MATERIAL TECHNOLOGY (SPR1201)

UNIT – IV (Heat Treatment of Steel)

Heat Treatment is the controlled heating and cooling of metals to alter their physical and mechanical properties without changing the product shape. Heat treatment is sometimes done inadvertently due to manufacturing processes that either heat or cool the metal such as welding or forming. Heat Treatment is often associated with increasing the strength of material, but it can also be used to alter certain manufacturability objectives such as improve machining, improve formability, restore ductility after a cold working operation. Thus it is a very enabling manufacturing process that can not only help other manufacturing process, but can also improve product performance by increasing strength or other desirable characteristics. Steels are particularly suitable for heat treatment, since they respond well to heat treatment and the commercial use of steels exceeds that of any other material.

Steels are heat treated for one of the following reasons:

1. Softening 2. Hardening 3. Material Modification

1.Softening: Softening is done to reduce strength or hardness, remove residual stresses, improve toughnesss, restore ductility, refine grain size or change the electromagnetic properties of the steel. Restoring ductility or removing residual stresses is a necessary operation when a large amount of cold working is to be performed, such as in a cold-rolling operation or wiredrawing. Annealing — full Process, spheroidizing, normalizing and tempering — austempering, martempering are the principal ways by which steel is softened.

2.Hardening: Hardening of steels is done to increase the strength and wear properties. One of the pre-requisites for hardening is sufficient carbon and alloy content. If there is sufficient Carbon content then the steel can be directly hardened. Otherwise the surface of the part has to be Carbon enriched using some diffusion treatment hardening techniques.

3.Material Modification: Heat treatment is used to modify properties of materials in addition to hardening and softening. These processes modify the behavior of the steels in a beneficial manner to maximize service life, e.g., stress relieving, or strength properties, e.g., cryogenic treatment, or some other desirable properties, e.g., spring aging.

Heat Treatment of Steel Steels can be heat treated to produce a great variety of microstructures and properties. Generally, heat treatment uses phase transformation during heating and cooling to change a microstructure in a solid state. In heat treatment, the processing is most often entirely thermal and modifies only structure. Thermomechanical treatments, which modify component shape and structure, and thermochemical treatments which modify surface chemistry and structure, are also important processing approaches which fall into the domain of heat treatment. The iron-carbon diagram is the base of heat treatment.

According to cooling rate we can distinguish two main heat treatment operations: • annealing – upon slow cooling rate (in air or with a furnace) • quenching – upon fast cooling (in oil or in water) annealing - produces equilibrium structures according to the Fe-Fe_3C diagram quenching - gives non-equilibrium structures Among annealing there are some important heat treatment processes like: • normalising • spheroidising • stress relieving

Normalising: The temperature depends on carbon content. After soaking the alloy is cooled in still air. This cooling rate and applied temperature produces small grain size. The small grain structure improve both toughness and strength (especially yield strenght). During normalising we use grain refinement which is associated with allotropic transformation upon heating $\gamma \rightarrow \alpha$

Spheroidising: The process is limited to steels in excess of 0.5% carbon and consists of heating the steel to temperature about A1 (727°C). At this temperature any cold worked ferrite will recrystallise and the iron carbide present in pearlite will form as spheroids or "ball up". As a result of change of carbides shape the strength and hardness are reduced.

Quenching: Material is heated up to the suitable temperature and then quenched in water or oil to harden to full hardness according to the kind of steels. Material is heated to the suitable temperature for hardening, then cooled rapidly by immersing the hot part is water, oil or another suitable liquid to transform the material to a fully hardened structure. Parts which are quenched usually must be aged, tempered or stress relieved to achieve the proper toughness, final hardness and dimensional stability. Alloys may be air cooled, or cooled by quenching in oil, water, or another liquid, depending upon the amount of alloying elements in the material and final mechanical properties to be achieved. Hardened materials are tempered to improve their dimensional stability and toughness.

Tempering: Tempering is done to develop the required combination of hardness, strength and toughness or to relieve the brittleness of fully hardened steels. Steels are never used in the as quenched condition. The combination of quenching and tempering is important to make tough parts. This treatment follows a quenching or air cooling operation. Tempering is generally considered effective in relieving stresses induced by quenching in addition to lowering hardness to within a specified range, or meeting certain mechanical property requirements. Tempering is the process of reheating the steel at a relatively low temperature leading to precipitation and spheroidization of the carbides present in the microstructure. The tempering temperature and times are generally controlled to produce the final properties required of the steel. The result is a component with the appropriate combination of hardness, strength and toughness for the intended application. Tempering is also effective in relieving the stresses induced by quenching.

Critical Temperatures: The "critical points" of carbon tool steel are the temperatures at which certain changes in the chemical composition of the steel take place, during both heating and cooling. Steel at normal temperatures has its carbon (which is the chief hardening element) in a certain form called pearlite carbon, and if the steel is heated to a certain temperature, a change occurs and the pearlite becomes martensite or hardening carbon. If the steel is allowed to cool slowly, the hardening carbon changes back to pearlite. The points at which these changes occur are the decalescence and recalescence or critical points, and the effect of these molecular changes is as follows: When a piece of steel is heated to a certain point, it continues to absorb heat without appreciably rising in temperature, although its immediate surroundings may be hotter than the steel. This is the **decalescence point**. Similarly, steel cooling slowly from a high heat will, at a certain temperature, actually increase in temperature, although its surroundings may be colder. This takes place at the **recalescence point**. The recalescence point is lower than the decalescence point by anywhere from 85 to 215 degrees F., and the lower of these points does not manifest itself unless the higher one has first been fully passed. These critical points have a direct relation to the hardening of steel. Unless a temperature sufficient to reach the decalescence point is obtained, so that the pearlite carbon is changed into a hardening carbon, no hardening action can take place; and unless the steel is cooled suddenly before it reaches the recalescence point, thus preventing the changing back again from hardening to pearlite carbon, no hardening can take place. The critical points vary for different kinds of steel and must be determined by tests in each case. It is the variation in the critical points that makes it necessary to heat different steels to different temperatures when hardening.

Hardening: The use of this treatment will result in an improvement of the mechanical properties, as well as an increase in the level of hardness, producing a tougher, more durable item. Alloys are heated above the critical transformation temperature for the material, then cooled rapidly enough to cause the soft initial material to transform to a much harder, stronger structure. Alloys may be air cooled, or cooled by quenching in oil, water, or another liquid, depending upon the amount of alloying elements in the material. Hardened materials are usually tempered or stress relieved to improve their dimensional stability and toughness. Steel parts often require a heat treatment to obtain improved mechanical properties, such as increasing increase hardness or strength. The hardening process consists of heating the components above the critical (normalizing) temperature, holding at this temperature for one hour per inch of thickness cooling at a rate fast enough to allow the material to transform to a much harder, stronger structure, and then tempering. Steel is essentially an alloy of iron and carbon; other steel alloys have other metal elements in solution. Heating the material above the critical temperature causes carbon and the other elements to go into solid solution. Quenching "freezes" the microstructure, inducing stresses. Parts are subsequently tempered to transform the microstructure, achieve the appropriate hardness and eliminate the stresses.

Annealing Heat Treatment: Annealing heat treatment process is heating the material above the critical temperature, holding long enough for transformation to occur and slow cooling. Full annealing heat treatment differs from normalizing heat treatment in that the annealing temperature is typically 150-200F lower than the normalizing temperature and the cooling rate is slower. This establishes a soft microstructure and thus a soft product.

Austenitizing: Austenitizing heat treatment is heating a steel above the critical temperature, holding for a period of time long enough for transformation to occur. The material will be hardened if austenitizing is followed by quenching at a rate that is fast enough to transform the austenite into martensite.

Normalizing: Normalizing Heat Treatment process is heating a steel above the critical temperature, holding for a period of time long enough for transformation to occur, and air cooling. Normalized heat treatment establishes a more uniform carbide size and distribution which facilitates later heat treatment operations and produces a more uniform final product. Solution Annealing - Solution Heat Treatment Definition Some alloys (aluminum, PH stainless steels, Ti) harden by precipitating microscopic particles during aging. Solution heat treatment /

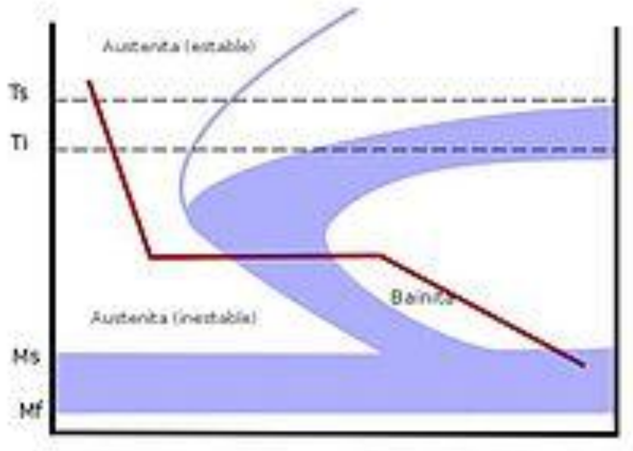
solution annealing takes these particles and puts them back into solution. In the solution annealing process, the alloy is heated to a high temperature, held for a period of time related to the section size of the material and air cooled or faster. This traps the precipitates in solution.

Steel Aging (also referred to as Precipitation Hardening): Precipitation Hardening is the heating of alloys, in the solution treated condition, to a lower temperature, which allows a relatively uniform distribution of microscopic particles throughout the alloy. The aging process results in alloy strengthening.

Stress Relieving Heat Treatment: Stress Relieving heat treatment process is heating to a temperature in order to relieve internal stresses in the material and lower the hardness of the surface of the material.

Austempering: Austempering is a technique used to form pure bainite, a transitional microstructure found between pearlite and martensite. In normalizing, both upper and lower bainite are usually found mixed with pearlite. To avoid the formation of pearlite or martensite, the steel is quenched in a bath of molten metals or salts. This quickly cools the steel past the point where pearlite can form, and into the bainite-forming range. The steel is then held at the bainite-forming temperature, beyond the point where the temperature reaches an equilibrium, until the bainite fully forms. The steel is then removed from the bath and allowed to air-cool, without the formation of either pearlite or martensite.

Depending on the holding-temperature, austempering can produce either upper or lower bainite. Upper bainite is a laminate structure formed at temperatures typically above 350 °C (662 °F) and is a much tougher microstructure. Lower bainite is a needle-like structure, produced at temperatures below 350 °C, and is stronger but much more brittle.In either case, austempering produces greater strength and toughness for a given hardness, which is determined mostly by composition rather than cooling speed, and reduced internal stresses which could lead to breakage. This produces steel with superior impact resistance. Modern punches and chisels are often austempered. Because austempering does not produce martensite, the steel does not require further tempering.



In the above given Time-temperature transformation (TTT) diagram. The red line shows the cooling curve for austempering.

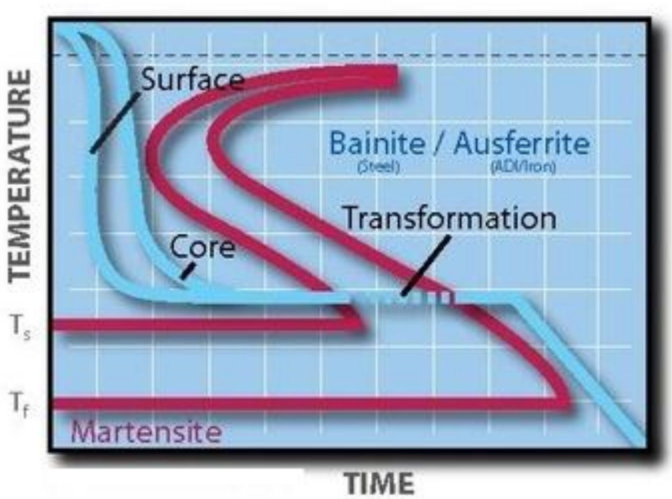
Martempering: Martempering is similar to austempering, in that the steel is quenched in a bath of molten metal or salts to quickly cool it past the pearlite-forming range. However, in martempering, the goal is to create martensite rather than bainite. The steel is quenched to a much lower temperature than is used for austempering; to just above the martensite start temperature. The metal is then held at this temperature until the temperature of the steel reaches an equilibrium. The steel is then removed from the bath before any bainite can form, and then is allowed to air-cool, turning it into martensite. The interruption in cooling allows much of the internal stresses to relax before the martensite forms, decreasing the brittleness of the steel. However, the martempered steel will usually need to undergo further tempering to adjust the hardness and toughness, except in rare cases where maximum hardness is needed but the accompanying brittleness is not. Modern files are often martempered

Embrittlement: Embrittlement occurs during tempering when, through a specific temperature range, the steel experiences an increase in hardness and a reduction in ductility, as opposed to the normal decrease in hardness that occurs to either side of this range. The first type is called tempered martensite embrittlement (TME) or one-step embrittlement. The second is referred to as temper embrittlement (TE) or two-step embrittlement.

Recrystallization: Recrystallization is a process by which deformed grains are replaced by a new set of defects-free grains that nucleate and grow until the original grains have been entirely consumed. Recrystallization is usually accompanied by a reduction in the strength and hardness of a material and a simultaneous increase in the ductility. Thus, the process may be introduced as a deliberate step in metals processing or may be an undesirable byproduct of another processing step. The most important industrial uses are the softening of metals previously hardened by cold work, which have lost their ductility, and the control of the grain structure in the final product.

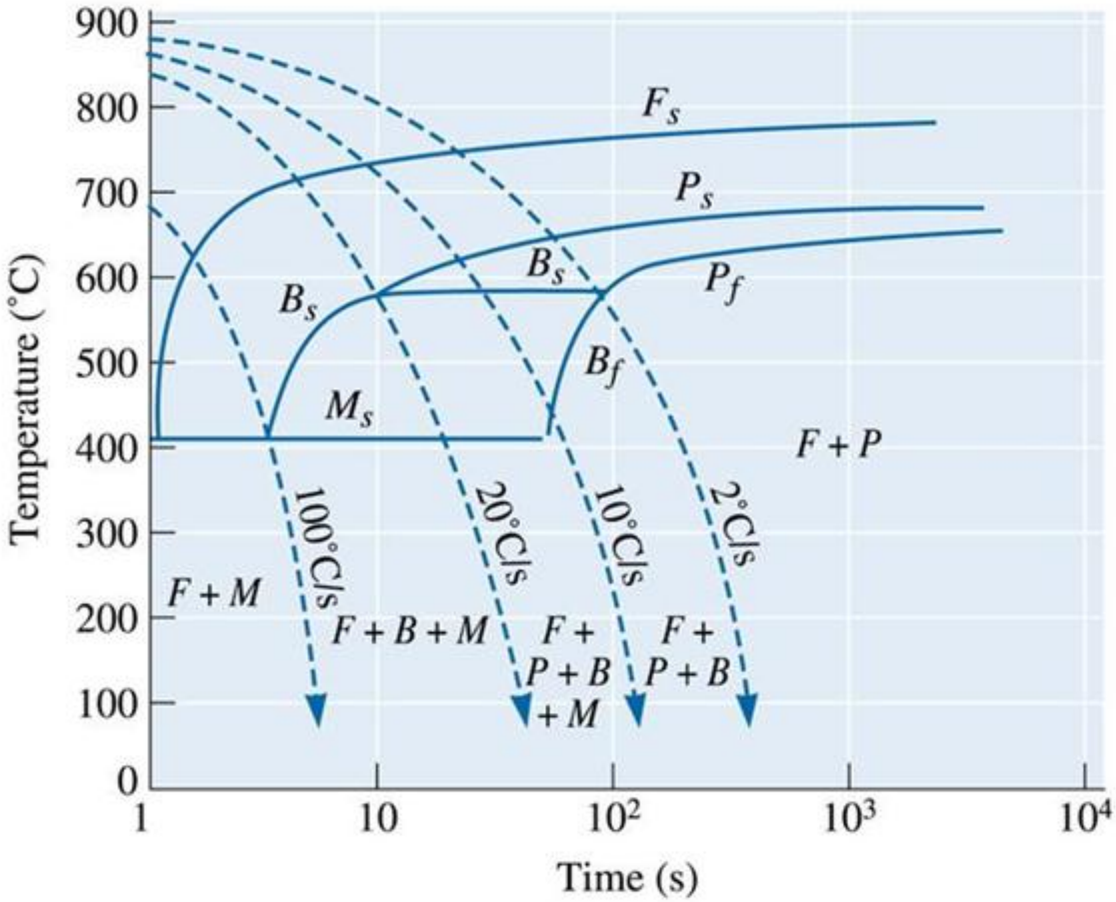
There are two main types of transformation diagram that are helpful in selecting the optimum steel and processing route to achieve a given set of properties. These are time-temperature transformation (TTT) and continuous cooling transformation (CCT) diagrams. CCT diagrams are generally more appropriate for engineering applications as components are cooled (air cooled, furnace cooled, quenched etc.) from a processing temperature as this is more economic than transferring to a separate furnace for an isothermal treatment. Time-temperature transformation (TTT) diagrams measure the rate of transformation at a constant temperature. In other words a sample is austenitised and then cooled rapidly to a lower temperature and held at that temperature whilst the rate of transformation is measured, for example by dilatometry. Obviously a large number of experiments is required to build up a complete TTT diagram. Continuous cooling transformation (CCT) diagrams measure the extent of transformation as a function of time for a continuously decreasing temperature. In other words a sample is austenitised and then cooled at a predetermined rate and the degree of transformation is measured, for example by dilatometry. Obviously a large number of experiments is required to build up a complete CCT diagram. TTT diagrams are time temperature transformation or isothermal transformation diagrams.

The essential difference between both the diagrams is the method of cooling. In TTT diagrams, after cooling to a transformation temperature, you keep the temperature constant until the transformation of austenite to the required transformation product (usually pearlite or bainite) is complete and then cool to the room temperature. One such process is austempering in which austenite is transformed to bainite isothermally. Below is a TTT diagram showing the austempering process.



The red lines form the transformation diagram and blue line denote the process. In this case the component which had an austenitic structure was cooled to just above Ts temperature; held at that temperature until the transformation was complete and then cooled further to the room temperature.

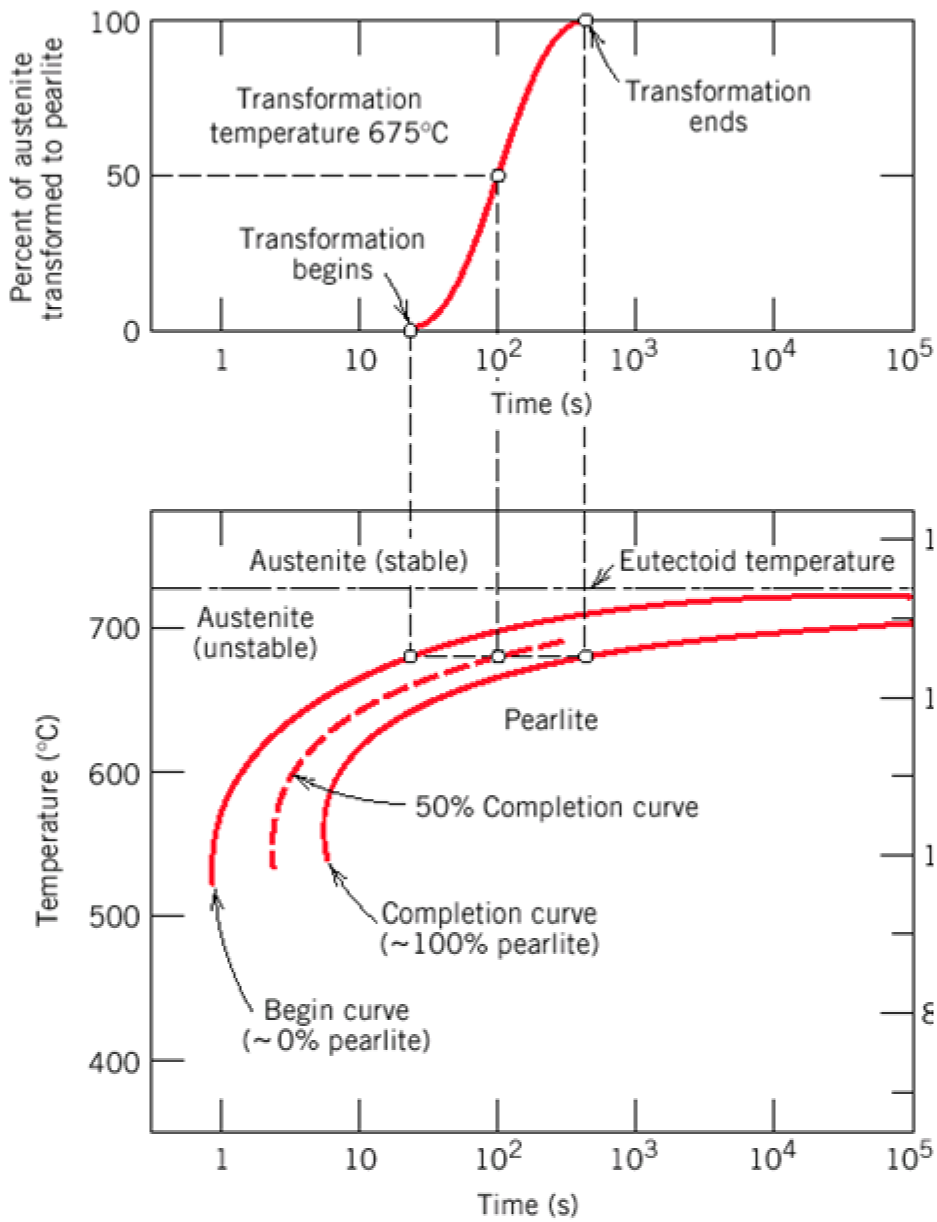
In CCT diagrams, there is continuous cooling i.e. there is no holding of temperature. The components are cooled at a constant or varying rates. The end products are usually martensite or pearlite depending on the cooling media as well as the material of components. Fully bainitic structure cannot be obtained using continuous cooling. Below is a CCT diagram:



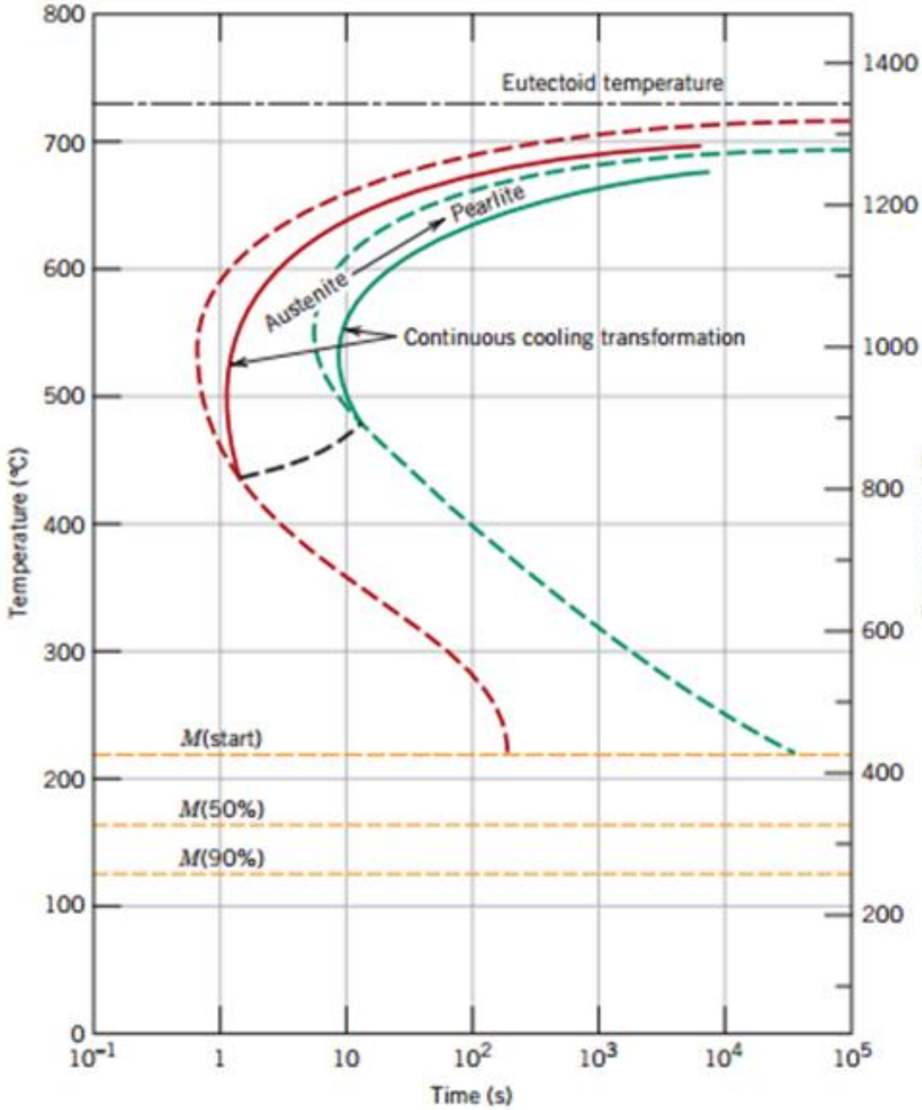
In the above figure: F – Ferrite, P – Pearlite: B – Bainite: M – Martensite: s subscript denotes start temperature and f subscript denotes finish temperature.

So a CCT diagrams simply gives the various transformation products which will be obtained at different cooling rates. It can be seen from the diagram that at cooling rates of more than 100 degrees celsius, ferrite and martensite will be obtained; for cooling rates between 20 and 100 degrees celsius, ferrite, bainite and martensite will be obtained and so on. These cooling rates are dependent on the cooling media. CCT diagrams are more practical than TTT diagrams as most of the processes employ continuous cooling rather than isothermal transformation. Also it is more difficult to hold the temperature constant.

Different steels have different TTT and CCT diagrams. In the diagram the time is noted where the transformation of austenite to a particular product (in this case, it is pearlite) begins and the time at which the transformations ends.



Then these transformation start times and transformation end times are plotted for different temperatures as shown. These points, when joined, give us the TTT diagrams. For continuous cooling, the time required for the transformation to begin and end is delayed. Thus the TTT diagram's curves are shifted to longer times and lower temperatures.

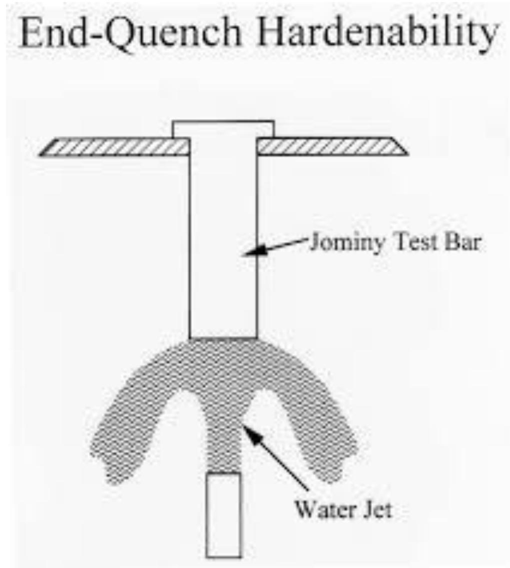


The dashed lines form TTT diagrams and the solid lines form the CCT diagrams. It can be seen that CCT diagram can be obtained by moving the TTT curves a little to the downward right.

Hardenability:

To achieve a full conversion of austenite into hard martensite, cooling needs to be fast enough to avoid partial conversion into perlite or bainite. If the piece is thick, the interior may cool too slowly so that full martensitic conversion is not achieved. Thus, the martensitic content, and the hardness, will drop from a high value at the surface to a lower value in the interior of the piece. Hardenability is the ability of the material to be hardened by forming martensite.

Hardenability is measured by the Jominy end-quench test (shown in figure). Hardenability is then given as the dependence of hardness on distance from the quenched end. High hardenability means that the hardness curve is relatively flat.



Influence of Quenching Medium, Specimen Size, and Geometry:

The cooling rate depends on the cooling medium. Cooling is fastest using water, then oil, and then air. Fast cooling brings the danger of warping and formation of cracks, since it is usually accompanied by large thermal gradients.

The shape and size of the piece, together with the heat capacity and heat conductivity are important in determining the cooling rate for different parts of the metal piece. Heat capacity is the energy content of a heated mass, which needs to be removed for cooling. Heat conductivity measures how fast this energy is transported to the colder regions of the piece.

Precipitation Hardening: Hardening can be enhanced by extremely small precipitates that hinder dislocation motion. The precipitates form when the solubility limit is exceeded. *Precipitation hardening is also called age hardening* because it involves the hardening of the material over a prolonged time. Precipitation hardening is achieved by:
a) solution heat treatment where all the solute atoms are dissolved to form a single-phase solution.

b) rapid cooling across the solvus line to exceed the solubility limit. This leads to a supersaturated solid solution that remains stable (metastable) due to the low temperatures, which prevent diffusion.

c) precipitation heat treatment where the supersaturated solution is heated to an intermediate temperature to induce precipitation and kept there for some time (aging).

If the process is continued for a very long time, eventually the hardness decreases. This is called overaging.