**Chapter Four : 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. Typical heat treatment operation is presented in Fig. 4-1

Fig.4-1 Thermal history of heat treatment operation.

 According to cooling rate we can distinguish three main heat treatment operations:

• Annealing – upon slow cooling rate (in a furnace)

 • Normalizing – upon medium cooling (in air)

• Hardening – upon fast cooling (in oil or in water)

**Process Annealing—Eliminating Cold Work**

The recrystallization heat treatment used to eliminate the effect of cold working in steels with less

than about 0.25% C is called a process anneal. The process anneal is done 80°C to 170°C below the *A*1 temperature. The intent of the process anneal treatment for steels is similar to the annealing of inorganic glasses in that the main idea is to significantly reduce or eliminate residual stresses.

**Full Annealing**

Steels can be dispersion-strengthened by controlling the fineness of pearlite. The steel is initially

heated to produce homogeneous austenite (FCC γ phase), a step called austenitizing. Annealing, or a full anneal, allows the steel to cool slowly in a furnace, producing coarse pearlite.

For annealing, austenitizing of hypoeutectoid steels is conducted about 30°C above the *A*3, producing 100% γ; however, austenitizing of a hypereutectoid steel is done at about 30°C above the *A*1, producing austenite and Fe3C. This process prevents the formation of a brittle, continuous film of Fe3C at the grain boundaries that occurs on slow cooling from the 100% \_ region. In both cases, the slow furnace cool and coarse pearlite provide relatively low strength and good ductility.

**Spheroidizing—Improving Machinability**

Steels that contain a large concentration of Fe3C have poor machining characteristics. It is possible

to transform the morphology of Fe3C using *spheroidizing*. During the spheroidizing treatment, which requires several hours at about 30°C below the *A*1, the Fe3C phase morphology changes into large, spherical particles in order to reduce boundary area. The microstructure, known as spheroidite, has a continuous matrix of soft, machinable ferrite . After machining, the steel is given a more sophisticated heat treatment to produce the required properties. A similar microstructure occurs when martensite is tempered just below the *A*1 for long periods of time. As noted before, alloying elements such as Pb and S are also added to improve machinability of steels and, more recently, lead-free “green steels” that have very good machinability have been developed. The following example shows how different heat treatment conditions can be developed for a given composition of steel

**.Normalising**

The soaking temperature is 30-50°C above A3 or Acm in austenite field range. 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 strength).

During normalising we use grain refinement which is associated with allotropic transformation upon heating γ→α .



Figure 4-2 Schematic summary of the simple heat treatments for (a) hypoeutectoid steels and (b) hypereutectoid steels

**Effect of Changes in Carbon Concentration on the TTT Diagram**

In either a hypoeutectoid or a hypereutectoid steel, the TTTdiagram must reflect the possible formation of a primary phase. The isothermal transformationdiagrams for a 1050 and a 10110 steel are shown in Figure. The mostremarkable change is the presence of a “wing” that begins at the nose of the curve andbecomes asymptotic to the *A*3 or *A*cm temperature. The wing represents the ferrite start(*F*s) time in hypoeutectoid steels or the cementite start (*C*s) time in hypereutectoid steels.When a 1050 steel is austenitized, quenched, and held between the *A*1 and the *A*3, primary ferrite nucleates and grows. Eventually, equilibrium amounts of ferrite and austenite result. Similarly, primary cementite nucleates and grows to its equilibrium amount in a 10110 steel held between the *A*cm and *A*1 temperatures. If an austenitized 1050 steel is quenched to a temperature between the nose and the *A*1 temperatures, primary ferrite again nucleates and grows until reaching the equilibrium amount. The remainder of the austenite then transforms to pearlite. A similar situation, producing primary cementite and pearlite, is found for the hypereutectoid steel. If we quench the steel below the nose of the curve, only bainite forms, regardless of the carbon content of the steel. If the steels are quenched to temperatures below the *M*s, martensite will form.

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 Figure 4-3 The TTT diagrams for (a) a 1050 and (b) a 10110 steel. Note γu = unstable austenite

**Transformation of Austenite**

Thus far the discussion has been confined to heating of the steel and the phases that result from various combinations of temperature and carbon content. Now what happens when the alloy is cooled? Referring to Fig. 4-4, assume that a steel containing 0.50% C is heated to 815 OC. All of the carbon will be dissolved (assuming, of course, that holding time is sufficient). Under these conditions, all of the carbon atoms will dissolve in the interstices of the FCC crystal. If the alloy is cooled slowly, transformation to the BCC or alpha phase begins when the temperature drops below approximately 790 O C. As the temperature continues to decrease, the transformation is essentially complete at 723O C During this transformation, the carbon atoms escape from the lattice because they are essentially insoluble in the alpha crystal (BCC). Thus, in slow cooling, the alloy for all practical purposes, returns to the same state (in terms of phase) that it was before heating to form austenite. The same mechanism occurs with higher carbon steels, except that the austenite-to-ferrite transformation does not go through a two-phase zone In addition to the entry and exit of the carbon atoms through the interstices of the iron atoms, other changes occur that affect the practical aspects of heat treating. First, a magnetic change occurs at 770 O C as shown in Fig. 1. The heat of transformation effects may chemical changes, such as the heat that is evolved when water freezes into ice and the heat that is absorbed when ice melts. When an iron-carbon alloy is converted to austenite by heat, a large absorption of heat occurs at the transformation temperature. Likewise, when the alloy changes from gamma to alpha (austenite to ferrite), heat evolves. What happens when the alloy is cooled rapidly? When the alloy is cooled suddenly, the carbon atoms cannot make an orderly escape from the iron lattice. This cause “atomic bedlam” and results in distortion of the lattice, which manifests itself in the form of hardness and/or strength. If cooling is fast enough, a new structure known as martensite is formed, although this new structure (an aggregate of iron and cementite) is in the alpha phase.

Figure 4-4 Schematic representation of the formation of pearlite from austenite; direction of carbon diffusion indicated by arrows

**Continuous Cooling Transformation Diagrams**

We can develop a *continuous cooling transformation* (CCT) diagram by determining the microstructures produced in the steel at various rates of cooling. The CCT curve for a 1080 steel is shown in Figure 4-5. The CCT diagram differs from the TTT diagram in that longer times are required for transformations to begin and no bainite region is observed. If we cool a 1080 steel at 5°C/s, the CCT diagram tells us that we obtain coarse pearlite; we have annealed the steel. Cooling at 35°C/s gives fine pearlite and is a normalizing heat treatment. Cooling at 100°C/s permits pearlite to start forming, but the reaction is incomplete and the remaining austenite changes to martensite. We obtain 100% martensite and thus are able to perform a quench and temper heat treatment, only if we cool faster than 140°C/s. Other steels, such as the low-carbon steel have more complicated CCT diagrams. In various handbooks, you can find a compilation of TTT and CCT diagrams for different grades of steels.



 **Figure 4-5** The CCT diagram (solid lines) for a 1080 steel compared with the TTT diagram (dashed lines).

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 **Figure 4.6**The complete isothermal transformation diagram for an eutectoid composition: A, austenite; B, bainite; M, martensite; P, pearlite.

**Quench and Temper Heat Treatments**

Hardening is a process in which steel is heated to a temperature above the critical points, held at this temperature and quenched ( rapidly cooled) in suitable quenching medium such as water, oil, or molten salt bath. The structure result from this process is needle shape structure known as martensite.

Quenching hardens most steels and tempering increases the toughness. This has been known for perhaps thousands of years. For example, a series of such heat treatments has been used for making Damascus steel and Japanese Samurai swords. We can obtain an exceptionally fine dispersion of Fe3C and ferrite (known as tempered martensite) if we first quench the austenite to produce martensite and then temper. The tempering treatment controls the final properties of the steel (Figure 4-6). Note that this is different from a spheroidizing heat treatment.



 **Figure 4-7** The effect of temperingtemperature on the mechanicalproperties of a 1050 steel.

**Retained Austenite**

There is a large volume expansion when martensite forms from austenite. As the martensite plates form during quenching, they surround and isolate small pools of austenite which deform to accommodate the lower density martensite. As the transformation progresses, however, for the remaining pools of austenite to transform, the surrounding martensite must deform. Because the strong martensite resists the transformation, either the existing martensite cracks or the austenite remains trapped in the structure as **retained austenite**. Retained austenite can be a serious problem. Martensite softens and becomes more ductile during tempering. After tempering, the retained austenite cools below the *M*s and *M*f temperatures and transforms to martensite, since the surrounding **tempered** **martensite** can deform. But now the steel contains more of the hard, brittle martensite! .A second tempering step may be needed to eliminate the martensite formed from the retained austenite. Retained austenite is also more of a problem for high-carbon steels. The martensite start and finish temperatures are reduced when the carbon content increases . High-carbon steels must be refrigerated to produce all martensite.

**Residual Stresses and Cracking**

Residual stresses are also produced because of the volume change or because of cold working. A stress-relief anneal can be used to remove or minimize residual stresses due to cold working. Stresses are also induced because of thermal expansion and contraction. In steels, there is one more mechanism that causes stress. When steels are quenched, the surface of the quenched steel cools rapidly and transforms to martensite. When the austenite in the center later transforms, the hard surface is placed in tension, while the center is compressed. If the residual stresses exceed the yield strength, **quench cracks** form at the surface (Figure 4-8). To avoid this, we can first cool to just above the *M*s and hold until the temperature equalizes in the steel; subsequent quenching permits all of the steel to transform to martensite at about the same time.



**Figure 4-8** Formation of quench cracks caused by residual stresses produced during quenching. The figure illustrates the development of stresses as the austenite transforms to martensite during cooling.

**Tempering process**

Tempering of steel is a process in which previously hardened or normalized steel is heated to a temperature below the transformation range and cooled at suitable rate, primarily to increase ductility and toughness. Steels are tempered to obtain specific values of mechanical properties and to relieve quenching stresses and ensure dimensional stability. Tempering can be divided depending upon heating temperature to :

1) Low temperature tempering from 0oC to 200 oC

2) Medium temperature tempering from200oC to 400 oC

3) High temperature tempering from400oC to 650 oC

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 **Figure 4.9** Possibletransformationsinvolving thedecomposition ofaustenite

 **Table 4.1 Summary of Microstructures and Mechanical Properties for Iron–Carbon Alloys**

 **Table 10.2 Summary of Microstructures and Mechanical Properties for Iron–Carbon Alloys**30

Hardening and Tempering

Hardening is process in which steel is heated to a temperature above the

critical point, held at this temperature and quenched (rapidly cooled) in

water, oil or molten salt baths.

As earlier mentioned that if a piece of steel is heated above its upper

critical temperature and plunged into water to cool it an extremely hard,

needle-shaped structure known as martensite is formed. In other words,

sudden quenching of steel greatly increases its hardness.

After hardening steel must be tempered to