# Section 3: HEAT TREATMENT

## *Introduction*

## *Objectives of Heat Treatment*

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, and 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

## *Common Heat Treatments*

## *Softening*

Softening is done to reduce strength or hardness, remove residual stresses, improve toughness, 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.

Softening processes include:

Annealing — Full Process,
Spheroidizing,
Normalizing
Tempering — austempering and martempering

## *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.

## *Material Modification*

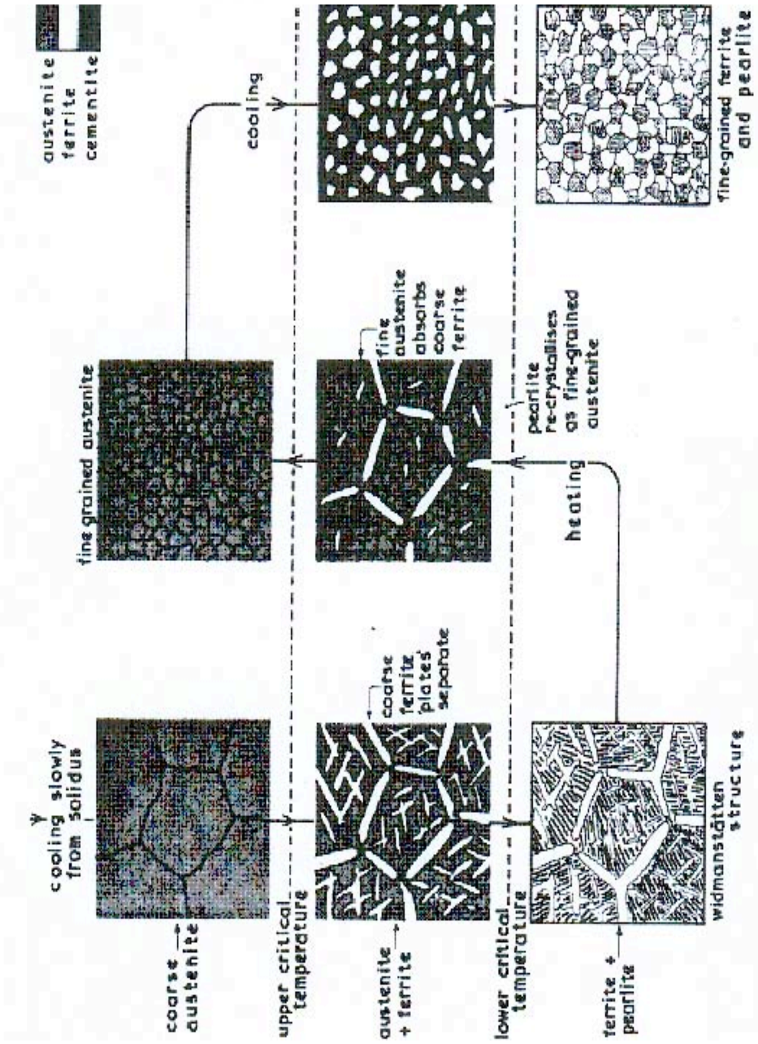
Heat treatment is used to modify properties of materials in addition to hardening and softening. These processes modify the behavior of the steels in a beneficial manner to maximize service life, e.g., stress relieving, or strength properties, e.g., cryogenic treatment, or some other desirable properties,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

For the purpose of this presentation we will examine Softening Annealing and Direct Hardening in relation to modifying the microstructures which were formed in Figure 9. Other heat treatment processes can be discussed at a later date.

## *Softening – Annealing*

### *Full Annealing*

Full annealing is the process of slowly raising the temperature about 50 ºC (90 ºF) above the Austenitic temperature line $A_3$ or line $A_{CM}$ in the case of Hypoeutectoid steels (steels with < 0.77% Carbon) and 50 ºC (90 ºF) into the Austenite-Cementite region in the case of Hypereutectoid steels (steels with > 0.77% Carbon).
It is held at this temperature for sufficient time for all the material to transform into Austenite or Austenite-Cementite as the case may be. It is then slowly cooled at the rate of about 20 ºC/hr (36 ºF/hr) in a furnace to about 50 ºC (90 ºF) into the Ferrite-Cementite range. At this point, it can be cooled in room temperature air with natural convection. The grain structure has coarse Pearlite with ferrite or Cementite (depending on whether hypo or hyper eutectoid). The steel becomes soft and ductile. This process is illustrated in Figure 11.



Structural changes occurring during the annealing of a steel casting (approx 0.35% carbon). The as-cast Widmanstätten structure is reheated to some temperature above its upper critical and then allowed to cool in the furnace.

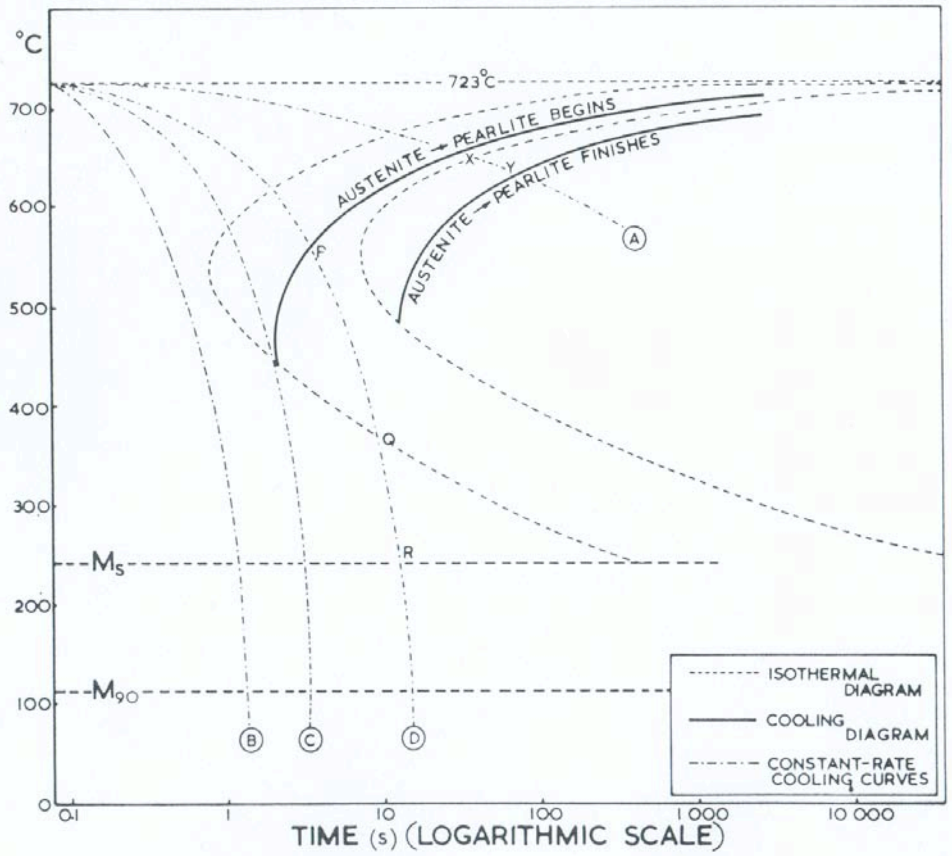
*Figure 11*

## *Direct Hardening*

Hardness is a function of the Carbon content of the steel. Hardening of steel requires a change in structure from the body-centered cubic structure found at room temperature to the face-centered cubic structure found in the Austenitic region. The steel is heated to Autenitic region. When suddenly quenched, *Martensite* is formed. This is a very strong and brittle structure. When slowly quenched it would form Austenite and Pearlite which is a partly hard and partly soft structure. When the cooling rate is extremely slow then it would be mostly Pearlite which is extremely soft. This relationship between structure and rate of cooling can be studied for a given steel with the help of a set isothermal transformation curves which are known as TTT (Time-Temperature-Transformation) curves. Such a curve is shown in Figure 12. It indicates the time necessary for transformation to take place and the structure which will be produced when austenite is super cooled to any predetermined transformation temperature.

*Figure 12*

Figure 13 represents four curves which have been produced by varying the cooling rate. Curve A represents a rate of cooling of approximately 5°C per second such as might be encountered during normalising. Here transformation will begin at X and can be completed at Y, the final structure being one of fine pearlite. Curve B, on the other hand, represents very rapid cooling at a rate of approximately 400°C per second. This is typical of conditions prevailing during a water-quench, and transformation will not begin until 220°C, when martensite begins to form. The structure will consist of 90% martensite at 110°C and so contain a little retained austenite at room temperature. The lowest rate, at which this steel (of eutectoid composition) can be quenched, in order to obtain a structure which is almost wholly martensitic, is represented by curve C (140°C per second). This is called the critical cooling rate for the steel, and if a rate lower than this is used some fine pearlite will be formed. For example, in the case of the curve D, which represents a cooling rate of about 50°C per second, transformation would begin at P with the formation of some fine pearlite. Transformation, however, is interrupted in the region of Q and does not begin again until the $M_s$ line is reached at R, when the remaining austenite begins to transform to martensite. Thus the final structure at room temperature is a mixture of pearlite, martensite and traces of retained austenite.



The relationship between TTT curves and curves representing continuous cooling.

*Figure 13*

The TTT curves illustrated in Fig. 12 are those for a steel of eutectoid composition. If the carbon content is either above or below this, the curves will be displaced to the left so that the critical cooling rate necessary to produce a completely martensitic structure will be greater. In order to obtain a structure which is entirely martensitic the steel must be cooled at such a rate that the curve representing its rate of cooling does not cut into the 'nose' of the modified 'transformation begins' curve in the region of 550°C. Obviously, if the steel remains in this temperature range for more than one second, then transformation to pearlite will begin. Hence the need for drastic water-quenches to produce wholly martensitic structures in plain carbon steels.

For a steel containing less than 0.3% carbon the transformation-begins curve has moved so far to the left that it has become impossible to obtain a wholly martensitic structure however rapidly it is cooled. Large quantities of ferrite will inevitably precipitate when the transformation-begins curve is unavoidably cut in the upper temperature ranges. The resulting structure will be most unsatisfactory since hard martensite will be interspersed with soft ferrite.

Fortunately, the addition of alloying elements has the effect of slowing down transformation rates so that the TTT curves are displaced to the right. This means that much slower rates of cooling can be used, in the form of oil- or even air-quenches, and a martensitic structure still obtained. Small amounts of elements, such as nickel, chromium and manganese, are effective in this way and this is one of the most important effects of alloying.

## *Hardenability*

Hardenability, which is a measure of the depth of full hardness achieved, is related to the type and amount of alloying elements. Different alloys, which have the same amount of Carbon content, will achieve the same amount of maximum hardness; however, the depth of full hardness will vary with the different alloys. The reason to alloy steels is not to increase their strength, but increase their hardenability — the ease with which full hardness can be achieved throughout the material.

Usually when hot steel is quenched, most of the cooling happens at the surface, as does the hardening. This propagates into the depth of the material. Alloying helps in the hardening and by determining the right alloy one can achieve the desired properties for the particular application.

Such alloying also helps in reducing the need for a rapid quench cooling — thereby eliminating distortions and potential cracking. In addition, thick sections can be hardened fully.

## *Summary*

Steel is a combination of iron and carbon. In its softened state, the base is a matrix composed of simple iron molecules (ferrite), in which are suspended molecules of iron carbide (cementite). When steel is heated to prescribed temperatures, then cooled at a specific rate, it undergoes physical internal changes which manifest themselves in the form of various micro-structures such as pearlite, bainite, and martensite. These micro-structures (and others) provide a wide range of mechanical properties, making steel an extremely versatile metal.