12-3 SIMPLE HEAT TREATMENTS

Four simple heat treatments are commonly used for steels. These heat treatments (Figure 12-4) are used to accomplish one of three purposes.

Process Anneal – Eliminating Cold Work. The ferrite in steels with less than 0.25% C is strengthened by cold working. The recrystallization heat treatment used to eliminate the effect of cold working is called a process anneal. The process anneal is done 80°C to 170°C below the A1 temperature.

Annealing and Normalizing – Controlling Dispersion Strengthening. Plain-carbon steels are dispersion strengthened by controlling the amount, size, shape, and distribution of Fe₃C. As the carbon increases, more Fe₃C is present and, up to a point, the strength of the steel increases.

We can refine the Fe₃C by controlling the cooling rate as the austenite transforms to pearlite. If we permit very slow cooling, the pearlite is coarse - this heat treatment is called annealing or a full anneal. Faster cooling produces fine pearlite - this heat treatment is normalizing.

1. Hypoeutectoid steels are annealed by heating the steel about 30°C above the A₃ temperature to produce homogeneous austenite. This is the austenitizing treatment. Then the steel is furnace cooled. By permitting both the furnace and the steel to cool together, slow cooling rates are produced. Because lots of time is available for diffusion, primary ferrite and pearlite are coarse and the steel has a low strength and good ductility.

2. Hypereutectoid steels are annealed by first heating to 30°C above the A₁. The steel is not heated above the Acm to produce all austenite because, on slow cooling, Fe₃C would form as a continuous film on the austenite grain boundaries and cause embrittlement. Austenitizing just above the A₁ permits the Fe₃C to become rounded. After austenitizing, the steel is furnace cooled to produce discontinuous Fe₃C and coarse pearlite.

3. Steels are normalized by heating to 55°C above either the A₃ or Acm, depending on the composition of the steel. After austenitizing, the steel is removed from the furnace and air cooled. Air cooling gives faster cooling rates and finer pearlite. The hypereutectoid steel
can be normalized above the $A_{cm}$ because, due to the faster cooling rate, the Fe$_3$C has less opportunity to form as a continuous film at the austenite grain boundaries. Figure 12-5 shows the typical properties obtained by annealing and normalizing.

![Graph showing properties of steel]

**Spheroidizing – Improving Machinability.** High-carbon steels, which contain a large amount of Fe$_3$C, have poor machining characteristics. During the spheroidizing treatment, which requires long times at about 30°C below the $A_1$, the Fe$_3$C changes into large, spherical particles in order to reduce boundary area. The microstructure, known as spheroidite, now has a continuous matrix of soft, machinable ferrite (Figure 12-6). After machining, the steel is given a more sophisticated heat treatment to produce the required properties. A similar structure would occur if martensite were tempered just below the $A_1$ for long times.

![Microstructure of spheroidite with Fe$_3$C particles dispersed in a ferrite matrix](x850)

Fig. 12-6: The microstructure of spheroidite with Fe$_3$C particles dispersed in a ferrite matrix (x850). From Metals Handbook, Vol. 7, 8th Ed. American Society for Metals.
Example 12-4

Recommend temperatures for the process annealing, annealing, normalizing, and spheroidizing of 1020, 1080, and 10120 steels.

**Answer:**

If we consult Figure 12-2, we can determine the critical $A_1$, $A_3$, or $A_{cm}$ temperatures for each steel. We can then specify the heat treatment based on these temperatures.

<table>
<thead>
<tr>
<th>Process</th>
<th>1020</th>
<th>1080</th>
<th>10120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical</td>
<td>$A_1 = 723^\circ C$</td>
<td>$A_1 = 723^\circ C$</td>
<td>$A_1 = 723^\circ C$</td>
</tr>
<tr>
<td>temperatures</td>
<td>$A_1 = 830^\circ C$</td>
<td>$A_1 = 830^\circ C$</td>
<td>$A_{cm} = 895^\circ C$</td>
</tr>
<tr>
<td>annealing</td>
<td>723 – (80 to 170) =</td>
<td>Not done</td>
<td>Not done</td>
</tr>
<tr>
<td></td>
<td>553$^\circ C$ to 643$^\circ C$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annealing</td>
<td>830 + 30 =</td>
<td>723 + 30 =</td>
<td>723 + 30 =</td>
</tr>
<tr>
<td></td>
<td>860$^\circ C$</td>
<td>753$^\circ C$</td>
<td>753$^\circ C$</td>
</tr>
<tr>
<td>Normalizing</td>
<td>830 + 55 =</td>
<td>723 + 55 =</td>
<td>895 + 55 =</td>
</tr>
<tr>
<td></td>
<td>885$^\circ C$</td>
<td>778$^\circ C$</td>
<td>950$^\circ C$</td>
</tr>
<tr>
<td>Spheroidizing</td>
<td>Not done</td>
<td>727 – 30 =</td>
<td>723 – 30 =</td>
</tr>
<tr>
<td></td>
<td>693$^\circ C$</td>
<td>693$^\circ C$</td>
<td></td>
</tr>
</tbody>
</table>

**11-10 CONTROLLING EUTECTOID REACTION BY CONTROLLING THE TRANSFORMATION TEMPERATURE**

The solid-state eutectoid reaction is rather slow and the steel may cool below the equilibrium eutectoid temperature before the transformation begins. The transformation temperature affects the fineness of the structure (Figure 11-19), the time required for transformation, and even the arrangement of the two phases. This information is contained in the time-temperature-transformation (TTT) diagram (Figure 11-20). This diagram, also called the isothermal transformation (I-T) diagram or the C-curve, permits us to predict the structure, properties, and heat treatment required in steels.

**Fig. 11-19:** The effect of the austenite transformation temperature on the interlamellar spacing in pearlite.
(a) The Fe-Fe₃C phase diagram. (b) An expanded version of the Fe₃C diagram showing only the eutectoid portion of the diagram at temperatures above 700°C.

<table>
<thead>
<tr>
<th>AISI-SAE Number</th>
<th>% C</th>
<th>% Mn</th>
<th>% Si</th>
<th>% Ni</th>
<th>% Cr</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>1020</td>
<td>0.18-0.23</td>
<td>0.30-0.60</td>
<td>0.95-1.00</td>
<td>0.15-0.30</td>
<td>0.80-1.10</td>
<td>0.15-0.25% Mo</td>
</tr>
<tr>
<td>1040</td>
<td>0.37-0.44</td>
<td>0.60-0.90</td>
<td>0.75-1.00</td>
<td>0.15-0.30</td>
<td>0.70-0.90</td>
<td>0.15-0.25% Y</td>
</tr>
<tr>
<td>1080</td>
<td>0.37-0.44</td>
<td>0.60-0.90</td>
<td>0.75-1.00</td>
<td>0.15-0.30</td>
<td>0.70-0.90</td>
<td>0.15-0.25% Mo</td>
</tr>
<tr>
<td>1095</td>
<td>0.90-1.03</td>
<td>0.30-0.50</td>
<td>0.75-1.00</td>
<td>0.15-0.30</td>
<td>0.70-0.90</td>
<td>0.15-0.25% Mo</td>
</tr>
<tr>
<td>1150</td>
<td>0.37-0.44</td>
<td>0.70-1.00</td>
<td>0.15-0.30</td>
<td>0.80-1.10</td>
<td>0.15-0.25% Mo</td>
<td></td>
</tr>
<tr>
<td>4140</td>
<td>0.38-0.43</td>
<td>0.75-1.00</td>
<td>0.15-0.30</td>
<td>0.80-1.10</td>
<td>0.15-0.25% Mo</td>
<td></td>
</tr>
<tr>
<td>4340</td>
<td>0.38-0.43</td>
<td>0.60-0.80</td>
<td>0.15-0.30</td>
<td>1.65-2.00</td>
<td>0.70-0.90</td>
<td>0.15-0.25% Y</td>
</tr>
<tr>
<td>4620</td>
<td>0.17-0.22</td>
<td>0.45-0.65</td>
<td>0.15-0.30</td>
<td>1.65-2.00</td>
<td>0.70-0.90</td>
<td>0.15-0.25% Y</td>
</tr>
<tr>
<td>52100</td>
<td>0.98-1.10</td>
<td>0.25-0.45</td>
<td>0.15-0.30</td>
<td>1.30-1.60</td>
<td>0.20-0.30% Mo</td>
<td></td>
</tr>
<tr>
<td>8620</td>
<td>0.18-0.23</td>
<td>0.70-0.90</td>
<td>0.15-0.30</td>
<td>0.40-0.70</td>
<td>0.40-0.60</td>
<td>0.15-0.25% Y</td>
</tr>
<tr>
<td>9260</td>
<td>0.56-0.64</td>
<td>0.75-1.00</td>
<td>1.80-2.20</td>
<td>0.80-1.10</td>
<td>0.15-0.25% Y</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 11-20: The time-temperature-transformation (TTT) diagram for a eutectoid steel.

1. **Nucleation and growth of pearlite.** If we quench to just below the eutectoid temperature, the austenite is only slightly undercooled. Long times are required before stable nuclei for ferrite and cementite form; nucleation does not begin until near the pearlite start (Ps) time. After pearlite begins to grow, atoms diffuse rapidly and coarse pearlite is produced; the transformation is complete at the pearlite finish (Pf) time.

Austenite quenched to a lower temperature is more highly undercooled. Consequently, nucleation occurs more rapidly and the Ps is shorter. However, diffusion is also slower, so atoms diffuse only short distances and a finer pearlite is produced. Even though growth rates are slower, the overall time required for the transformation is reduced because of faster nucleation. Finer pearlite forms in shorter times as we reduce the isothermal transformation temperature to about 550°C, which is the nose or knee of the TTT curve (Figure 11-20).

**Example 11-14**

Describe the complete heat treatment and the microstructure after each step required to isothermally produce a hardness of R, 32 in a eutectoid steel.

**Answer:**

Note that Rockwell C hardnesses are shown as a function of transformation temperature in the IT diagram (Figure 11-20). A hardness of RC 32 is obtained by transforming at 650 °C, where the Ps time is 5 s and the Pf time is 50 s. The heat treatment and microstructures are as follows:

1. Austenitize above 723°C and hold for about 1 h. The steel contains 100% austenite.
2. Quench to 650°C and hold for at least 50 s. After 5 s, pearlite nucleates from the unstable austenite. Pearlite grows until, after 50 s, the microstructure contains 100% pearlite. The pearlite has a medium fineness. (Note that we returned to time zero when we quenched!)
3. Cool in air to room temperature. The microstructure remains all pearlite.
2. **Nucleation and growth of bainite.** At a temperature just below the nose of the TTT diagram, nucleation occurs rapidly but diffusion is slow. No transformation is detected until somewhat longer times, and total transformation times increase due to very slow growth.

In addition, we find a different microstructure. At low transformation temperatures, the lamellae in pearlite would have to be extremely thin and consequently the boundary area between the ferrite and Fe₃C lamellae would be very large. Because of the energy associated with the ferrite-cementite interface, the total energy of the steel would have to be very high. The steel can reduce its internal energy by permitting the cementite to precipitate as discrete, rounded particles in a ferrite matrix. This new microconstituent, or arrangement of ferrite and cementite, is called bainite. Transformation begins at a bainite start (Bₙ) time and ends at a bainite finish (Bₕ) time.

---

**Example 11-15**

Excellent combinations of hardness, strength, and toughness are obtained from bainite. One heat treater austenitized a eutectoid steel at 750°C, quenched and held the steel at 250°C for 15 min, and finally permitted the steel to cool to room temperature. Did he produce the required bainitic structure?

**Answer:**

Let’s examine the heat treatment using Figure 11-20. After heating at 750°C, the microstructure is 100% γ. After quenching to 250°C, unstable austenite remains for slightly more than 100 s, when fine bainite begins to grow. After 15 min, or 900 s, about 50% fine bainite has formed and the remainder of the steel still contains unstable austenite. As we will see later, the unstable austenite transforms to martensite when the steel is cooled to room temperature and the final structure is a mixture of bainite and hard, brittle martensite. The heat treatment was not successful. The heat treater should have held the steel at 250°C for at least 10⁴ s, or about 3 h.

---

The times required for austenite to begin and finish its transformation to bainite increase and the bainite becomes finer as the transformation temperature continues to decrease. The bainite that forms just below the nose of the curve is called coarse bainite, upper bainite, or feathery bainite. The bainite that forms at lower temperatures is called fine bainite, lower bainite, or acicular bainite.

Figure 11-21 shows typical microstructures of bainite. Figure 11-22 shows the effect of transformation temperature on the properties of a eutectoid steel. As the temperature decreases, there is a general trend towards higher strength and lower ductility due to the finer microstructure that is produced.

---

![Fig. 11-21: (a) Upper bainite (grey, feathery plates) (x600). (b) Lower bainite (dark needles) (x400). From Metals Handbook, Vol. 8, 8th Ed., American Society for Metals, 1973.](image-url)
12-4 ISOThermal HEAT tREATMENTS AND DISPERSION STRENGTHEnING

The effect of transformation temperature on the properties of a 1080 (eutectoid) steel was discussed in Chapter 11. As the isothermal transformation temperature decreases, pearlite become progressively finer before bainite begins to form instead. At very low temperatures, martensite is obtained. As the microstructure of a 1080 steel becomes finer, better dispersion strengthening is obtained. Also, the fine, rounded microstructure of bainite produces higher strengths and hardnesses than pearlitic structures while maintaining usable ductility and toughness.

Austempering and Isothermal Annealing. The isothermal transformation heat treatment used to produce bainite is called austempering, and simply involves austenitizing the steel, quenching to some temperature below the nose of the TTT curve, and holding at that temperature until all of the austenite transforms to bainite (Figure 12-7).

Annealing and normalizing are usually used to control the fineness of pearlite. However, pearlite formed by an isothermal anneal (Figure 12-7) may give more uniform properties, since the cooling rates and microstructure obtained during annealing and normalizing vary across the cross section of the steel.

Isothermal Transformations in Hypoeutectoid and Hypereutectoid Steels. In either a hypoeutectoid or a hypereutectoid steel, the TTT diagram must reflect the possible formation of a primary phase. The isothermal transformation diagrams for a 1050 and a 10110 steel are shown in Figure 12-8. The most remarkable change is the presence of a “wing” which begins at the nose of the curve and becomes 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 at a temperature between the \( A_1 \) and the \( A_3 \), primary ferrite nucleates and grows; eventually an equilibrium amount of ferrite and austenite result. Similarly, primary cementite will nucleate and grow 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 below the nose of the curve, only bainite forms, regardless of the carbon content of the steel. Bainite, unlike pearlite, does not have a fixed composition.
Fig. 12-8: The TTT diagrams for (a) a 1050 steel and (b) a 10110 steel.
Example 12-5

A 1050 steel is isothermally heat treated to give a hardness of RC 23. Describe the heat treatment and the amount of each microconstituent after each step of the heat treatment.

Answer:

From Figure 12-2, the $A_3$ temperature is 755°C. The desired hardness is obtained by transforming the steel at 590°C, where $F_s = 0.9$, $P_s = 1.1$, and $P_i = 5$.

1. Austenitize at $755 + (30$ to $55) = 785°C$ to $810°C$ and hold for perhaps 1 h. The microstructure is 100% $\gamma$.

2. Quench and hold at 590°C for at least 5 s. Primary ferrite begins to precipitate from the unstable austenite after about 0.9 s. After 1.1 s pearlite begins to grow, and the austenite is completely transformed to ferrite and pearlite after 5 s. From the lever law

$$\text{Primary } \alpha = (0.80-0.50)/(0.80-0.035) \times 100 = 39 \%$$

$$\text{Pearlite} = (0.50-0.035) / (0.80-0.035) \times 100 = 61 \%$$

3. Cool in air to room temperature. The structure will still contain the equilibrium amounts of primary ferrite and pearlite.

Interrupting the Isothermal Transformation. Complicated microstructures are produced by interrupting the isothermal heat treatment. For example, we could austenitize the 1050 steel (Figure 12-9) at 800°C, quench to 650°C and hold for 10 s (permitting some ferrite and pearlite to form), then quench to 350°C and hold for 1 h (3600 s). Whatever unstable austenite remained before quenching to 350°C transforms to bainite. The final structure is ferrite, pearlite, and bainite.

We could complicate the treatment further by interrupting the treatment at 350°C after 1 min (60 s) and quenching. Any austenite remaining after 1 min at 350°C forms martensite. The final structure now contains ferrite, pearlite, bainite, and martensite. Note that each time we change the temperature we start at zero time!

![Diagram](image_url) Fig. 12-9: Producing complicated structures by interrupting the isothermal heat treatment of a 1050 steel.
Figure 12-10 shows the structure obtained by interrupting the transformation to bainite of a 0.5% C steel by quenching the remaining austenite to martensite.

Because such complicated mixtures of microconstituents produce unpredictable properties, these structures are seldom produced intentionally.

---

**Example: 12-6**

A 1050 steel is held at 800 °C for 1 h, quenched to 700 °C and held for 50 s, quenched to 400 °C and held for 20 s, and finally quenched to room temperature. What is the final microstructure of the steel? Use the TTT diagram (Figure 12-8) for a 1050 steel.

**Answer:**

1. After 1 h at 800 °C, 100% austenite forms.
2. Ferrite begins to form after 20 s at 700 °C but, after 50 s, the steel contains only ferrite and unstable austenite.
3. Immediately after quenching to 400 °C, the steel is still only ferrite and austenite. Bainite begins to form after 3 s and, after 20 s, the steel contains ferrite, bainite, and still some unstable austenite.
4. After quenching to room temperature, the remaining austenite crosses the $M_s$ and $M_f$ temperatures and transforms to martensite. The final structure is ferrite, bainite and martensite.
12-5 QUENCH AND TEMPER HEAT TREATMENT

We can obtain an even finer dispersion of Fe₃C if we first quench the austenite to produce martensite, then temper. During tempering an intimate mixture of ferrite and cementite forms from the martensite, as discussed in Chapter 11. By controlling the quench and temper heat treatment, we also control the final properties of the steel (Figure 12-11). Several factors affect the martensite reaction and the execution of the quench and temper heat treatment in plain carbon steels.

Fig. 12-11: The effect of tempering temperature on the mechanical properties of a 1050 steel.

Example 12-7

Select a quench and temper heat treatment that will produce a yield strength of 1000 MPa and an elongation greater than 15% in a 1050 steel.

Answer:

From Figure 12-11, we find that the yield strength exceeds 1000 MPa if the steel is tempered below 460°C, while the elongation exceeds 15% if tempering is done above 425°C. One possible heat treatment is as follows.

1. Austenitize above the A₃ temperature of 755°C for 1 h. An appropriate temperature may be 755 + 55 = 810°C.

2. Quench rapidly to room temperature. Since the M₁ is about 250°C, martensite will form.

3. Temper by heating the steel to 440°C. Normally, 1 h will be sufficient if the steel is not too thick.

4. Cool to room temperature.
Effect of Carbon on the $M_s$ and $M_f$. The martensite start and finish temperatures are reduced when the carbon content increases (Figure 12-12). High carbon steels must be refrigerated to produce all martensite.

Retained Austenite. As the martensite plates form during quenching, they surround and isolate small pools of austenite (Figure 12-13). For the remaining austenite to transform, the surrounding martensite must deform, but 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 hard, brittle martensite! A second tempering step may be needed to eliminate the martensite formed from the retained austenite.
**Residual Stresses and Cracking.** Residual stresses are also produced because of the volume change. The hard surface is placed in tension, while the centre is compressed. If the residual stresses are high enough, quench cracks form at the surface (Figure 12-14). However, if we first cool to just above the $M_s$ and hold until the temperature equalizes through the steel, subsequent quenching permits all of the steel to transform to martensite at about the same time. This heat treatment is called marquenching or martempering (Figure 12-15).

**Quench Rate.** In the TTT diagram, we assumed that we could cool from the austenitizing temperature to the transformation temperature instantly. Because this is not true, undesired microconstituents may form during quenching. For example, pearlite may form as the steel cools past the nose of the curve, particularly since the time of the nose is less than one second in plain-carbon steels.

---

![Fig. 12-14: Formation of quench cracks due to residual stresses produced during quenching. The figure illustrates the development of stresses as the austenite transforms to martensite during cooling.](image)

![Fig. 12-15: The marquenching heat treatment, designed to reduce residual stresses and quench cracking.](image)
The rate at which the steel cools during quenching depends on two primary factors. First, the surface always cools faster than the centre of the steel. In addition, as the size of the part increases, the cooling rate at any location is slower. Second, the cooling rate depends on the temperature and heat transfer characteristics of the quenching medium (Table 12-2). Quenching in oil, for example, produces a lower H coefficient, or slower cooling rate, than quenching in water or brine.

Continuous Cooling Transformation Diagrams. We can develop a continuous cooling transformation (CCT) diagram by determining the microstructures produced in a steel at various rates of cooling. The CCT curve for a 1080 steel is shown in Figure 12-16. The CCT diagram differs from the TTT diagram (Figure 11-20) in that transformations begin at slightly longer times and no bainite region is observed.

Table 12-2: The H coefficient, or severity of the quench, for several quenching media (From The Making, Shaping, and Treating Steels, 9th Ed., United States Steels, 1971)

<table>
<thead>
<tr>
<th>Medium</th>
<th>H Coefficient</th>
<th>Cooling Rate in 25 mm Bar (°C/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil (no agitation)</td>
<td>0.25–0.30</td>
<td>16–20</td>
</tr>
<tr>
<td>Oil (violent agitation)</td>
<td>0.80–1.10</td>
<td>40–50</td>
</tr>
<tr>
<td>H₂O (no agitation)</td>
<td>0.90–1.00</td>
<td>44–47</td>
</tr>
<tr>
<td>H₂O (violent agitation)</td>
<td>4.0</td>
<td>190</td>
</tr>
<tr>
<td>Brine (no agitation)</td>
<td>2.0</td>
<td>90</td>
</tr>
<tr>
<td>Brine (violent agitation)</td>
<td>5.0</td>
<td>250</td>
</tr>
</tbody>
</table>

Fig. 12-16: The CCT diagram (solid lines) for a 1080 steel compared with the TTT diagram (dashed lines).
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, or 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 have more complicated CCT diagrams. Figure 12-17 shows the CCT diagram for a slightly alloyed 1020 steel. Cooling rates between 10°C/s and 20°C/s give a combination of ferrite, pearlite, bainite, and martensite.

![CCT diagram for a slightly alloyed 1020 steel.](image)

**Problem 12-8:**

A slightly alloyed 1020 steel cools at 8°C/s when quenched in oil and at 50°C/s when quenched in water. What microstructure is produced by each of the heat treatments?

**Answer:**

From Figure 12-17, an 8°C/s cooling curve crosses the Fs, Ps, Bs and Bt lines. The structure is ferrite, pearlite and bainite.

At 50°C/s, the cooling curve crosses the Fs, Bs and Ms lines. The structure is ferrite, bainite, and martensite. There may also be a small amount of retained austenite.