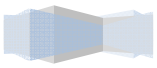
Module 35

Heat treatment of steel V

Lecture 35

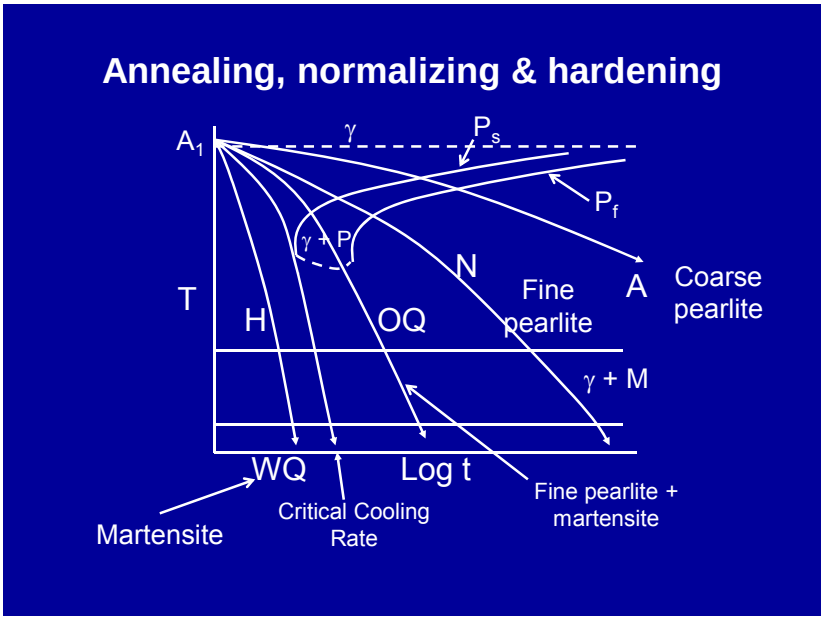
Heat treatment of steel V



Keywords : Origin of residual stress, remedy, martempering, austempering, effect of alloy addition on phase diagram, TTT diagram & tempering, hardenability, ideal critical diameter, mechanism of heat transfer during quenching, ideal quenching medium

Introduction

We are by now familiar with the wide variety of microstructures that can be produced in steel by proper choice of composition and heat treatment. The main reasons why it is so are as follows: (i) iron has more than one crystal structure: the room temperature form of iron is BCC whereas that at high temperature is FCC (NB. If a metal has more than one crystal structure the more close packed structure should be thermodynamically stable at lower temperatures. Iron is an exception. It has unfilled 3d shell. As a consequence the free energy of BCC form of iron becomes less than its FCC structure because of its transformation from paramagnetic state to ferromagnetic state due to exchange interaction) and (ii) the solubility of carbon in the higher in FCC austenite than the in BCC ferrite. If steel is cooled rapidly from austenite although the crystal structure transforms, carbon is retained within solid solution. This results in an extremely fine structure with excess solute atoms and lattice strain. The resultant product is known as martensite. It is extremely hard and brittle. Therefore the process is known as hardening (H). Hardened steel is prone to cracking because of the presence of retained austenite and excessive residual strain. If it is left as it is it may crack. This is why hardening is always followed by tempering. This makes it soft and tough with little drop in hardness. On the other extreme if steel is cooled slowly in a furnace after austenitization you get a very soft and ductile structure. The treatment is known as annealing (A). Normalizing (N) adopts a little faster cooling rate than that of annealing. It gives a finer microstructure having a little higher hardness than that of annealing. Just to recollect slide 1 shows the effect of various cooling rates on the evolution of microstructures in eutectoid steel. Usually it is necessary to adopt water quenching (WQ) to get completely martensitic structure. A little slower cooling like oil quenching may give a structure consisting of fine pearlite and martensite.



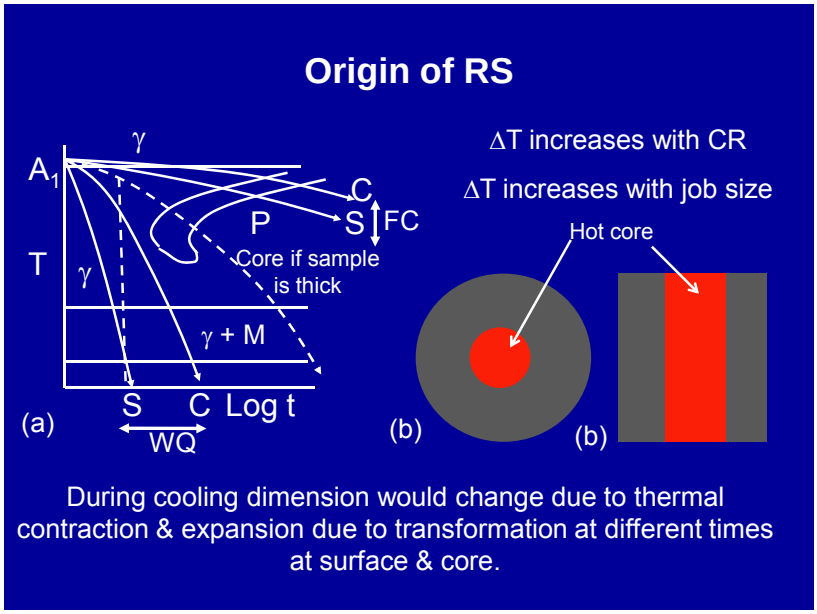
Slide 1

In each of the three heat treatment processes the job is cooled continuously. Therefore in order to predict its structure the cooling curves were superimposed on the CCT diagram of the specific steel in slide 1. However continuous cooling has several limitations. It is not possible to get bainite in plane carbon steel by continuous cooling. Bainitic structure can be obtained only by isothermal transformation. Bainite is an extremely fine structure consisting of a mixture of ferrite and carbide. It has a similarity with the structure you get on tempering of hardened steel. Another limitation of continuous cooling is the development of thermal stresses due to the temperature gradient set up within the component. The severity increases with increasing cooling rate and specimen size. In this lecture we shall look at how these can problems can be avoided by isothermal transformation. Apart from this we shall look at specimen size effect on heat treatment a little more critically.

Origin of residual stress:

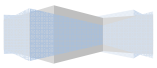
Residual stress develops in steel during cooling because of thermal contraction and the volume expansion due to phase transformation. This is illustrated with the help of a set of sketches in slide 2. The sketch (a) gives the CCT diagram of eutectoid steel. It has a set of cooling curves labeled as S denoting the temperature of the surface of a sample as a function of time and C denoting the temperature of the core of sample as a function of time. Surface would always cool faster. The fig (b) and (c) in this slide are the sectional views of a spherical and a cylindrical job which have been water quenched after homogenization at A_1+30°C at a particular instant. Red color indicates that the core is hot indicating that it is yet to transform into pearlite or martensite even though the surface is cold and it has completely transformed into either martensite or pearlite. Let ΔT represent the difference in temperatures at the surface and the

core of the sample at any instant. It depends on sample size, cooling rate and thermo-physical properties of steel and the surrounding medium. However it is not just the temperature difference but the volume change accompanying martensitic transformation that determines the magnitude of residual stress.



Slide 2

Note that if cooling rate is slow the temperature difference between the surface and centre is not large. The stress due to thermal contraction is low but that due to volume expansion associated with phase transformation may be high. However the transformation is complete when the job is still soft. Therefore the stress gets relaxed by plastic deformation of both the core and the surface. It does not result in distortion or high residual stress. Look at the two cooling curves (labeled FC: furnace cooled) superimposed on the CCT diagram in sketch (a) of slide 2. As against this during water quenching because of large ΔT the transformation at the surface is complete much before it sets in at the core. When the core begins to transform it expands. This would induce tensile stress at the surface. But the surface is already cold and hard. If it is too high it may crack or if the surface is not so hard it may get deformed resulting in distortion. This is further illustrated with the help of a set of sketches in fig 1.



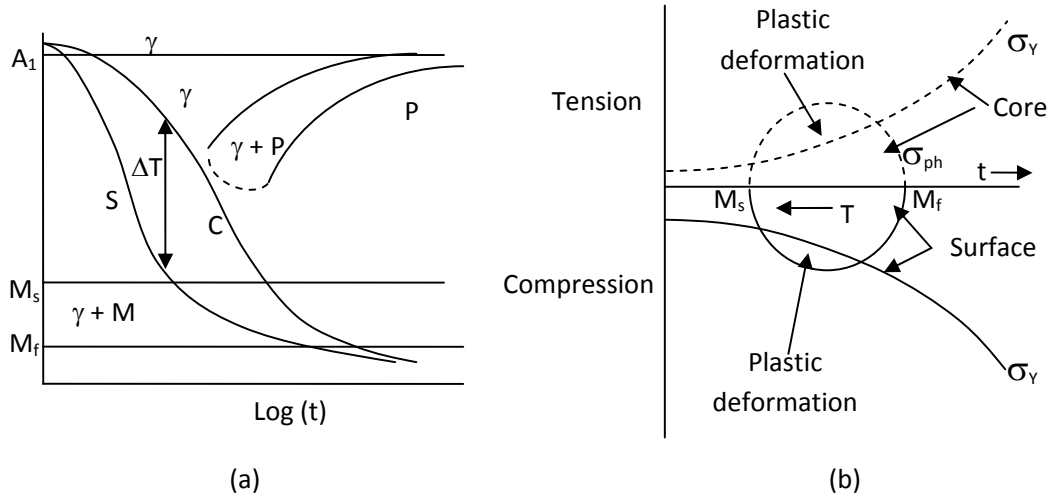


Fig 1: (a) Shows the cooling curves at the centre and the surface of a job on quenching from A_1 + 30°C superimposed on the CCT diagram of 0.8%C steel. (b) Shows yield strength (σ_Y) as a function of T. It decreases with increasing temperature. It also shows stress due to phase transformation (σ_{Ph}) as the temperature drops below M_s. Plastic deformation takes place if $\sigma_{Ph} > \sigma_Y$. (c) Shows how residual stress evolves at the surface and the centre of the job as a function of T (or time t).

Figure 1(a) gives a set of cooling curves of the surface and the centre of a sample quenched in water from 100% austenitic state. Note that the shape of the cooling curves is different from those in slide 2. This is because it represents Newton's law of cooling whereas that in slide 2 represents constant cooling rate. This is the most likely cooling curve you would expect during conventional water quenching. Note that ΔT initially increases reaches a maximum thereafter it decreases until it becomes negligible. Therefore the thermal stress too would pass through a peak. If it exceeds the yield strength of steel somewhere within the sample it would result in local plastic deformation. When the elastic stress in the surrounding region becomes zero once the temperature within the sample becomes uniform, it would try to contract if the stress were tensile or expand if it were compressive. As a consequence the region which has undergone plastic deformation would experience a compressive residual stress if it had deformed under tensile stress or vice versa. The magnitude of thermal stress is given by $\sigma_{th} = E\alpha\Delta T = E\alpha(T_s - T_c)$ where E is the elastic modulus, T_s = temperature of the surface, T_c = temperature of the core and α is the coefficient of linear expansion of steel. On quenching the temperature of the surface becomes less than that of the centre ($T_s < T_c$) and cooling is accompanied by

contraction (α < 0). The thermal stress is therefore tensile at the surface. As the surface contracts the core is subjected to compressive stress and the surface is subjected to tensile stress. The core is hot. Its yield strength is low. It undergoes plastic deformation. However the surface being cold its yield strength is high. It would deform if it exceeds yield strength in tension. On further cooling as the temperature difference decreases the regions surrounding the plastically deformed region would undergo elastic contraction or expansion. As a result there would be compressive residual stress at the surface whereas tensile residual stress at the core. This is often preferred in engineering applications where the component is subjected to fatigue loading. The presence of residual compressive stress at the surface prevents crack initiation. This would enhance its fatigue life. However the residual stress pattern that develops in steel on quenching is a little different. This is because of the martensitic transformation that takes place during quenching.

The transformation of austenite into martensite is accompanied by volume expansion (ΔV). It depends on %C. This is given by $\frac{\Delta V}{V} = 0.0464 - 0.0053(\%C)$. The corresponding linear expansion is given by $\frac{\Delta V}{3V}$. Note that martensitic transformation occurs within a specific range of temperatures from M_s to M_f. The fraction transformed (f) is nearly zero at M_s and it approaches 1 at M_f. It is a function of temperature. Mathematically it may be represented as f = 0 if T > M_s and T < M_f. If M_s > T > M_f, 0 < f(T) < 1; in other words it is a function of temperature. The stress due to volume expansion associated with phase transformation is given by $\sigma_{ph} = E\frac{\Delta V}{3V}f(T)$. Clearly the stress due to phase transformation would far exceed that due to thermal stress. Figure 1(a) shows that martensitic transformation starts at the surface as soon as its temperature drops below M_s. It is accompanied by volume expansion. However the core where the transformation is yet to start would not allow the surface to expand. As a result compressive stress develops at the surface. This is illustrated in fig 1(b). It shows the evolution of stress due to martensitic transformation at the surface (shown by firm line) and the core (shown by dotted line) of the component as a function of temperature. Figure 1(b) also includes plots denoting yield strengths of steel in tension and compression as functions of temperature. Note that plastic deformation occurs first at the surface due to compressive stress and later at the core due to tensile stress. There would be elastically deformed regions surrounding the deformed zones. These would contract or expand depending on the nature of the stress. As a result residual tensile stress would develop at the surface and compressive stress at the core. Figure 1(c) shows the evolution of residual stress at the surface and the core of the component as functions of temperature. A general thumb rule is that the region that transform later is under compression. Tensile residual stress is harmful. It should be avoided. However the presence of compressive stress on the surface of critical components like landing gears of aircrafts is beneficial. It helps prevent the initiation of fatigue crack at the surface. One of the

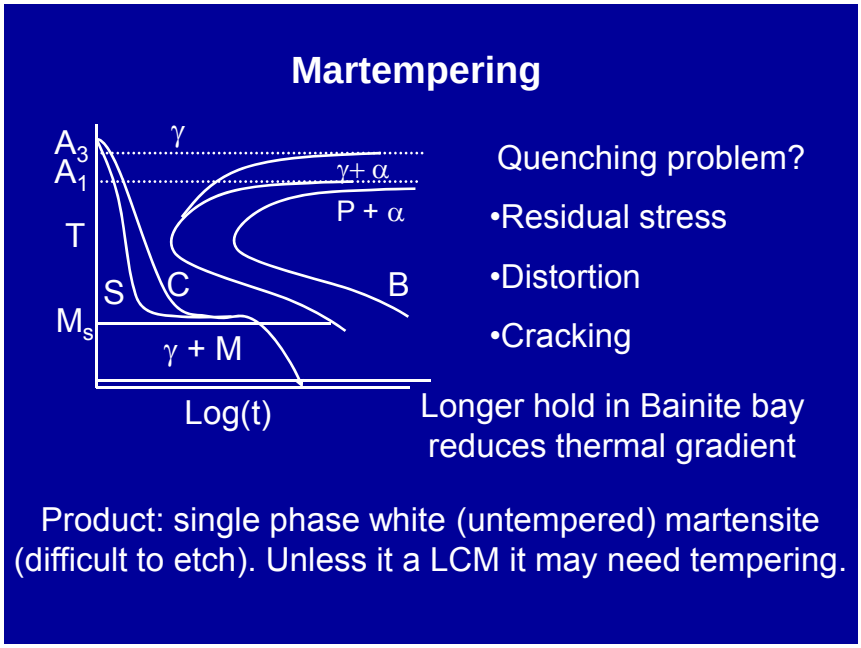
objectives of surface hardening which will be covered in a subsequent module is to introduce compressive residual stress at the surface.

How do we avoid adverse effect of residual stress?

Occurrence of quench cracks is a major problem encountered during hardening of steel. The main reason is the large difference in the temperature (ΔT) at the surface and that at the core of a part to be hardened by water quenching. As a result martensitic transformation occurs first at the core and later at the surface. The time gap (Δt) between the two results in residual tensile stress at the surface. If it exceeds fracture stress it leads to cracking. Larger the time gap higher is the residual stress. This depends on the size of the part to be hardened. If the part is thin (example hack saw or razor blade), the time gap is short. Therefore the residual stress may not be a problem. The key to avoid quench crack in thicker parts is to reduce the time gap (Δt) or the temperature difference (ΔT). This can be done in two ways: (i) allow the part to stay at a temperature a little above M_s so that the temperature becomes uniform before final quenching (ii) alloy addition to suppress diffusion controlled transformation so that steel could transform to martensite at less severe cooling rates. Let us s look at these aspects.

Martempering:

This is a special heat treatment technique to decrease the severity of quenching to minimize residual stress. Instead of direct quenching to room temperature the part is first quenched in a bath maintained at a temperature a little above M_s. It is kept there for a while before final quenching. The isothermal hold helps reduce the temperature difference between the surface (S) and the core (C) of the part. During the final quenching when ΔT is not expected to be low. The surface and the core may undergo martensitic transformation more or less at the same time. This is illustrated with the help of a diagram given in slide 3.

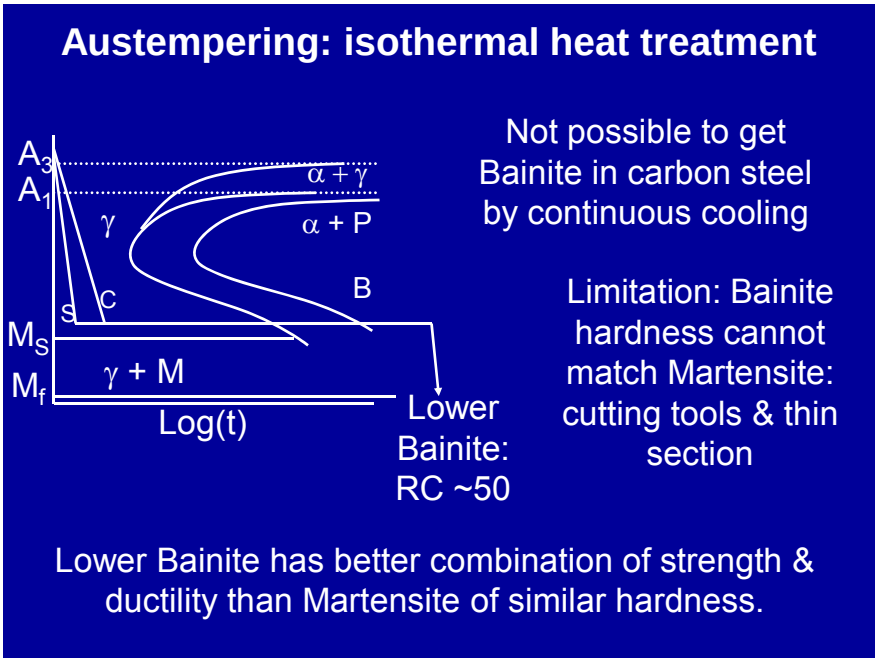


Slide 3

The sketch in slide 3 has cooling curves of the surface and the centre superimposed on the TTT diagram of hypo-eutectoid steel. Isothermal hold in the bainitic bay helps reduce the temperature difference. The treatment is known as martempering. It helps reduce residual stress, susceptibility to distortion and cracking. One of the objectives of tempering is to reduce quenching stress. It can be avoided if %C in the steel is low. The final structure would consist of 100% un-tempered martensite. It is difficult to etch. If %C in martensite is high it should be tempered.

Austempering:

It is an isothermal heat treatment process where you get 100% bainite all through the section of a part. Bainitic structure has certain advantages. It is hard yet tough. Hardness of lower bainite can be as high as Rc50. It has better combination of strength and toughness than that of martensite of similar hardness. Maternsite needs to be tempered. On tempering its structure becomes a mixture of ferrite and carbide. Bainite being is a mixture of ferrite and carbide. This is similar to that of tempered martensite. Therefore austempered structure need not be tempered again. Besides this the isothermal hold allows enough time for temperature within the part to become uniform. As a result transformation occurs simultaneously at the surface and the centre. There is no chance of developing any residual stress. Besides this it is the only way you could get bainite in plain carbon steel. Slide 4 illustrates with the help of a TTT diagram important steps to be followed during austempering of hypo-eutectoid steel.

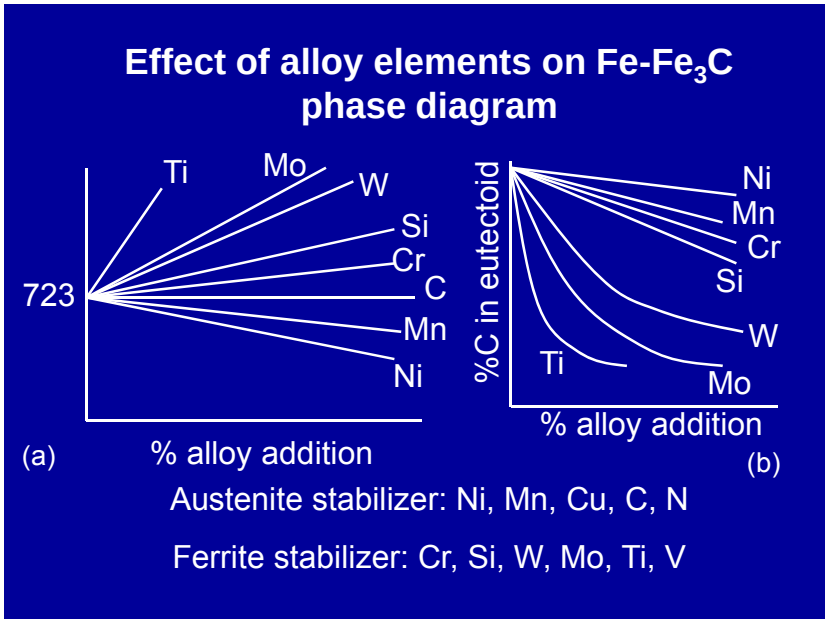


Slide 4

The sketch in slide 4 has cooling curves of the surface and the centre superimposed on the TTT diagram of hypo-eutectoid steel. Isothermal hold in the bainitic bay helps reduce the temperature difference between the surface(S) and the centre(C).

Effect of alloy addition on Fe-Fe3C phase diagram:

So far we have considered steel to be an alloy of iron and carbon. However all commercial grades of steel have several other alloy elements. Some of these may be present as impurities that were difficult to remove whereas there may be others that are intentionally added. Two of the most common impurities in steel are sulfur (S) and phosphorous (P). Sulfur segregates to grain boundaries. It is responsible for hot shortness of steel. The presence of P makes steel cold short or brittle at room temperature. Therefore all attempts are made to keep the two within 0.05%. The presence of dissolved oxygen too is harmful. De-oxidation is an important step in all steel making processes. The most common practice is the addition of ferroalloys (Fe-Si-Mn) or Al. As a consequence most steel would have some amount of Si and Mn. Therefore it would be worthwhile to look at the effect of alloy addition on the structure and properties of steel.



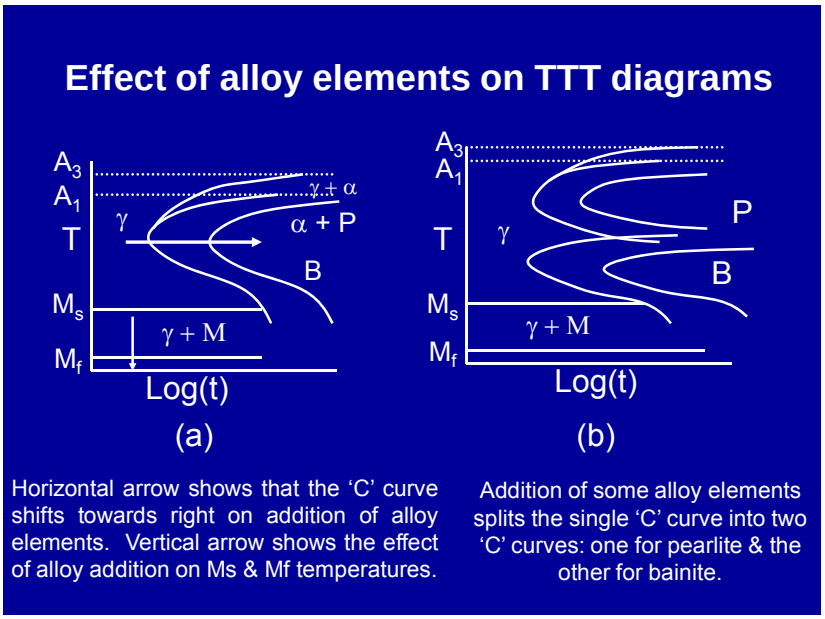
Slide 5

Slide 5 shows the effect of alloy addition on the eutectoid temperature and eutectoid composition. In the binary Fe-Fe_3C system these are 723°C and 0.8%C respectively. Note that the addition of Ti, Mo, W, Si and Cr increases the eutectoid temperature. In other words they increase the stability of ferrite to a stll higher temperature. These are often referred to as ferrite stabilizer. Elements like Mn & Ni decreases the eutectoid temperature. They increase the stability of austenite to lower temperature. Therefore these are known as austenite stabilizer. There are steels having very high amount of Ni or Mn that remain as austenite even at room temperature. Likewise there are steels that do not transform into austenite at all on heating. Such steels cannot be given hardening heat treatment. C & N are also considered as austenite stabilizer. This is because A_3 temperature decreases with increasing amounts of C & N. Recall that A_3 is the temperature at which during heating steel transforms into 100% austenitic structure. The diagram (b) in slide 5 shows the effect of alloy addition on the composition of the eutectoid. Note that it decreases with increasing alloy addition. Some of the alloy elements (Ti) are more effective than others (Ni) in decreasing %C of eutectoid steel.

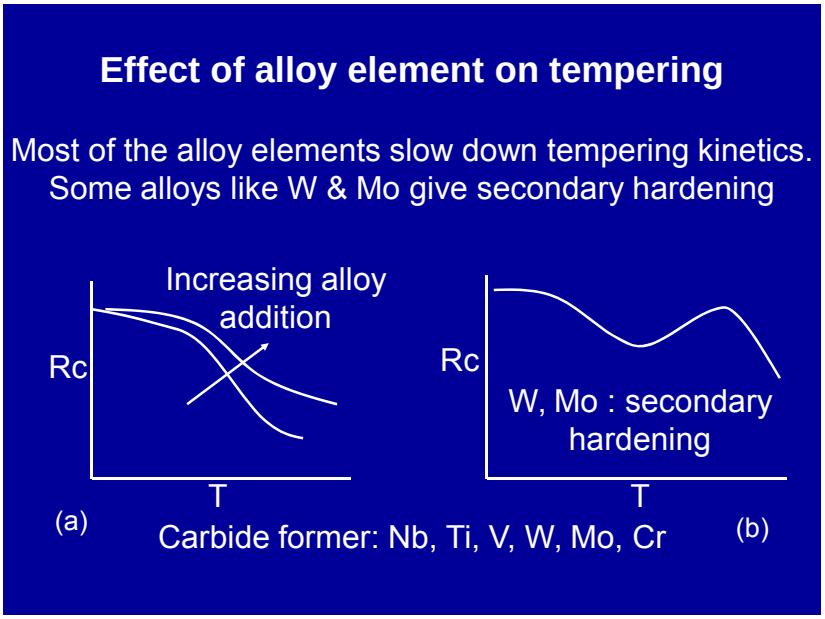
Effect of alloy addition on TTT diagram:

Slide 6 shows the effect of alloy addition on the TTT diagram of hypo-eutectoid steel. All alloy elements (except Co) slow down diffusion controlled transformation: TTT / CCT diagrams shift to higher time zones (see sketch (a) in slide 6). It may make steel hardenable at a much slower cooling rate. Therefore alloy addition is one of the ways to avoid quench cracking. This is because you need not quench at all for hardening. Alloy addition also affects M_s& M_f temperature. They decrease with increasing alloy addition. The sketch (b) in slide 6 shows the

effect of alloy addition that affects pearlitic & bainitic transformation differently. A single 'C' curve splits into two 'C' curves.



Slide 6

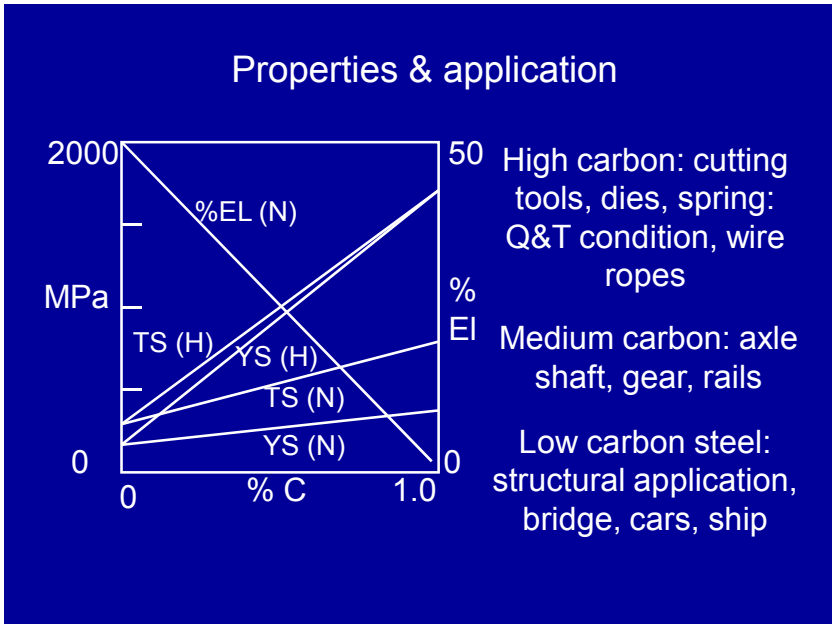


Slide 7

Effect of ally addition on tempering

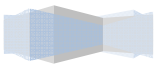
Slide 7 shows the effect of alloy addition on the tempering behavior of steel. The sketch (a) shows how hardness drops with increasing tempering temperature. The addition of alloy elements slows down the transformation processes that result in hardness drop. Alloy elements present in steel are classified into two groups on the basis of their affinity for carbon. Elements

like Nb, Ti, V, W, Mo and Cr are known as carbide former. Others like Si, Ni, Mn prefer to remain within ferrite lattice. Usually hardness drops with increasing tempering temperature. However in the presence of Mo & W, steel exhibits secondary hardening. The sketch (b) in slide 7 shows the effect of Mo & W on the hardness versus tempering temperature plot.



Slide 8

Slide 8 shows the effect of %C on tensile strength (TS), yield strength (YS) and ductility (%El) of steel. The strength and ductility of steel apart from %C depends on heat treatment as well. The strength of steel can be increased 10 fold by increasing %C and giving appropriate heat treatment. For example hardening gives maximum strength but minimum ductility. The TS & YS of steel increases but its ductility decreases significantly on hardening. The strength increases with increasing %C, the rate of increase in strength in the case of hardening is much more than that in the case of normalizing. Slide 8 also includes some of the major applications of steel. On the basis of %C steel can be put into three main categories. Low carbon steel which is tough and ductile. It can be easily welded without any need for preheating or post weld heat treatment. It is used for structural applications. Medium carbon steel has higher strength and good wear resistance. If required it can be hardened and tempered, but it is difficult to weld. High carbon steels are used mostly in quenched and tempered condition. High hardness and wear resistance are the main criteria for its selection. These are difficult to weld. Wire ropes made of high carbon steel are used in cold drawn condition. It has extremely high strength. It is given a special isothermal heat treatment called patenting at a temperature near the nose of the TTT diagram so as to produce extremely fine pearlitic structure.



Hardenability:

We are by now familiar with the difficulty in getting a uniformly hardened structure from the surface to the core of a component made of steel. Superimposition of the expected cooling rates at the surface and the core of a component on the CCT diagram of the particular grade of steel may give an idea about how uniformly it can be hardened. This is illustrated with the help of a set of diagrams in fig 2. Figure 2(c) gives a schematic representation of the temperature gradient that is set up during the cooling of a cylindrical component. The surface would always cool faster that the centre. The cooling curves at each of these locations have been superimposed on the CCT diagram of low carbon steel in fig 2(a) and on that of medium carbon steel in fig 2(b). Note the difference between the two CCT diagrams. A_1 temperature remains unchanged. A_3, M_s and M_f temperatures of medium carbon steel are slightly lower than those of low carbon steel. However the major difference lies in the locations of the lines representing the starting and the finishing points of the diffusion controlled transformations. The two diagrams indicate that the structures at the surface of low carbon steel should be a mixture of ferrite, pearlite and martensite whereas that in medium carbon steel should be 100%M. Similarly the structure at the centre of low carbon steel is expected to be a mixture of ferrite and pearlite and that at the centre of medium carbon steel is expected to be a mixture of ferrite and martensite. In other words it is much easier to harden medium carbon steel whereas it is difficult to harden low carbon steel. This however is only a qualitative approach. A more quantitative parameter is needed to define the ability of steel to harden on quenching. It should be independent of the size and shape of the component and the quenching medium. Hardenability is such a parameter.

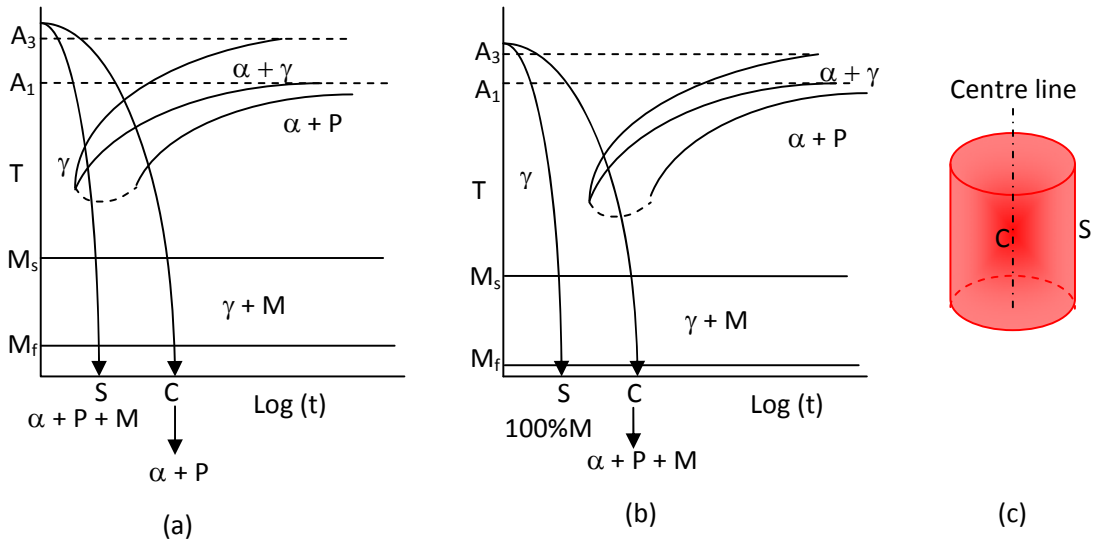


Fig 2: Shows a set of cooling curves at the surface and the centre of a part superimposed on the CCT diagrams of (a) low carbon steel and (b) medium carbon steel. The sketch (c) gives a schematic representation of temperature gradient that develops during cooling.

Hardenability may be defined as the ability of steel to become hard all through the section on quenching from its austenitic state. When you quench steel in cold water a blanket of steam would immediately surround it. This has relatively poor conductivity. Therefore the initial heat extraction rate may not be very high. However as the steam blanket disintegrates into small bubbles that float up due to the difference in density the cooling rate increases significantly. This stage is known as nucleate boiling. It is promoted by agitation. It may soon reach a steady state when the heat flow from the core to the surface of the part by conduction becomes equal to the heat being extracted by convection current set up within the water due to boiling and agitation. Clearly under such a situation the cooling rates at the centre and the surface cannot be the same. The difference between the two is a function of the size of the part made of the same steel. This is illustrated with help of a set of diagrams given in fig 3. Note that on quenching the surfaces of the two parts come in contact with water at the same temperature. We may therefore assume that the cooling rates at the surface to be the same. However the cooling rates at the centers are widely different. Figure 3(a) shows that as a result of the difference in cooling rates the structure at the centre of the thin cylinder is a mixture of ferrite, pearlite and martensite, whereas that at the center of the thick cylinder is a mixture of ferrite and pearlite. This is why there is a significant difference in the hardness versus normalized distance plots of the two samples given in fig 3(c). There is a dotted horizontal line superimposed on fig 3(c) at a fixed value of hardness (R_c = 54) that corresponds to a mixture of say 50% martensite and balance consists of ferrite and pearlite. It intersects the two plots at a

normalized distance of $2x_{thin}/D_{thin}$ and $2x_{thick}/D_{thin}$. Note that $\frac{2x_{thin}}{D_{thin}} > \frac{2x_{thick}}{D_{thick}}$. It means that the normalized depth of hardness is higher in the case of the thin cylinder than that of the thick cylinder. For a particular grade of steel the magnitudes of the normalized distance corresponding to a particular hardness is a function of the specimen size and the quenching medium (or the cooling rate). Although a set of plots like those in fig 3(c) gives some idea of the expected depth of hardened zone under a given quenching condition it is of little use. In order to know the ability of a particular grade of steel to respond to hardening we need to find a parameter which is independent of the specimen size, geometry and quenching medium. Hardenability is such a parameter.

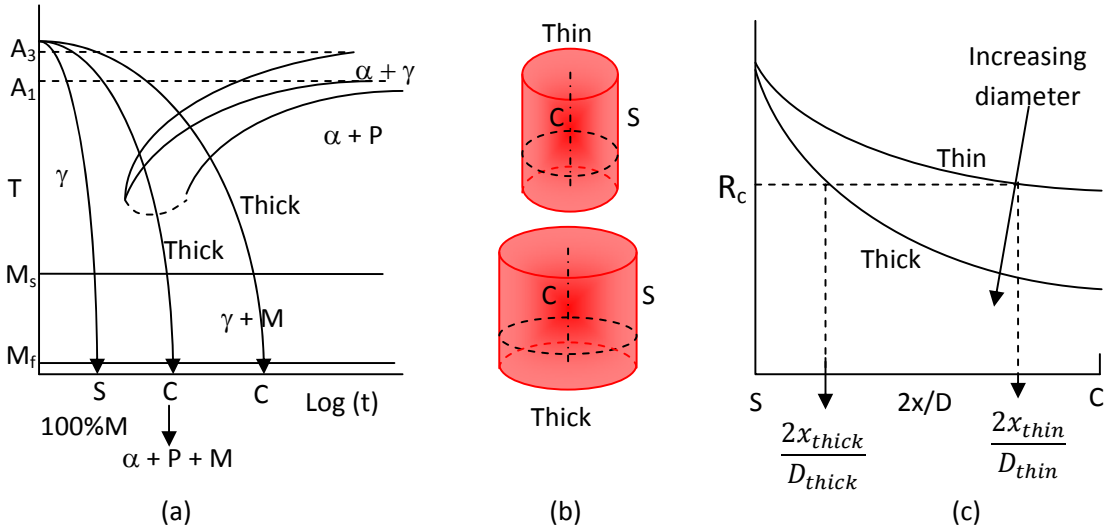
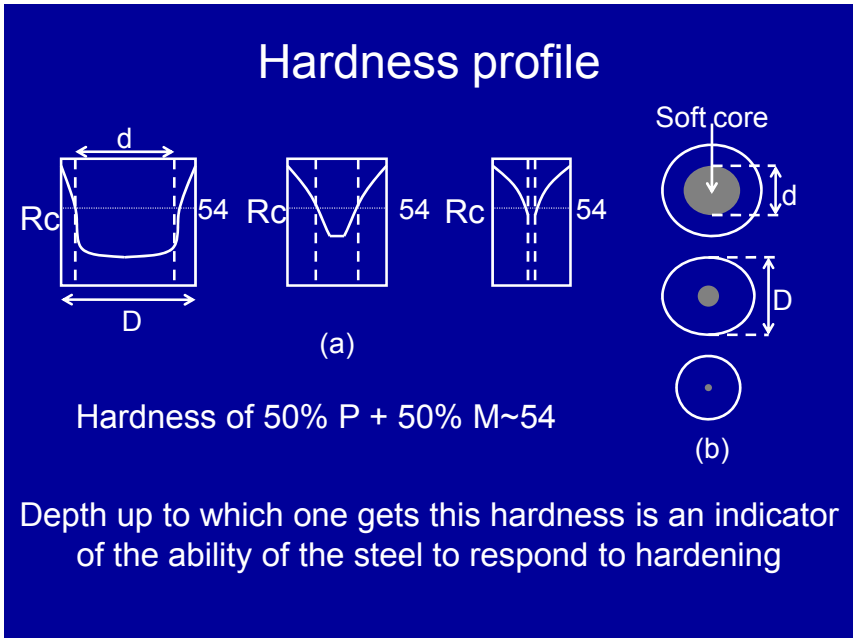


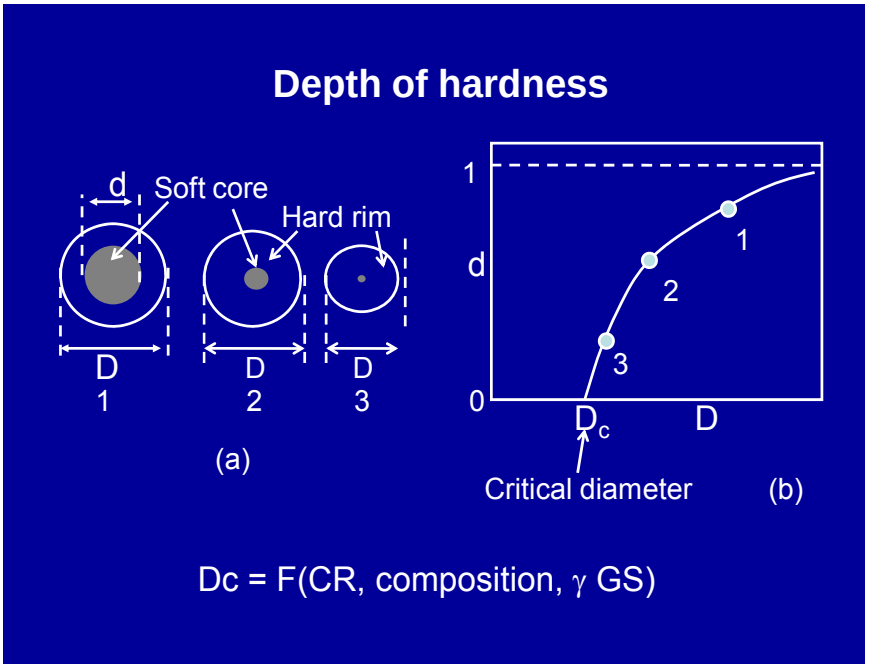
Fig 3(a): Shows a set of cooling curves at the surface and the centers of the two parts superimposed on the CCT diagrams of medium carbon steel. Fig 3(b): Sketches of a thin and a thick cylindrical parts whose cooling curves on quenching are shown in (a). Fig 3(c): Hardness versus normalized distance plots of the two parts shown in (b). Hardness in Rockwell C scale was measured on the surface marked by the dotted circles after the cylindrical samples were cut along these planes. After the samples are cut they may need light polishing on emery paper to help measure hardness properly. 'x' denote the thickness of the hardened zone.

Ideal critical diameter:

A set of slides 9-10 explains with the help of a set of diagrams and plots the origin of a parameter that could represent the ability of a particular grade of steel to respond to hardening on quenching from its austenitization temperature. The parameter is known as ideal critical diameter. It is independent of the specimen size and the cooling rate.



Slide 9



Slide 10

Slide 9 explains with the help of a set of sketches the method of estimating the depth of hardening in a set of cylindrical specimens. Take a number of cylindrical samples of different diameters. Quench these in water after homogenization at the recommended austenitizing temperature. Cut them into two halves along a plane perpendicular to the axis of the cylinder. Polish and etch the cut faces. Martensite is difficult to etch. Regions that are mostly martensitic appear bright against light whereas those having little or no martensite appear dull. The boundary between the hard rim and the region having only 50% martensite is very sharp. It is

easily detectable under optical microscope. This is the reason why it is used to find the depth of hardness. This is illustrated with the help of a set of sketches in fig (b) of slide 9. The diameter of the soft core is denoted as d. However precise measurement of d from the microstructure is a bit tedious. It is much easier to determine this by measuring hardness across the section. Figure (a) in slide 9 gives hardness versus distance plot of the three samples as a function of distance. There are horizontal dotted lines drawn at R_c54 (it is the hardness of a structure having 50% martensite and 50% pearlite) on each of the three plots. These lines intersect the hardness plots at two points as shown in fig (a) of slide 9. The distance between the two gives a more precise estimate of the size of the soft central zone. Note that as the diameter of the cylinder decreases the size of the soft core (d) becomes extremely small. The diameter D_c at which it disappears is known as the critical diameter. This is illustrated in slide 10. The sketch (a) shows how the width of the hard rim increases but the size of the soft core decreases with increasing diameter of the cylindrical specimens. The sketch (b) of the same slide shows a plot of d versus D. Note that d decreases as the diameter of specimen decreases. The trend may not be linear. However extrapolation of the same gives an estimate of the critical diameter D_c. It is independent of size but depends on cooling rate. The cooling in a quenching medium is a little more complex. Let us look at it in a little more detail.

Mechanism of heat transfer during quenching:

When red hot steel comes in contact with cold water the temperature (T) of its surface suddenly comes down almost to the level of the surrounding. However the centre still retains its initial temperature. As a result a temperature gradient develops within the job. Steel being a good conductor heat flow from its centre to its periphery is governed by laws of conduction. The net heat flux $(\dot{q})$ depends on the temperature gradient and the conductivity of steel (k). For simplicity let us consider the expression for the heat flux due to conduction along the direction x only. This is given by:

$$\dot{q} = -k\frac{dT}{dx} \qquad (1)$$

This heat is absorbed by the water surrounding it. Water is a bad conductor. When it comes in contact with red hot steel its temperature suddenly shoots up so much that it gets converted in to steam. This is accompanied by a sudden temperature drop at the surface and it gets covered by a thin layer of steam. The process is known as film boiling. The conductivity of steam is even less. The heat flux during this stage is primarily determined by the rate of conversion of water into steam. It may be assumed to be constant. As the film grows it breaks down into a number of tiny bubbles. This is known as nucleate boiling. The bubbles float up and setup unusually high convection current due to agitation within the water surrounding it. Therefore the effective heat transfer coefficient suddenly shoots up. As the temperature drops further nucleation of

bubbles ceases but normal convection current still persists because of temperature difference within the medium. The heat flux during this stage is given by:

$$\dot{q} = h(T_S - T_E) \qquad (2)$$

T_S is the temperature of water at the surface of the sample, T_E is the temperature of water away from the surface and 'h' is the heat transfer coefficient. Figure 3 explains the mechanism of heat transfer on quenching with the help of two diagrams. One at the left shows three distinct processes involved during heat extraction from red hot steel.

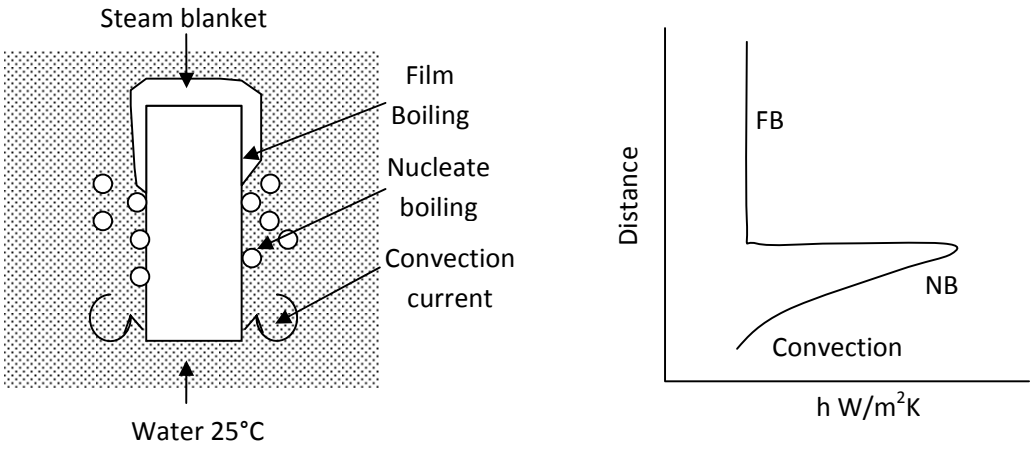
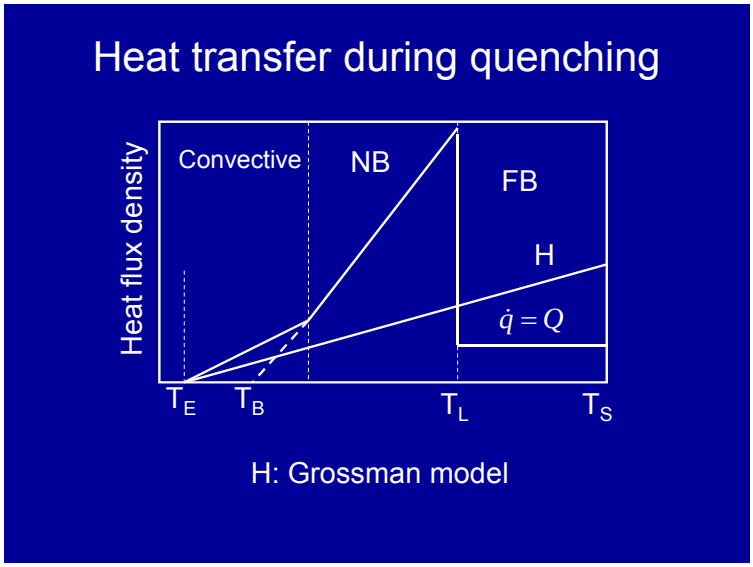


Fig 4: Shows three different stages of heat extraction during quenching. When red hot steel is quenched in water it is immediately covered by a blanket of steam due to film boiling. When it ruptures nucleate boiling begins. As the temperature of water near the surface drops below the boiling point of water cooling takes place due to convection. The sketch on the left shows the state at an intermediate stage. The sketch on the right shows how the heat transfer coefficient varies with distance.



Slide 11

Heat transfer during quenching is indeed quite a complex process. The governing equations during each of the three stages are different. This is explained with the help of a diagram in slide 11. For simplicity the concept of an effective or an average heat transfer coefficient was introduce by Grossman. It includes the contribution of heat conduction within the sample as well as that from the surface due to convection and radiation. This is shown in slide 11 by the line labeled H. Heat flux density is assumed to be proportional to the temperature difference within the quenching medium. The slope of the plot is the effective heat removal rate or more appropriately the severity of quench. It is represented as H. It depends on both thermal conductivity of steel and the effective heat transfer rate from the surface. It is given by

$$H = \frac{h}{2k} \qquad (3)$$

Note that the dimension of effective heat transfer coefficient due to convection and radiation is $W/m^2°K$ whereas that of thermal conductivity is W/m °K. Thus the dimension of H is m^{-1}. However; when the concept was introduced by Grossman the values of H were reported in in^{-1}. The same convention is still being followed in heat treatment industries. If this is multiplied by the diameter of the body (*D*), their product corresponds to the well known dimensionless Biot's number (B_i). All bodies having same Biot number exhibit similar heat flow behaviour.

$$HD = \frac{h}{2k} D = B_i \qquad (4)$$

Thermal conductivity (k) of steel is around 54W/mK at room temperature. It is much higher than those of air (0.024) or water (0.58). However the main mechanism of heat transfer in water is due to local boiling, agitation, convection and radiation. The effective heat transfer coefficient in still water is around $50W/m^2K$.

All bodies having the same Biot number exhibit similar heat flow behaviour. If the thermal conductivity is assumed to be constant, H depends only on heat transfer rate at the interface. It gives the cooling capacity of a quenching medium. The magnitude of H for a hypothetical ideal quenching medium is assumed to be infinity (∞). If steel is quenched in such a medium temperature of its surface instantaneously attains that of the quenching medium. This is impossible to happen if specimens of finite size. H has dimension of in^{-1}. Table 1 gives the values of H for several quenching media under various states of agitation.

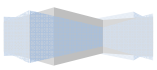
Table 1: Severity of quenching (H) in in^{-1} for different quenching condition

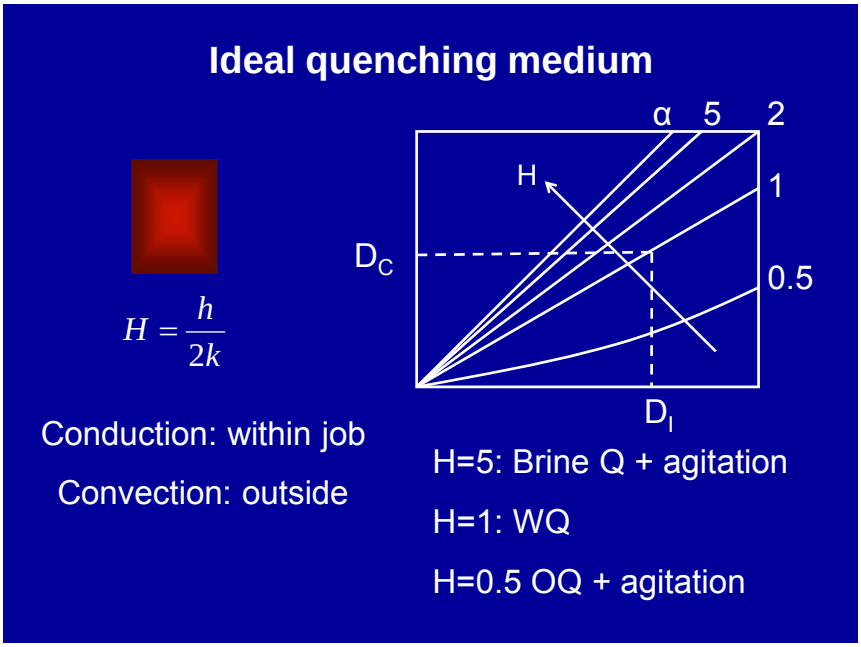
Quenching method	H value		
	Oil	Water	Brine
No agitation	0.25-0.30	1.0	2.0
Mild agitation	0.30-0.35	1.0-1.1	2.0-2.2
Moderate agitation	0.35-0.40	1.2-1.3	
Good agitation	0.40-0.50	1.4-1.5	
Strong agitation	0.50-0.80	1.6-2.0	
Violent agitation	0.80-1.10	4.0	5.0

Water is certainly the most common medium of quenching followed by oil. Water is nontoxic and readily available but its severity of quenching is rather high. This often leads to quench cracks. Oil has lower H but it also has several disadvantages. This includes limited quenching rate, fire hazard, smoke emission and disposal problem. Many applications need moderate quenching rates between that of oil and water. In such cases use of polymer quenching medium is an option. Major attraction for the use of aqueous polymer quenching medium is the reduction of fire risk associated with oil. It thickens water and reduces its quenching severity. Polyvinyl alcohol and a few cellulosic derivatives are the most common thickeners. H for polymer quenching media depending on its constituent may vary from 0.2 to 1.2.

Ideal critical diameter (DI):

It is the diameter of the cylindrical sample which on quenching from the appropriate austenitizing temperature in an ideal quenching medium gives 50% martensite and 50% fine pearlite at its centre. The magnitude of H for such a medium is infinity. Clearly D_I should be greater than D_{crit} for a particular quenching medium. There are charts and tables that are obtained empirically or by numerical solution of heat transfer equations under appropriate convective boundary conditions at the surface to convert D_{crit} to D_I. Slide 12 gives an example of the same. The chart D_c versus D_I has a set of lines representing the correlation between the two. It illustrates how to convert D_c to D_I with the help of a pair of dotted lines if it denotes the critical diameter for water quenching.





Slide 12

Ideal critical diameter adequately describes hardenabilty of steel. It is a material property. It does not depend on the size and geometry of steel. It gives an estimate of the depth of hardness of steel on quenching in an ideal quenching medium having infinite severity of quench (H). However it depends on the composition of steel, austenitizing temperature (or austenite grain size) and the homogeneity of austenite. It will form a part of the next lecture.

Summary:

Most of the commercial heat treatment processes like annealing, normalizing and hardening adopt continuous cooling. If the cooling rate is very high residual stresses develop in the component. The nature of the stress and the reason for its origin has been explained. The stress due to phase transformation is much more than that due to thermal stress. A general thumb rule for steel is that the region that transforms last has compressive residual stress. Tensile stress at the surface is harmful. One way of avoiding it is a two step quenching process with adequate isothermal hold at a temperature a little above M_s. It helps in reducing the temperature gradient within the component. The time gap between the transformations at the surface and the centre is also less. As a result the there is little residual stress after heat treatment. Austempering and martempering are the two processes that adopt this strategy. Commercial grades of steel apart from carbon may contain several other alloy elements. Some of these are present as impurities while others are added intentionally to improve its properties and performance. The effect of alloy additions on iron-carbon phase diagram, TTT / CCT diagrams has been explained. One of the main reasons of alloy addition is to improve the response of steel to hardening treatment. The ability of steel to respond to hardening

treatment depends on its section size, composition and austenitizing temperature. This is best described by the term hardenability. Its physical concept and how it can be estimated have been explained. It is obtained experimentally. For a specific quenching medium every grade of steel has a specific critical diameter. It is the diameter of a cylindrical rod which on quenching in this medium has 50%M and 50% FP at its centre. The quenching medium plays a major role during hardening. The ability of a quenching medium to extract heat from red hot steel is best described by a term called severity of quench (H). In order to understand the origin of this parameter it is necessary to know a little about the mechanism of heat transfer during quenching. The concept of a hypothetical quenching medium has been introduced. Its severity of quench is infinity. The critical diameter corresponding to an ideal medium having infinite quenching severity is known as ideal critical diameter. It is a material property. It does not depend on cooling rate, shape , size or geometry of the specimen.

Exercise:

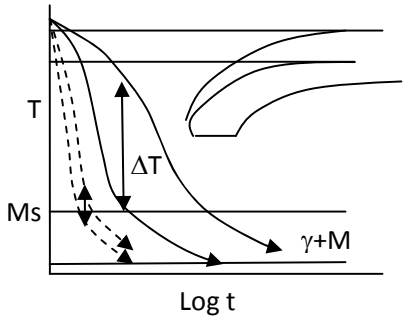
1. Cooling rate at the center of a steel rod on quenching in oil from 850°C is given by $1.4 \times 10^4 \times d^{-1.9}$ °C/s, where d is diameter in mm. Which of the following steel would have 100% martensite at its centre if its diameter is 50mm? Critical cooling rate (CCR °C/sec) of steel to get 100% martensite is a function of composition. Assume that it is given by $\log(CCR) = 4.3 - 3.3C + (Mn + Ni + Cr + Mo)/1.6$ (a) AISI 4340 steel having 0.4C, 0.7Mn, 1.8Ni, 0.8Cr,0.25Mo (b) AISI 3130: 0.3C,0.7Mn,1.3Ni,0.6Cr
2. Find out the diameters of the above steels (see problem 1) that would have 100% martensite at its center on quenching in the same medium.
3. Explain why thicker sections are more susceptible to cracking during hardening heat treatment.
4. Critical diameter of a certain grade of steel for oil quench, water quench and ideal quench are D_O, D_W and D_I respectively. Arrange these in descending order.
5. List the factors that determine hardenability of steel. Which of these are preferred? Give reasons.
6. What is meant by severity of quench? List the factors that determine this. What is its dimension?

Answer:

1. Cooling rate at the centre = $1.4 \times 10^4 \times 50^{-1.9} = 8.28$ °C/sec. CCR of the two steels are (a) 5.8 °C/s (b) 48.4 °C/s. Cooling rate is higher than CCR of (a) but lower than that of (b). Therefore (a) will have 100% martensite at its center.

2. (a) $5.8 = 14000 \times d^{-1.9}$ $\therefore d = \left(\frac{14000}{5.8}\right)^{1.9} = 60.5mm$ (b) $d = \left(\frac{14000}{48.4}\right)^{1.9} = 20mm$

3. The difference in cooling rate between the centre and the surface is much more in a thicker section. As soon as the temperature at the surface crosses M_s temperature, martensite forms accompanied by volume expansion. The core is still soft austenite and can accommodate deformation if required. However later when its temperature goes below Ms it would expand, when outer core which is already transformed is hard and cannot accommodate deformation. A tensile stress therefore develops at the surface and it becomes prone to cracking. If thickness is less the difference in temperature is not large. Transformation takes place almost simultaneously with little chance of developing high tensile stress at the surface. The following sketch illustrates this.



Dotted line: thin sheet

Firm line: thick sheet.

4. D_I, D_W, D_O

5. Hardenability increases with increasing carbon content, alloy addition (except cobalt), lower inclusion content and coarse austenite grain size. The first three are preferred. Finer grain size gives better crack resistance (toughness). Martensite formed in coarse austenite grain is more prone to cracking.

6. It a measure of the rate at which heat can be extracted from the quenched steel. It is defined as the ratio of h/2k where k is the thermal conductivity of steel and h is convective heat transfer coefficient between steel and quenching medium. Dimension = $\frac{Joule}{m^2 K\, s} \times \frac{m^2\, K}{Joule \times m} = \frac{1}{m}$. Therefore note that HD is a dimensionless quantity.