Module 34

Heat Treatment of steel IV

Lecture 34

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Keywords: Austenitization of hypo & hyper eutectoid steel, austenitization temperature, effect of heat treatment on structure & properties of hypo & hyper eutectoid steel, tempering, effect of tempering on structure & properties of steel, tempering parameter, recalescence

Introduction

The wide variety of phase transformations that takes place in steel makes it one of the most attractive engineering materials. We are now familiar with the basic principles of each of these. The Fe-Fe₃C phase diagram helps one guess the microstructure and properties of steel as a function of composition provided the cooling rate is extremely slow. It suggests that eutectoid austenite below a critical temperature (A₁) transforms into a mixture of ferrite and carbide. If the cooling rate is slow or if it is allowed to decompose at a temperature a little below A₁ it gives a coarse lamellar structure consisting of alternate layers of ferrite and cementite plates. This type of structure is known as pearlite. This is a diffusion controlled process where carbon atoms move over a long distance in austenite. As against this if it is cooled extremely fast the carbon in austenite (FCC) is not allowed to come out of the solid solution when it transforms into ferrite (which is BCC). The resultant structure gets distorted due the presence of excess carbon in its octahedral interstices. It consists of a homogeneous phase called martensite having BCT crystal. It is extremely hard and brittle. It forms without any diffusion when the temperature drops below a critical temperature (Mₗ) and the process continues until the temperature reaches Mᵢ. Apart from the two extreme cases there is a range of temperature over which the austenite decomposes into a very fine mixture of ferrite and carbide. The carbide size and shape is distinctly different from that of pearlite. This structure is known as bainite. The structural features of steel as a function of time and temperature are represented with the help of a TTT diagram. It depends on composition of the steel and the temperature at which austenitization has been done. We are familiar with the main features of such diagrams for hypo-eutectoid, eutectoid and hyper-eutectoid steels. These are useful in planning heat treatment schedules based on isothermal holds at different temperatures. However most commonly used heat treatments processes adopt continuous cooling. A different version of transformation diagram is needed to guess the type of structure that is expected in steel on cooling at a given rate. These are known as CCT diagram. Like TTT diagram it is a function of %C in steel and the temperature at which it is transformed into austenite. Towards the end of the last module its usefulness in predicting the microstructure of steel during annealing, normalizing and hardening of eutectoid steel was explained. Table 1 gives a comparison of the main characteristics of the 3 heat treatment processes with respect to eutectoid steel. Slide 1 shows the heating & cooling cycles used and the CCT diagram with cooling curves for the 3 processes. In each of the three common heat treatment processes conversion of ferrite carbide structure into austenite is important. This occurs through a diffusion controlled process. Let us begin this module by looking at this process a little critically.
Table 1

<table>
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<th>Characteristics</th>
<th>Annealing</th>
<th>Normalizing</th>
<th>Hardening</th>
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<tr>
<td>Cooling rate</td>
<td>Furnace cooled</td>
<td>Air cooled</td>
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<tr>
<td>Microstructure</td>
<td>Coarse pearlite</td>
<td>Fine pearlite</td>
<td>Martensite</td>
</tr>
<tr>
<td>Hardness</td>
<td>$R_e (10 – 20)$</td>
<td>$R_e 30 - 35$</td>
<td>$R_e 64$</td>
</tr>
<tr>
<td>Ductility</td>
<td>Very good</td>
<td>Good</td>
<td>poor</td>
</tr>
<tr>
<td>Residual stress</td>
<td>Negligible</td>
<td>Low</td>
<td>Very high</td>
</tr>
<tr>
<td>Structural stability</td>
<td>Best</td>
<td>Moderate</td>
<td>Least</td>
</tr>
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</table>

Annealing, normalizing & hardening: eutectoid steel

This is the first stage of transformation during annealing, normalizing or hardening of steel. The main purpose is to get a homogeneous austenite. At room temperature steel has two phases: ferrite and cementite. During heating when the temperature goes beyond $A_1$ cementite reacts with adjacent ferrite to form austenite.
Figure 1: shows what happens at the ferrite cementitite interface when the temperature goes beyond $A_1$, the lower critical temperature. Tiny nuclei of austenite form at the ferrite cementite boundary. Figure 1(a) gives an enlarged view of pearlite having alternate plates of cementite and ferrite. It shows the formation of a tiny austenite nucleus. It would setup a concentration gradient within the austenite grain. The origin of concentration gradient is easily understood from fig 1(b). The horizontal line at the austenitization temperature intersects $A_3$ at $C_{cm}$. This represents the concentration of carbon in austenite at the ferrite / austenite boundary. Similarly the point of intersection of this line with $A_{cm}$ represents the concentration of carbon in austenite at the austenite / cementite interface. Note that $C_{cm} > C_{cm}$. Therefore carbon would diffuse from the austenite/ cementite interface to the austenite / ferrite interface. As a result the cm and ferrite regions would shrink and the austenite nucleus would grow. The diffusion of carbon in austenite would primarily determine the kinetics of transformation. The mass flow rate due to diffusion depends on diffusivity and concentration gradient. Exactly at $A_1$ there is hardly any concentration gradient. Therefore the transformation rate is negligible. Some amount of superheating beyond $A_1$ is necessary for the transformation of pearlite to austenite. The extent of transformation is a function of both temperature and time. It can be represented in the form a time– temperature transformation diagram. An example of such a diagram for eutectoid steel is given in fig 2. It helps in the estimation of the time needed to transform eutectoid steel into homogeneous austenite at a temperature above $A_1$. Higher the temperature the shorter is the time required.

![Time-Temperature Transformation Diagram](image-url)
Slide 2 shows the process of austenitization of hypo-eutectoid steel of a particular composition. The aim of austenitization is to get homogeneous γ. Let us look at this process with respect to a particular grade of steel whose location on the relevant part of the phase diagram is shown by the dashed line in the sketch on the left in slide 2. The conversion of pearlite to austenite begins as soon as the temperature goes beyond A₁. The sketch on the right shows a time temperature diagram of this steel representing the various stages of transformation. The time it takes for this to begin at A₁ is extremely long but it decreases with increasing temperature. The structure now consists of ferrite, austenite and cementite. Although austenite has formed still there may be a significant amount of pearlite (recall that pearlite is a mixture of ferrite and cementite). The time at which pearlite disappears from the structure is also a function of temperature. It is longer at lower temperature. After the conversion of pearlite to austenite the structure consists of α + γ. The amount of ferrite decreases with increasing temperature and time. The transformation diagram in slide 2 shows a line beyond which there is no ferrite. However still it may not be homogeneous austenite. The region is labeled as γ_{het}. It takes a little more thermal exposure for the concentration of carbon in austenite to be uniform. The sketch includes a line that gives the time needed for this to happen as a function of temperature. If the samples are kept too long a time beyond that required for homogeneous austenite to form the grain may become unusually coarse. Coarse grain austenite on subsequent cooling gives relatively poor toughness. Therefore too high a temperature or too long a time should be avoided. The phase diagram in slide 2 shows the range of recommended austenitization temperature for annealing (A), normalizing (N), and hardening (H) of hypo-eutectoid steel. It is usually 30°- 40°C higher than the upper critical temperature (A₃).
Hyper eutectoid steel

Normalizing: Air cooled from $A_{cm} + 30$ C. Air cooling suppresses cm network formation. Cm network makes the steel brittle: unusable.

The phase diagram in slide 3 shows the recommended austenitization temperature for annealing (A), normalizing (N) and hardening (H) of hyper-eutectoid steel. The purpose of annealing is to get a soft and ductile structure. If the steel is heated beyond $A_{cm}$ to form homogeneous austenite, on cooling it is likely to give a continuous network of pro-eutectoid cementite around austenite before the remaining austenite transforms into coarse pearlite. This is because during annealing the component is furnace cooled (FC). The corresponding cooling curve has been superimposed on the TTT diagram given in slide 3. Precipitation of pro-eutectoid cementite begins soon after the temperature drops below $A_{cm}$. The grain boundaries are the most preferred site for precipitation. Cementite is brittle. This makes the structure prone to intergranular cracking. Therefore the purpose of annealing is lost. As against this if austenitization is done at $A_1 + 30^\circ C$ before slow furnace cooling begins the structure consists of globules of cementite surrounding the prior-austenite grains which subsequently transforms into coarse pearlite. There is no chance of forming a brittle network around the prior austenite grain boundaries. Therefore this is the recommended austenitization temperature for annealing of hyper-eutectoid steel.
Figure 3(a) shows the microstructure of hyper-eutectoid steel if it is furnace cooled (FC) from $A_{cm} + 30^\circ C$. This type of structure has poor resistance to withstand shock loading. It is responsible for poor ductility. Therefore it should be avoided. Figure 3(b) shows the microstructure of hyper-eutectoid steel when it is furnace cooled (FC) after soaking at $A_1 + 30^\circ C$. During soaking at a temperature higher than $A_1$ the pro-eutectoid cementite has enough time to become spherical. The driving force for such a change is the decrease in total surface energy of carbide. This is because a sphere has the least surface area to volume ratio. The amount of pro-eutectoid cementite may still be the same. However in the absence of a continuous grain boundary network of brittle cementite there is no easy path for a crack to grow. Therefore such a microstructure has excellent toughness or resistance to crack growth. This is the most desired structure of annealed hyper-eutectoid steel.

The austenitization temperature for normalizing of hyper eutectoid steel is shown on the phase diagram in slide 3 by a bar labeled N. It is around $A_{cm} + 30^\circ C$. After homogenization the sample (or the job) is cooled in air. The cooling rate is relatively fast. The corresponding cooling curve is superimposed on the schematic TTT diagram given in slide 3. The time allowed for the precipitation of pro-eutectoid cementite is much less. Therefore the amount of pro-eutectoid cementite will be less than that in the case of annealing. The amount often is not high enough to form a continuous carbide net work. Figure 4 shows a schematic microstructure of normalized hyper-eutectoid steel.

![Fig 4: Shows the main features of the microstructure of normalized hyper-eutectoid steel. It has broken network of pro-eutectoid cementite around the prior austenite grain boundaries. The pearlite is expected to be much finer than that of the annealed steel.](image)

The purpose of hardening is to get maximum possible hardness in steel. The temperature at which steel is austenitized has a marked influence on its hardness. It would have the maximum hardness if it has 100% martensitic structure and %C in martensite is greater than 0.6. The phase diagram in slide 3 gives the austenitizing temperature for hardening of hyper-eutectoid steel. It is given by $A_1 + 30^\circ C$. It is same for all hyper-eutectoid steel. On austenitization at this temperature it has at least 0.8%C in solid solution. On quenching therefore martensite is likely to have 0.8% C. This is high enough to give the maximum possible hardness. Recall that the $M_f$ temperature of steel decreases with increasing %C in austenite. If hyper-eutectoid steel is austenitized above $A_{cm}$ it would have much higher amount of carbon in solid solution. Its $M_f$ temperature may even be lower than the room temperature. Therefore even on quenching to room temperature the martensitic transformation may not be complete. There will be some amount of retained austenite. As a result the hardness will be lower than the expected value.
The purpose of hardening will be defeated. This is why $A_{cm} +30^\circ C$ is the optimum austenitization temperature for hardening of hyper-eutectoid steel.

**Effect of heat treatment on the structure and properties of hypo-eutectoid steel:**

Annealing, normalizing and hardening are the 3 most common heat treatments given to hypo-eutectoid steel. During each of the 3 processes austenitization is done at a temperature 30°—40°C higher than the upper critical temperature of steel. Subsequently it is water quenched in the case of hardening, air cooled in the case of normalizing and furnace cooled in the case of annealing. The microstructures and properties after these heat treatments are going to be widely different. Slide 4 explains the origin of the marked difference in their structure and properties using an appropriate CCT diagram.

The cooling rate in the case of annealing is extremely slow. The sample after austenitization remains within the furnace, only the power supply is cut off. The cooling rate corresponds to equilibrium cooling rate. The cooling curve during the process has been superimposed on the CCT diagram of hypoeutectoid steel. It is labeled as A. The precipitation of pro-eutectoid ferrite begins when the curve ‘A’ intersects the curve labeled $f_s$. It continues until the cooling curve intersects $P_s$ it denotes the onset of decomposition of austenite into pearlite. The entire transformation process is complete when the cooling curve intersects the line labeled $P_f$. The final structure therefore consists of pro-eutectoid ferrite and coarse pearlite. The amount of ferrite can be estimated using lever rule if the composition is known. Alternatively if the amount of pro-eutectoid ferrite can be determined $\%C$ can be calculated using lever rule. This is possible because the cooling rate is extremely slow.
The cooling rate in the case of normalizing is moderate. The sample after austenitization is taken out of the furnace and allowed to cool in air. The cooling rate is higher than the equilibrium cooling rate. This is likely to affect diffusion controlled transformation. The cooling curve during the process has been superimposed on the CCT diagram of hypoeutectoid steel. It is labeled as N. The precipitation of pro-eutectoid ferrite begins when the curve ‘N’ intersects the curve labeled fₜ. Note that the transformation begins at a temperature lower than that in the case of annealing. Precipitation of ferrite continues until the cooling curve intersects Pₜ it denotes the onset of decomposition of austenite into pearlite. This occurs at a relatively lower temperature. The pearlite that forms is likely to be finer. The entire transformation process is complete when the cooling curve intersects the line labeled P₁. The final structure therefore consists of pro-eutectoid ferrite and fine pearlite. The amount of pro-eutectoid ferrite is less than that you get during annealing.

The cooling rate in the case of hardening is extremely fast. The sample after austenitization is directly quenched in water. The temperature of the sample as it cools on quenching has been superimposed on the CCT diagram in slide 3 in the form of a cooling curve labeled as ‘H’. It avoids the nose of the C curve. It only intersects the horizontal lines representing Mₘ and Mₗ temperatures. It suggests that austenite should transform completely into martensite. The process is athermal and there is no diffusion of carbon atoms within the lattice. The %C in martensite is exactly same as that in austenite before quenching. Recall that martensite can be considered as a super saturated solid solution of carbon in BCC ferrite. The presence of excess carbon within the interstitial site results in tetragonal distortion. This is responsible for the change over from body centered cubic (BCC) in ferrite to body centered tetragonal structure (BCT) in martensite in the presence of excess carbon. The c/a ratio of BCT martensite is a function of %C. It is around 1.05 in martensite having 0.8%C. Note that its crystal structure is marginally different from that of BCC. The morphology of martensite depends on its carbon content. If %C is less than 0.6 the austenite grains get subdivided into a large number of laths of martensite crystal. It %C is greater than 0.6 the austenite transforms into a large number of plates of martensite. The microstructure shown in slide 4 is that of plate or acicular martensite. The size of lath or plate is extremely small. Therefore the 3 main factors responsible for the unusually high hardness of martensite are (i) solid solution strengthening due the presence of excess carbon in solid solution (ii) strengthening due to extremely fine laths / plates (grain size effect) (iii) asymmetric lattice distortion due to the presence of carbon atoms in octahedral interstices. Martensitic transformation is accompanied by volume expansion. The regions surrounding the laths or plates are highly stressed. This too may add to strengthening. Excessive stress may also suppress the transformation of austenite to martensite. Often after hardening steel may have some amount of untransformed austenite at room temperature even if it is lower than Mₘ. In other words apart from being hard and brittle steel after hardening has
very high residual stress and unstable retained austenite. Therefore it is given an additional heat treatment called tempering.

**Effect of heat treatment on the structure and properties of hyper-eutectoid steel:**

Annealing, normalizing and hardening are also the 3 most common heat treatments given to hyper-eutectoid steel. The main difference lies in the selection of appropriate austenitization temperature. Hyper-eutectoid steel becomes 100% austenite on heating to a temperature a little beyond $A_{cm}$, representing the temperature at which cementite dissolves in the matrix. During normalizing hyper-eutectoid steel is soaked at $A_{cm} + 30^\circ C$ so that it converts entirely into homogeneous austenite. Subsequently it is allowed to cool in air. As against this the soaking temperatures of hyper-eutectoid steel for annealing and hardening are $A_1 + 30^\circ C$ (look at slide 3). During this stage the room temperature structure gets converted into one consisting of globules of cementite dispersed within homogeneous austenite. Subsequently it is water quenched in the case of hardening, and furnace cooled in the case of annealing. The microstructures and properties after these heat treatments are going to be widely different. Slide 5 explains the origin of the marked difference in their structure and properties using an appropriate CCT diagram.

Slide 5 gives two CCT diagrams. One on the left is used to predict or describe the evolution of structural changes when hyper-eutectoid steel is cooled after homogenization at $A_{cm} +30^\circ C$. It has two cooling curves superimposed on the CCT diagram. One represents furnace cooling (FC:...
extremely slow cooling) and other air cooling (AC: moderate cooling). Annealing means furnace cooling. If homogeneous austenite is allowed to cool in furnace the pro-eutectoid cementite would precipitate along the austenite grain boundary forming a continuous network. When the temperature drops below \( A_1 \) the remaining austenite transforms into coarse pearlite. Such a structure is brittle. This is why hyper-eutectoid steel is not heated beyond \( A_{cm} \) if it is to be annealed. However in the case of normalizing it does not pose a problem because the cooling rate adopted is relatively fast to suppress complete precipitation of cementite. Look at the cooling curve labeled as AC. The time spent within the range of temperature where cm precipitates is very short. The amount of cm is not large enough to form a continuous network of brittle cm around the grains of austenite. One of the objectives of normalizing heat treatment is to break the continuous carbide network in cast hyper-eutectoid steel. The transformation gets over by the time the cooling curve intersects the line denoted as \( P_1 \). It falls within the fine pearlitic region of the CCT diagram. The final structure of normalized hyper-eutectoid steel consists of discontinuous carbide network along prior austenite grain boundaries in a matrix of fine nodules of pearlite. It is expected to be moderately hard and ductile.

Austenitization temperature for annealing of hyper-eutectoid steel is \( A_1 + 30^\circ C \). It is independent of %C. On completion of austenitization the microstructure consists of globules of cm in a matrix of austenite (see the sketch (a) in slide 5). The initial structure before the onset of cooling is different from that in the case of normalizing (here it is 100% austenite). This is why a different CCT diagram is needed to interpret its microstructure. Slide 5 shows such a diagram. A cooling curve labeled as FC (furnace cooling) has been superimposed on this diagram. This corresponds to the one adopted during annealing. Note that the transformation of austenite to pearlite begins when the cooling curve intersects the line \( P_1 \) and it is completed at a temperature where the plot intersects the line \( P_1 \). The transformation takes place in the temperature range where you expect coarse pearlite to form. The final structure of this steel after annealing consists of globules of cm in a matrix of coarse pearlite (see the sketch (c) in slide 5). It is expected to be soft and ductile.

Austenitization temperature for hardening of hyper-eutectoid steel is \( A_1 + 30^\circ C \). It is independent of %C. On completion of austenitization the microstructure consists of globules of cm in a matrix of austenite (see the sketch (a) in slide 5). The initial structure before the onset of cooling is similar to that in the case of annealing. This is why the CCT diagram used to interpret its microstructure is same as that used in the case of annealing (see slide 5). A cooling curve labeled as WQ (water quenched) has been superimposed on this diagram. This corresponds to the one used during hardening. Note that the transformation of austenite to pearlite is totally suppressed. The curve does not intersect the \( P_5 \) of the CCT diagram. However diffusion-less martensitic transformation takes place in this steel in the temperature range Ms
to Mf. The final structure of this steel after hardening consists of globules of cm in a matrix of martensite (see the sketch (b) in slide 5). %C in martensite is a little higher than that in eutectoid steel (0.8% C). The morphology of martensite depends on %C. If it is greater than 0.6 it is likely to have plate morphology. The speed at which the plates grow is extremely fast. It is accompanied by significant expansion in volume. The austenitic regions surrounding the plates get highly compressed. This may inhibit further transformation. This is why some amount of austenite may still exist in the tiny regions between the plates even if the room temperature is lower than Mf. Nevertheless the bulk of the microstructure would consist of plate martensite. It is very hard and brittle. It would also have high amount of residual stress. It may lead to cracking. Therefore it is necessary to give an additional heat treatment. It is known as tempering. It improves the toughness (or the resistance to crack growth) of steel.

**Tempering:**

Steel must be cooled rapidly if it is to be hardened. The most common practice is to quench it in water after it has been austenitized at an appropriate temperature. When you quench a piece of steel of finite size its surface no doubt cools very fast but its core would cool slowly. At any instant the temperature (T) at the core would be higher than that at its surface. The difference between the two (ΔT) is a function of the size of the specimen (or the job / component). It increases with the increase in the size of the specimen. The thermal stress that develops is proportional to ΔT. Therefore it is high in a thick component. Apart from this there would be additional stresses due to the change in volume associated with the transformation of austenite to martensite. The net stress is the sum of the two. Its magnitude might be high enough to cause distortion or cracking. This must be avoided. One obvious way is to adopt slow cooling. But it may not favor formation of martensitic structure. The other option is to heat the sample once again after quenching. The temperature should be high enough to relieve the stresses. The process is known as tempering. Apart from stress relief there are two more reasons that are worth noting. (i) High carbon marteniste is extremely brittle. Tempering would make it little more ductile and tough (higher impact / crack resistance). (ii) The presence of retained austenite poses an additional problem. It is unstable at room temperature. It may decompose into a ferrite - carbide structure with time. Such a transformation is accompanied by an expansion in volume. This may lead to cracking or a change in the dimension of the component.
Slide 6 shows the heating and cooling cycle for tempering of steel. It always follows hardening heat treatment. It is an isothermal heat treatment process. During tempering local plastic deformation due to the presence of residual stresses and diffusion controlled phase transformation take place. The kinetics of transformation depends on both time and temperature. After a specific thermal exposure the sample is either oil quenched or air cooled. Slide 6 gives hardness (Rc) versus time plots at three different temperatures. The change in hardness is a good indicator of the kinetics of transformation that takes place during tempering. It drops with increasing time at a constant temperature. It is more prominent at higher temperatures. If the hardness is plotted against a combined time temperature parameter the hardness data fall on common master plot as shown in slide 7. One of these is called Holloman – Jaffe tempering parameter. It is given by \( T(C + \log t) \) where \( T \) is the temperature in °K and \( t \) is time in hour and the constant \( C = 14.3 \).
Structural changes during tempering

Stage I: HCM=LCM+ $\varepsilon$ carbide

II: RA = $\alpha$ + carbide

III: $\varepsilon$ carbide dissolves & $M=\alpha+carbide$

Experimental techniques

- Microstructure
- X Ray diffraction
- Dilatometer

Slide 8 gives the structural changes that occur during tempering. Note that the hardness versus time – temperature parameter plot can be divided into three stages. During stage I high carbon martensite transforms into a mixture of low carbon martensite and epsilon carbide ($Fe_{2.4}C$). During stage II the retained austenite (RA) transforms into a mixture of ferrite and carbide. Its structure is similar to that of bainite. During stage III epsilon carbide is replaced by cm globules and low carbon martensite transforms into ferrite. When the globules of cementite coarsen there is a significant drop in the hardness of steel. The exact nature of the plot depends on the initial carbon content of martensite and the amount of retained austenite. Low carbon
martensite has lower hardness. In such a case precipitation of very fine epsilon carbides may be accompanied by a little increase in hardness. If %C is higher than 0.6 the hardness of martensite should be around R_c64. When it transforms into low carbon martensite it should be accompanied by a drop in hardness. However in the presence of very small precipitates the drop in hardness may not be significant. If hardened steel has a significant amount of retained austenite there may be an increase in hardness when it transforms into ferrite carbide aggregate. In short the trend shown by hardness plot may vary widely depending on the composition and microstructure of steel after hardening. Slide 9 gives a summary of the structural change expected in hardened steel as a function of tempering temperature. Apart from hardness there are several other ways of monitoring the transformations that occur during tempering. Slide 8 includes 3 such techniques. These are examination of microstructure, X-ray diffraction and dilatometer. The crystal structure of martensite is BCT. X-ray diffraction technique can be used to find its c/a ratio. There is a plot in slide 8 that shows how c/a ratio is expected to change as a function of time at a given tempering temperature.

### Structural changes during tempering

<table>
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<tr>
<th>Temp range</th>
<th>Microstructure</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 – 200 C</td>
<td>LCM + ε carbide</td>
<td>Slight increase in hardness</td>
</tr>
<tr>
<td>200 – 260 C</td>
<td>RA: decomposition</td>
<td>Hardness starts decreasing</td>
</tr>
<tr>
<td>260 – 360 C</td>
<td>ε carbides pick up C to form Cm: not resolved in OM</td>
<td>Marked decrease in hardness</td>
</tr>
<tr>
<td>360 – 723 C</td>
<td>Coarsening of Cm</td>
<td>Fully softened</td>
</tr>
</tbody>
</table>

Tempered martensite having R_c 25-45 has excellent combination of strength & toughness. Problem?

The drop in hardness during tempering is accompanied by an increase in its ductility and toughness. Tempered martensitic structure is known to have the best combination of strength and toughness. It is possible to get same hardness in steel by giving different heat treatments. For example you can get a hardness of R_c35 in a given piece of steel either by normalizing or by hardening and tempering but hardened and tempered steel has much higher impact toughness than the one which is normalized. Sometimes tempering can make steel brittle. One of these is associated with the precipitation of ε carbide. It occurs at low temperature. The other takes
place on slow cooling through a temperature range of 550° - 450°C after tempering. It is due to presence of a few unwanted alloy elements in steel. It can be avoided by fast cooling. Charpy V Notch (CVN) test is the best possible way to determine the susceptibility of a specific grade of steel to such embrittlement. It will be taken up later after we talk about the effect of alloy addition on structure and properties of steel.

Recalcescence:

It is associated with reheating during cooling as a result of eutectoid transformation. It is important in steel having higher percentage of pearlite. The cooling curves used to describe the effect of cooling rate on the evolution of structures in steel were assumed to be smooth. However because of reheating effect that occurs due to phase transformation it is often difficult to maintain a constant cooling rate. It can easily be demonstrated in the laboratory by heating a piano wire made of high carbon steel, held straight between a pair of grips, by passing electrical current from a power source until it becomes red hot and then let it cool in air. During heating wire expands but when it converts to austenite it contracts. The two balance each other. Therefore the wire remains straight. During cooling it becomes dull initially but again it gets heated when austenite begins to transform. This is because it is exothermic. The wire again becomes red & sags because of expansion due to both temperature increase & phase change. Recall that the transformation of austenite to pearlite or martensite is accompanied by an expansion in volume. This is illustrated with the help of sketches in fig 5. The effect is more prominent in high carbon steel.

![Piano wire becomes red when heated but remains straight. On cooling initially becomes dull grey but remains straight. Becomes red hot again when it begins to transform & sags.](image)

![Fig 5: Actual cooling curve with T & t at which eutectoid transformation begins](image)

An idea about recalcescence (the extent of reheating due to phase transformation) while steel is being cooled is of considerable importance in the design and selection of cooling scheme for continuous thermo-mechanical treatments (TMT). For example during the production of high strength bars / rods after TMT have to be cooled rapidly. During this stage it is necessary to
take away the heat contained within the product as well as that being generated due to phase transformation.

**Dual phase steel:**

Ever since the oil crisis of 1970s there have considerable efforts world over for the development of high strength steel so that more fuel efficient automobiles could be produced by reducing their weight. Ever since, several new grades of high strength low alloy steel has been introduced. Although some of these will be covered in subsequent modules it may be worthwhile to mention about dual phase steel in this module because high strength in this grade was achieved by adopting a simple but novel heat treatment scheme. Bulk of the steel used in load bearing members of automobiles or critical structures are made of low carbon steel. Strength of such steel can be substantially increased by quenching it from a temperature a little above $A_1$. This would have a microstructure consisting of soft ferrite and hard martensite. The amount of ferrite in this steel is around 70-80% and the balance being martensite. The ratio of the two can be controlled by proper selection of the temperature within the ferrite austenite field of the phase diagram. The presence of hard martensite in a soft matrix made of ferrite gives it an optimum combination of strength and ductility. Besides these it has a smooth stress strain curve. Unlike most low carbon steel it does not exhibit yield point phenomenon. Therefore it has excellent cold formability as well. The development took place almost concurrently during 1975-78 at Nippon steel, General Motors and Ford. It is commonly known as dual phase steel.

**Summary:**

In this lecture we looked at annealing, normalizing and hardening; the three common methods of heat treatment of steel. The principles behind the selection of austenitization temperature have been explained. The process of austenization is a diffusion controlled phenomenon. Its kinetics depends on both temperature and time. Therefore it can be represented by time – temperature transformation diagram. It depends on the composition of steel. The importance of CCT diagram in describing the evolution of microstructure during heat treatment has been emphasized. In order to harden steel it must be cooled rapidly. The final structure is unstable. It has retained austenite and high residual stresses. Therefore it must be tempered as early as possible. The structural changes that take place during tempering have been explained. The problem of reheating during air cooling of high carbon steel has been discussed. Its occurrence is due to exothermic eutectoid transformation. A simple experimental technique to demonstrate this has been described. The phenomenon is known as recalescence.
Exercise:

1. Suggest a simple experimental method for determination of Ms temperature of steel if you have only facility for heat treatment and metallographic examination.
2. Which of the two would require more severe cooling rate to get a fully hardened structure? (a) 0.8 % carbon steel (b) 1.0 % C steel.
3. A piece of steel which was quenched after prolonged holding at 700°C was found to have ferrite martensite structure. Explain when would you expect this to happen?
4. List the factors that determine the strength of properly hardened steel.
5. 0.2 % plain carbon steel in annealed condition has 25% coarse pearlite. If it is normalized (heat treatment) what changes would you expect in its microstructure?
6. A thin strip of 1.2% carbon steel is quenched in water from its fully austenitic state. What structure would you expect in this steel?

Answer:

1. Austenitize a steel specimen, quench in baths maintained at a temperature close to its expected Ms, heat it again by placing it in another bath maintained at a little higher temperature, and then quench in water after holding it for some time. Repeat the same steps with different combination of the intermediate quenching temperatures. Polish etch and examine the microstructures under microscope. If martensite forms at the first step cooling it will get tempered when it is put in a higher temperature bath. Tempered martensite etches easily and it appears dark under microscope. Amount of tempered martensite can be estimated. Plot % tempered martensite against intermediate quenching temperature. Extrapolate it to 0% tempered martensite. This gives an estimate of Ms. The experimental scheme is shown in the following figure for eutectoid steel

![Diagram](image)

2. Austenitization temperatures for both are same for hardening heat treatment. (a) being an eutectoid steel will have homogeneous austenite before quenching. Where as in (b) there will be cementite globules present which would provide sites for nucleation of
pearlite. Therefore the latter would need more severe quenching to get fully hardened structure.

3. Eutectoid temperature of steel is a function of its composition. For plain carbon steel it is around 720°C. To get martensite the steel should be heated beyond this temperature. However the presence of alloying elements which stabilize austenite (such as Mn, Ni) can bring down eutectoid temperature. In this case steel must be an alloy steel whose eutectoid temperature is less than 700°C. Therefore it must have been quenched from ferrite – austenite region and the austenite on quenching got transformed into martensite resulting in a ferrite – martensite structure.

4. A steel has maximum strength if has 100% martensite. This is obtained by quenching steel from austenitic state. Strength of martensite depends primarily on its carbon content. However the cooling rate needed to get 100% martensite in plain carbon steel is often difficult to achieve. Presence of additional alloy elements decreases critical cooling rate. Alloy steels are easy to harden. Therefore strength of hardened steel would depend on its carbon content, section size (thickness) and other alloy elements present & their amounts in the steel.

5. As against furnace cooling in the case of annealing the job is allowed to cool in air while normalizing. This being significantly faster normalized structure would have finer pearlite and a little less amount of ferrite. However the total amount of cementite would still be the same. Only the carbon content and therefore the amount of cementite in pearlite would decrease.

6. On quenching the microstructure of steel will consist of martensite and some retained austenite. Both Ms & Mf temperature of steel decreases with % carbon. Steels having beyond 0.7%C has subzero Mf temperature.