% responds to heat treatment as improvement in the ductility is concerned but has no effect in respect of its strength properties.

Medium carbon steels, having carbon content ranging from 0.25 to 0.70% improves in the machinability by heat treatment. It must also be noted that this steel is especially adaptable for machining or forging and where surface hardness is desirable.

High carbon steels, is steel-containing carbon in the range of 0.70 to 1.05% and is especially classed as high carbon steel. In the fully heat-treated condition it is very hard and it will withstand high shear and wear and will thus be subjected to little deformation.

Moreover, at maximum hardness, the steel is brittle and if some toughness is desired it must be obtained at the expense of hardness. Depth hardening ability (normally termed as hardenability) is poor, limiting the use of this steel.

Furthermore, as it has been seen that hardness, brittleness and ductility are very important properties as they determine mainly the way these different carbon content steels are used. Considering the microstructure of slowly cooled steel; for mild steel, for instance, with 0.2% carbon. Such steel consists of about 75% of proeutectoid ferrite that forms above the eutectoid temperature and about 25% of pearlite (pearlite and ferrite being microstructure components of steel). When the carbon content in the steel is increased, the amount of pearlite increases until we get the fully pearlitic structure of a composition of 0.8% carbon. Beyond 0.8%, high carbon steel contain proeutectoid cementide in addition to pearlite.

However, in slowly cooled carbon steels, the overall hardness and ductility of the steel are determined by the relative proportions of the soft, ductile ferrite and the hard, brottle cementite. The cementite content increases with increasing carbon content, resulting in an increase of hardness and a decrease of ductility, as we go from **low carbon** to **high carbon** steels.

Limitations of plain carbon steel.

Like everything, the plain carbon steels do have some appreciable properties but also consists of some limitations. These are:

1. There cannot be strengthening beyond about 100000 psi without significant loss in toughness (impact resistance) and ductility.

2. Large sections cannot be made with a martensite structure throughout, and thus are not deep hardenable.
3. Rapid quench rates are necessary for full hardening in medium-carbon leads to shape distortion and cracking of heat-treated steels.
4. Plain-carbon steels have poor impact resistance at low temperatures.
5. Plain-carbon steels have poor corrosion resistance for engineering problems.
6. Plain-carbon steel oxidises readily at elevated temperatures.

Influence of residual elements on the properties of Carbon steel:

Steel, is an alloy, which is mainly produced from pig iron. In fact, the manufacture of steel is quite a long process as it comprises of numerous stages and one of these stages is refining. Indeed, once produced in furnace, the steel does contain quite significant amount of impurity and thus, it requires to be refined to a certain degree. However, even after the refining process, the steel still contain small amounts of residual elements (also termed as trace elements) which has some negative influence on the properties of steel.

For instance, carbon steel is an alloy made up of mainly iron and carbon but still other elements do exists in this alloy as shown in table below:

Elements	**Maximum weight %**
C	1.00
Cu	1.60
Mn	1.65
P	0.40
Si	0.60
S	0.05

Out of these elements, Phosphorus, Sulphur and Silicon are considered as trace elements as they have negative impacts on the steel.

Indeed, there are many elements which are considered as being residual elements and these elements are:

Residual elements	**Symbol**
Phosphorus	P
Sulphur	S
Oxygen	O
Hydrogen	H
Tin	Sn
Arsenic	As

Effects of residual elements on steel.

Like stated above, the presence of these trace elements are undesirable due to their bad effects on the steel and its properties. In fact, here is in more details, the description of these elements as well as their drawbacks they cause on steel.

Phosphorus:

Phosphorus is an element, which affects primarily the ductility and the toughness of steel and this mostly when the steel is in the quenched and tempered conditions. In fact, the phosphorus has a tendency to react with the iron to form a compound known as iron phosphide (Fe_3P) which has the particularity of being brittle. Hence, phosphorus renders steel less tough and ductile while it increases brittleness.

Silicon:

Although the fact, that silicon is not that harmful to steel, still it has some bad effects on its properties. In fact, silicon has the particularity of impairing hot and cold workability and machinability. The presence of Silicon in low carbon steel is also detrimental since it affects the surface quality of the steel.

Oxygen:

Oxygen is really a poison to steel. Indeed, when present in steel, it has a very bad effect on its mechanical properties. To be more precise, oxygen reduces the impact strength of steel, whereas it has the tendency to increase its ageing brittleness, red shortness, woody and slanty fractures. In brief Oxygen reduces the toughness of steel.

Hydrogen:

Like Oxygen, Hydrogen also is injurious to steel as it causes embrittlement by decreasing of elongation and reduction of area without any increase of yield point and tensile strength. Indeed, hydrogen is the source of redoubtable snowflake formation and it favors the formation of ghost lines in the steel structure. Furthermore, atomic hydrogen engendered by pickling penetrates into the steel and forms blowholes. This element also acts as a decarburising agent when it is in the moisted form (at high temperatures).

Sulphur:

Sulphur is a trace element, which has a great tendency to segregate (that is to isolate itself in the structure). It also reacts with iron to form iron sulphide which produces red or hot-shortness, since the low melting eutectic forms a network around the grains so that these hold but loosely together, and the grain boundaries may easily break up during hot forming. Sulphur plays a great role also in the drop in weldability, impact toughness and ductility of steel.

Tin:

Tin is also considered as being a residual element and this simply because, just as steel, it causes hot shortness. In addition to this, tin is also a source of temper embrittlement.

Arsenic:

Arsenic, for its part, plays an important role in the rise of temper embrittlement in the properties of steel. Furthermore, it causes a considerable drop in toughness and it also impairs weldability.

Antimony:

This has as effect similar to Arsenic which also cause temper embrittlement and it affects quite considerably the toughness and the ductility of steel.

Nitrogen:

This is not the most harmful trace element since it only causes a decrease in toughness of the steel.

Effects of alloying elements in an alloy:

An alloy is a mixture of two or more metals, or a metal and some other material. Most alloy contain a large amount of one metal, called the **base metal**, and smaller amounts of one or more other metals or nonmetallic materials. Many pure metals are too soft, corrode too easily, or have other mechanical or chemical disadvantages can be overcome if the metals are combined with other metals into alloys. Most alloys are harder than the metals from which they are made. They are also less malleable. They are harder to hammer into shape. Most alloys are less ductile than pure metals. That is, they are less easily drawn into fine wires and similar shapes. But most alloy are more fusible and more easily melted, than the pure metals of which they are composed. Some alloys will even melt at the comparatively low temperature of hot water. Few alloys can conduct electricity as well as many metals in their pure forms.

General effects of alloying elements are:

(i) Improves tensile strength without appreciably lowering ductility.
(ii) Improves toughness.
(iii) Improves hardenability which permits hardening of larger sections than possible with plain carbon steels or allows quenching with less drastic rates.
(iv) Reducing the hazard of distortion and quench cracking.
(v) Retain strength at elevated temperatures.
(vi) Obtain better corrosion resistance.
(vii) Improves wear resistance.
(viii) Imparts a fine grain structure to the steel.
(ix) Improves special properties such as abrasion resistance and fatigue behaviour.

In fact, the properties of alloys are quite dependent on the relationship between chemical composition, processing and their microstructure. For instance, whenever an element is added to a pure metal, the latter alters the size of the lattice structure of the metal and depending on the alloy formed, it can also change its lattice type. Sometimes metals do react together to form intermetallic compounds with very complex lattice structure. Such compounds melt at a fixed temperature and have a lower conductivity and ductility but greater strength and hardness than an alloy of face centered body, centered or hexagonal lattice structure. Thus, alloys increses strength and hardness of metal by changing its structure. Furthermore, like stated above, alloying enables the formation of fine grain size since it favours the ability of the metal to be hardened by quenching in oil or air rather than in water. Indeed, oil is a cooling agent offering slow cooling rate and thus the grain form more regularly with time and hence they are finer.

Effects of alloying elements in steel:

Steel is one of the world’s cheapest and useful metals. Indeed, steel founds application in numerous fields, from building construction purposes to kitchen utensils. Hence, so as to be able to respond to such a great demand and to suit the requirements to different applications, steel needs to offer several desired properties and these properties is achieved by alloying it. Like stated above, several other elements need to be added to iron and carbon to form adequate alloys with enhanced properties. Alloyed steel in brief is made by adding a small percentage of alloying metals to liquid steel to subsequently alter the hardness, toughness, elasticity or durability. Naturally each of the alloying elements will have a specific property on the steel and are added to it in certain proportions on the different properties required.

The different alloying elements on steel are:

(i) Carbon
(ii) Magnesium
(iii) Silicon
(iv) Copper
(v) Chromium
(vi) Molybdenum
(vii) Vanadium
(viii) Nickel
(ix) Aluminium
(x) Boron
(xi) Titanium
(xii) Zirconium
(xiii) Calcium
(xiv) Lead
(xv) Nitrogen
(xvi) Tungsten

The effects of the above alloying elements in steel are:

Carbon:

Carbon is an element whose presence is imperative in all steel. Indeed, carbon is the principle hardening element of steel. That is, this alloying element determines the level of hardness or strength that can be attained by quenching. Furthermore, carbon is essential for the formation of cementite (as well as other carbides) and of pearlite, spheridite, bainite, and iron-carbon martensite, with martensite being the hardest of the microstructures. Carbon is also responsible for increase in tensile strength, hardness, resistance to wear and abrasion. However, when present in high quantities it affects the ductility, the toughness and the machinability of steel.

Manganese:

Manganese also contributes greatly towards increasing strength and hardness, but to a less extent than carbon. To be more precise, the degree to which manganese increases hardness and strength is dependent upon the carbon content of the steel. In fact, manganese contributes to the increasing the strength of the ferrite, and also toward increasing the hardness of penetration of steel in the quench by decreasing the critical quenching speed. Moreover, still consisting of a considerable amount of manganese can be quenched in oil rather than in water, and are therefore less susceptible to cracking because of reduction in the shock of the quenching. This alloying is also considered as a degasifier reacting favorably with sulfur to improve forging ability and surface quality. This is achieved by interacting with the sulphur to give manganese sulphide. Naturally in doing so, the risk of hot shortening is considerably decreased. In addition, manganese enhance the tensile strength, the hardness, the harden ability, the resistance to wear, and it increases also the rate of carbon penetrating in the coefficient of thermal expansion of steel whereas it is detrimental to both thermal and electrical conductivity.

Copper:

Although being favourable when it comes to render steel more resistant to corrosion, copper is not considered as such as being a good alloying element since it does have some bad repercussions on the steel. Indeed, copper is harmful to the surface quality of steel and it renders the steel less machinable at high temperatures.

Chromium:

Among the alloying elements of steel, chromium forms part of those which best promote hardenability. In fact, its effect on steel is quite similar to that of manganese in the way that it enhances much hardness penetration. When being present in reasonable quantities, chromium contributes much in reducing the quenching speed. In fact, such a slow quenching is achieved thereby enabling steel to be oil or air hardened. Chromium is also recommended when there is good wear resistant steel of appreciable toughness required. Chromium is also very popular as alloying element as it is quite efficient in rendering steel resistant to staining and corrosion. Moreover, chromium forms carbides that improve edge-holding capacity. Steel, rich in chromium have also high temperature strength and they are quite resistant to high-pressure hydrogenation.

Nickel:

Nickel is beneficial to steel in the way that it boost up the strength of ferrite. It is a fact that nickel causes considerable increase in the impact strength of steel. Nickel found its common use generally in low alloy steels. This is so because this alloying element increases appreciably toughness and hardenability. In addition, nickel also exhibits the tendency of reducing distortion and cracking of the steel.

Vanadium:

Vanadium has for main effect on steel that it helps controlling the grain growth during heat treatment. It is used rather in medium carbon steel where when added in relatively large quantities it causes a reduction in the hardenability of the steel. Indeed, vanadium is known as a strong carbide former and these carbide former and these carbide dissolves very difficulty in austenite thereby explaining why vanadium reduces hardness of steel.

Molybdenum:

Molybdenum is an alloying element which is seldomly used on its own. In fact, molybdenum is used in combination with other alloying elements. This alloying element increases the hardness penetration of steel and also contributes in slowing down the critical quenching speed. Molybdenum proves to be useful also for increasing tensile strength of steel. Furthermore, it prevents temper brittleness and it favours the formation of a fine grain structure. It is good also to mention that molybdenum forms carbides readily and it thus improves the cutting properties in high-speed steels. Hence, it can be said that molybdenum helps much in increasing machinability.

Aluminium

Aluminium is mainly used as an alloying element of steel because of its ability to deoxidize the steel and also because of its capacity of extracting gases from the steel. Aluminium also does offer to steel resistance to ageing. Moreover, aluminium helps in the formation of fine grain structure, and since it combines well with nitrogen to form very hard nitride, it is considered to be a favourable alloying constituent of nitriding steels.

Boron

Boron, is an alloying element that can be placed in the category of those whose main function is to enhance the hardenability of steel. However, the main interest in using boron to alloy steel is that it increases the hardenability of the material and this is, without having any effect on the ductility nor on the ferrite strength of the steel. As a result, formability and machineability of steel are boosted due to the presence of Boron.indeed thus alloying element finds most of its applications in low carbon steels.

Titanium

Titanium can be associated to boron as it plays also a great role in increasing the hardenability of steel. In fact, titanium helps much towards increasing the effectiveness of boron as an alloying element of steel.

Calcium

Calcium, for its part, is mainly used in a silicocalcium combination. In truth, calcium (as well as silicon) has for main function to deoxidize the steel. In doing so, the calcium does also contribute towards imparting the steel with a non-scaling property. In addition to this, calcium is also recommended for alloying purposes, as it is quite good in enhancing the toughness, the formability and the machinability of the alloyed material.

Nitrogen

Being a residual element, nitrogen is present, in small quantities, in all steels. In fact, the nitrogen will normally combine with other elements in the steel (like Aluminium, for example) to form hard nitrides. Thus nitrogen increases hardness, tensile and yield strength, but still, there are certain drawbacks related to nitrogen as it causes a considerable decrease in toughness and in ductibility of steel.

Tungsten

Being a very powerful carbide former, and the fact that its carbides are very hard, tungsten, do provide to steel good toughness and it inhibits grain growth. Tungsten is also quite good towards increasing the strength and hardness retention as well as wear resistance at high temperatures and cutting power.

Classification (composition, properties, codes) of steel used by SAE/AISI:

Generally, steel is classified according to the alloying element it contains, whereas these alloying elements are in turn classified according to their readiness to form carbides, austenites and ferrites. Being the main constituents, as well as the most important element used in alloyed steel, carbon is taken as reference for classifications purposes.

Classification of steel (SAE/AISI)

Concerning, the alloy steel, some standards do exists so as to facilitate its analysis and its classification. One of these standards is the one established by the Society of Automotive Engineer(SAE) which uses a four digits numeration system to classify steel. Out of this four digits, the first one, generally indicates whether the steel is a plain carbon typed one, whereas the second number give an idea about the type of modification to which the steel has been subjected. Regarding the last two digits; they simply point out the composition of carbon in the steel. For example, considering the type of steel referred to as SAE1040; it can be said that it is a plain carbon one , with a carbon content of

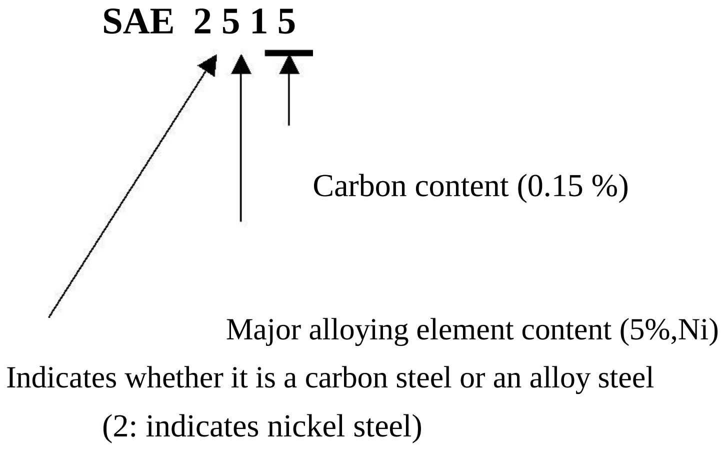
0.40%.generally, alloyed steel are written as 2xxx, 3xxx etc.

However, the American iron and steel institute (AISI) has redefined the percentages of alloying elements used in steel manufacture and prefixes have been added to the SAE classification system so as to indicate the method of production of the steel. The different prefixes are as follows:

A: alloy, basic open hearth
B: carbon, acid Bessemer
C: carbon, basic open hearth.
D: carbon, acid open hearth
E: Electric furnace.

Sometimes, over letters may be added to this classification system to designate hardenability (normally denoted by the letter H)

Interpretation of the classification system



Note : In AISI, the first 2 digits are also indication of the grades of the steel, as it is shown below:

10: Non resulfurized grades
11: Resulfurized grades
12: Resulfurized and rephosphorized grades
15: Non sulphurized grades; Max Mn content >1%

It is frequent to have the letter L or B placed in between the second and the third number of an AISI number. This is done so as to distinguishes leaded or boron typed steel

ex: AISI 15B48H
AISI 12L14

Table below shows the (SAE-AISI) classification of carbon steels and alloy steels

Classification	*Number*	*Range of numbers*
A. Carbon Steel SAE-AISI	1xxx	
Plain carbon	10xx	1006-1095
Free machining (resulphurized)	11xx	1108-1151
Resulphurized, rephosphorized	12xx	1211-1214
B. Alloy Steels		
Manganese (1.5%-2.0%)	13xx	1320-1340
Molybdenum	4xxx	
C-Mo (0.25% Mo)	40xx	4024-4068
CR-Mo (0.7% Cr, 0.15% Mo)	41xx	4130-4150
Ni-Cr-Mo (1.8% Ni, 0.65% Cr)	43xx	4317-4340
Ni-Mo (1.75% Ni)	46xx	4608-4640
Ni-Cr (0.45% Ni, 0.2% Mo)	47xx	
Ni-Mo (3.5% Ni, 0.25% Mo)	48xx	4812-4820
Chromium	5xxx	
0.5% Cr	50xx	
1.0% Cr	51xx	5120-5152
1.5% Cr	52xxx	52095-52101
Corrosion-heat resistant	514xx	(AISI 400 series)
Chromium-Vanadium	6xxx	
(1% Cr, 0.12% V)	61xx	6120-6152
Silicon Manganese (0.85% Mn, 2% Si)	92xx	9255-9262
Triple-alloy steels		
0.55% Ni, 0.50% Cr, 0.20% Mo	86xx	8615-8660
0.55% Ni, 0.50% Cr, 0.20% Mo	87xx	8720-8750
0.55% Ni, 0.50% Cr, 0.20% Mo	93xx	9310-9317
0.55% Ni, 0.50% Cr, 0.20% Mo	94xx	9437-9445
0.55% Ni, 0.50% Cr, 0.20%	97xx	9747-9763

Mo		
0.55% Ni, 0.50% Cr, 0.20% Mo	98xx	9840-9850
Boron (~0.005% Mn)	xxBxx	

Effect of Alloying Elements:

The alloying elements are used in steel so as to improve its properties and this is in the scope of rendering the steel appropriate for different uses. However, allowing is not only a matter of adding elements to steel, the quantity of alloying elements added is of prior importance so as to achieve the required hardness, toughness or machinability of steel. There is below a table showing the different composition range used for each alloying element together with their effect on the steel.

ALLOY ELEMENT	***RANGE***	***EFFECT***
CARBON	0-25 % 0.25-0.70% 0.70-1.50% >1.50%	_ Improves heat treatment and ductility _ Improves machinability _ Considerably increase in strength and hardness _ Reduction in ductility and malleability
MANGANESE	1.65-2.10% 10%-14%	_ Improve electrical resistance and magnetic property of steel and reduces its coefficient of expansion _ Improves hardness and toughness.
SILICON	0-0.30% 0.30-1%	_ Imparts good casting fluidity _ Increase heat resistance
COPPER	0.20-0.50% High amounts	_ Improves steel resistance to atmospheric corrosion _ Harmful to steel as it affects surface finish.

CHROMIUM	0-5% 14% -	_ Quenching speed reduced, increased toughness, and wear resistance imparted to steel. _ Stainless steel: resistance to corrosion increased, higher critical temperature imparted
VANADIUM	0-0.05% > 0.25% around 1 %	_ Harden ability is boosted up _ Induces resistance to softening at high temperatures _ Retain hardness at high temperature
NICKEL	0-5% 8-12% 15-25% 25-35% 36%	_ Favours refined grain structure and causes hardening abilities _ Resistance to low temperature impact _ High magnetic properties is imparted to steel _ Corrosion resistance is increased _ Invar is obtained, which has a low coefficient of temperature
BORON	0.0005-0.03%	_ Increased harden ability of steel
LEAD	0.15-0.35%	_ Increased machinability _ (favours formation of small chips)
TUNGSTEN	3-6%	- Improves cutting
MOLYBNENUM	0.15 – 0.25 %	- Used in combination with Chromium to improve hot hardness

Effect of residual elements in the Steel:

There are certainly some elements, which are present in all steel as residual elements. These residual elements are normally disadvantageous to the steel, but still if present in some amount, they are able to import some beneficial properties to the alloyed steel. That is, when present in relatively small or high quantities, these residual elements may be viewed as harmful to the alloyed but when present in a reasonable quantity, the beneficial effect on the steel may be optimized. For instance, manganese (although greatly beneficial to steel) and silicon are two trace elements found in steel. However when used in appropriate proportion, both of them have the ability to increase harden ability of steel. This is mainly because both of them have the power to dissolve in the austenite and thus cause a significant decrease in the transformation rate of the austenitic phase to pearlite or upper bainite. Hence, when adequately used, silicon can favours slow cooling rates of austenite to wanted hard martensite or lower bainite.

Residual elements may also react with other alloying elements so as to impart desirable properties to the steel. For instance silicon can be used as a deoxidiser. That is, even though, being harmful to steel, this residual element can be used to get rid of oxygen, which is even more harmful to the alloy. Another example is phosphorus, which can help in increasing hardness by reacting with the iron to form hard iron phosphide. Indeed, certain of these residual elements can be used efficiently so as to render the beneficial aspect on the steel predominant as compared to the bad influence.

Beneficial effects of residual steel on steel when used in reasonable amount

- Phosphorus: It increases strength and hardness of hot rolled steel. It is also beneficial to machinability
- Sulphur: increases machinability and cause formation of short chips
- Silicon: use as an deoxidiser of steel. It does also enhance resistance to scaling.
- Nitrogen: improves strength, hardness and machinability

Standards (BS, MS, AISI) used for steels:

There are many standards concerning steel and among the most commonly known are the *British standard (BS), the Indian Standard (IS), the American Iron and Steel Institute standard (AISI), the Society of Automotive Engineer Standard (SAE), and the ISO*. Mauritius has also established a standard classification of steel and it is called the *Mauritius Standard (MS)*. Here is listed below some examples of these standardized steels together with their common use.

Indian Standard:

1. *IS 11384: 1985 > Code of practice for composite construction in structural steel and concrete.*
2. *IS 10343: 1989 > Carbon and low alloy investment castings for general applications*

British Standard

1. *BSEN 10250-3 > Alloy steel used for die forging, open for general purposes*
2. *BS 7123 :1989 > Special for metal arc welding of steel and for concrete reinforcement.*

ASTM standard

1. *ASTM 216-S3T > Carbon Steel casting suitable for fusion welding for high temperature service.*
2. *ASTM 217-S5 > Alloy Steel casting for pressure containing parts suitable for high temperature services.*

ISO standard

1. *ISO 600: 1990> High tensile steel chains (round links) for chain conveyors and cold ploughs.*
2. *ISO 1129: 1980> Steel tube for boilers, superheaters and heat exchangers.*

Mauritian Standard

1. *MS10: 1999: specification for carbon steel bars for the reinforcement of concrete*

(first revision of MS10: 1980)

2. *MS 62: 1985 specification for arc welded steel pipes and specials.*

Set out requirements for arc welded carbon steel pipes in sizes 406.4mm to 2220 mm outside diameter for the convenience of water and sewerage and for other applications

AISI standard

1. *AISI 303 > Screw machine products, shafts, valves, bolts, bushings, and nuts;aircrafts fittings; bolts; nuts; rivets; screws; studs.*
2. *AISI 410 > machining parts, pump shfts, bolts, bushings, coal chutes, cutlery, tackle, hardware, jet engine parts, mining machinery, rifle barrel, screws, and valves.*