10.13 *In terms of heat treatment and the development of microstructure, what are two major limitations of the iron–iron carbide phase diagram?*

Solution

Two limitations of the iron-iron carbide phase diagram are:

(1) The nonequilibrium martensite does not appear on the diagram; and

(2) The diagram provides no indication as to the time-temperature relationships for the formation of pearlite, bainite, and spheroidite, all of which are composed of the equilibrium ferrite and cementite phases.

10.15 *Suppose that a steel of eutectoid composition is cooled to 550°C (1020°F) from 760°C (1400°F) in less than 0.5 s and held at this temperature.*

(a) How long will it take for the austenite-to-pearlite reaction to go to 50% completion? To 100% completion?

(b) Estimate the hardness of the alloy that has completely transformed to pearlite.

Solution

We are called upon to consider the isothermal transformation of an iron-carbon alloy of eutectoid composition.

(a) From Figure 10.22, a horizontal line at 550°C intersects the 50% and reaction completion curves at about 2.5 and 6 seconds, respectively; these are the times asked for in the problem statement.

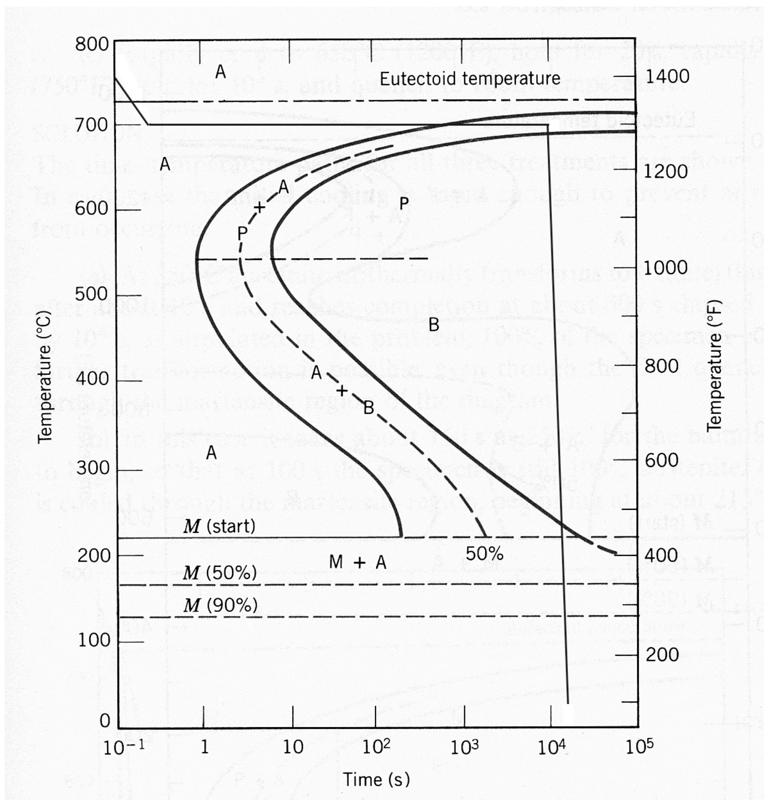
(b) The pearlite formed will be fine pearlite. From Figure 10.30*a*, the hardness of an alloy of composition 0.76 wt% C that consists of fine pearlite is about 265 HB (27 HRC).

10.18 *Using the isothermal transformation diagram for an iron–carbon alloy of eutectoid composition (Figure 10.22), specify the nature of the final microstructure (in terms of microconstituents present and approximate percentages of each) of a small specimen that has been subjected to the following time–temperature treatments. In each case assume that the specimen begins at 760°C (1400°F) and that it has been held at this temperature long enough to have achieved a complete and homogeneous austenitic structure.*

(a) Cool rapidly to 700°C (1290°F), hold for 10^4 s, then quench to room temperature.

Solution

Below is Figure 10.22 upon which is superimposed the above heat treatment.



After cooling and holding at 700°C for 10^4 s, approximately 50% of the specimen has transformed to coarse pearlite. Upon cooling to room temperature, the remaining 50% transforms to martensite. Hence, the final microstructure consists of about 50% coarse pearlite and 50% martensite.

(b) Reheat the specimen in part (a) to 700°C (1290°F) for 20 h.

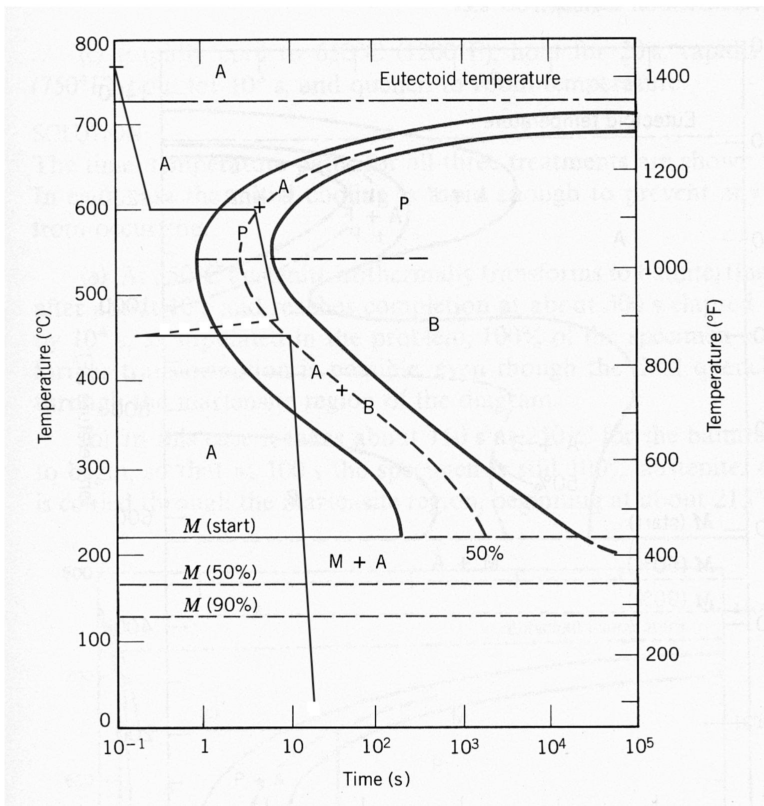
Solution

Heating to 700°C for 20 h the specimen in part (a) will transform the coarse pearlite and martensite to spheroidite.

(c) Rapidly cool to 600°C (1110°F), hold for 4 s, rapidly cool to 450°C (840°F), hold for 10 s, then quench to room temperature.

Solution

Below is Figure 10.22 upon which is superimposed the above heat treatment.

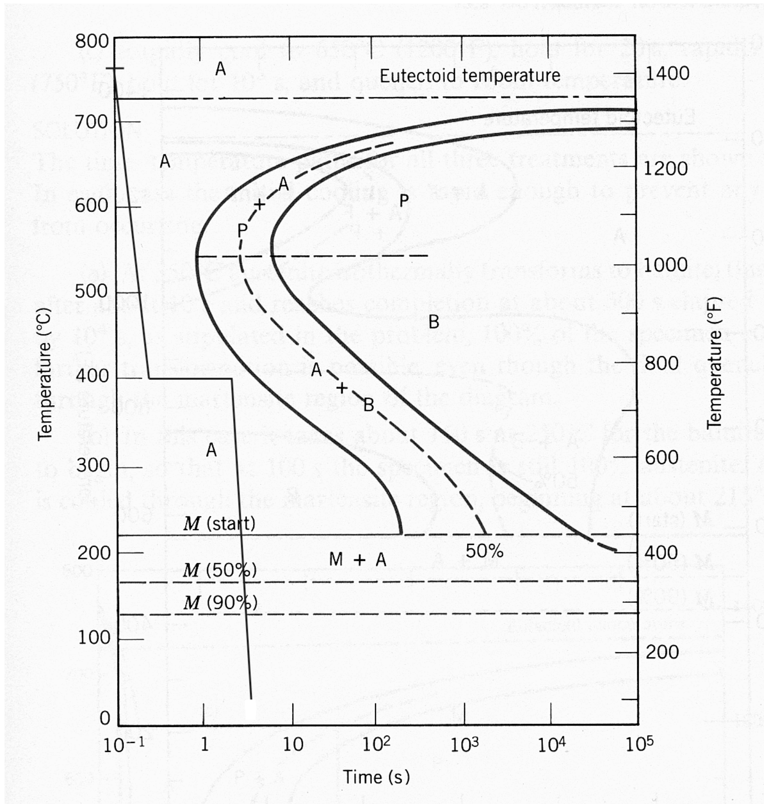


After cooling to and holding at 600°C for 4 s, approximately 50% of the specimen has transformed to pearlite (medium). During the rapid cooling to 450°C no transformations occur. At 450°C we start timing again at zero time; while holding at 450°C for 10 s, approximately 50 percent of the remaining unreacted 50% (or 25% of the original specimen) will transform to bainite. And upon cooling to room temperature, the remaining 25% of the original specimen transforms to martensite. Hence, the final microstructure consists of about 50% pearlite (medium), 25% bainite, and 25% martensite.

(d) Cool rapidly to 400°C (750°F), hold for 2 s, then quench to room temperature.

Solution

Below is Figure 10.22 upon which is superimposed the above heat treatment.

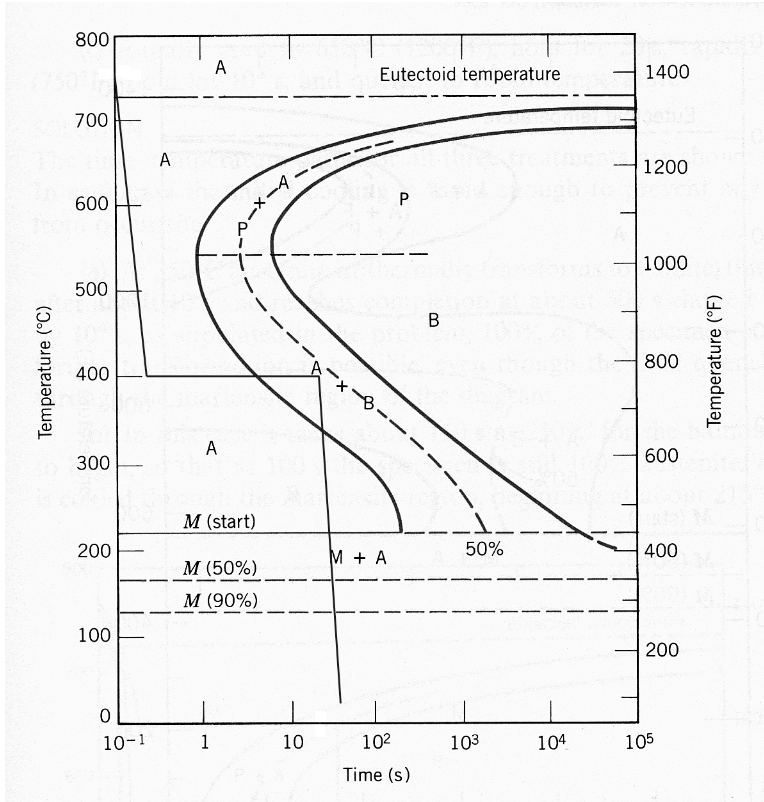


After cooling to and holding at 400°C for 2 s, no of the transformation begin lines have been crossed, and therefore, the specimen is 100% austenite. Upon cooling rapidly to room temperature, all of the specimen transforms to martensite, such that the final microstructure is 100% martensite.

(e) Cool rapidly to 400°C (750°F), hold for 20 s, then quench to room temperature.

Solution

Below is Figure 10.22 upon which is superimposed the above heat treatment.

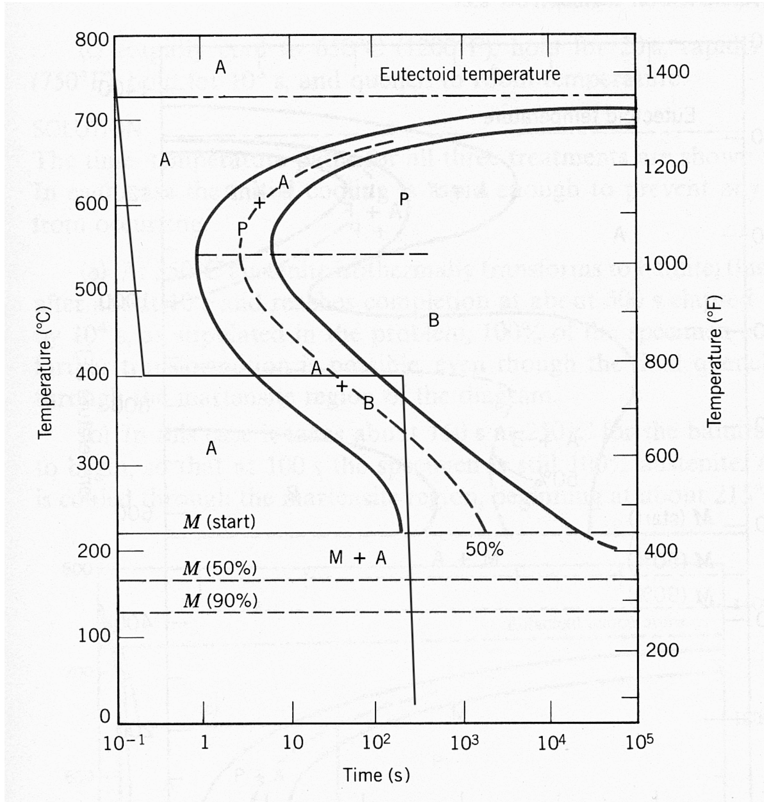


After cooling and holding at 400°C for 20 s, approximately 40% of the specimen has transformed to bainite. Upon cooling to room temperature, the remaining 60% transforms to martensite. Hence, the final microstructure consists of about 40% bainite and 60% martensite.

(f) Cool rapidly to 400°C (750°F), hold for 200 s, then quench to room temperature.

Solution

Below is Figure 10.22 upon which is superimposed the above heat treatment.

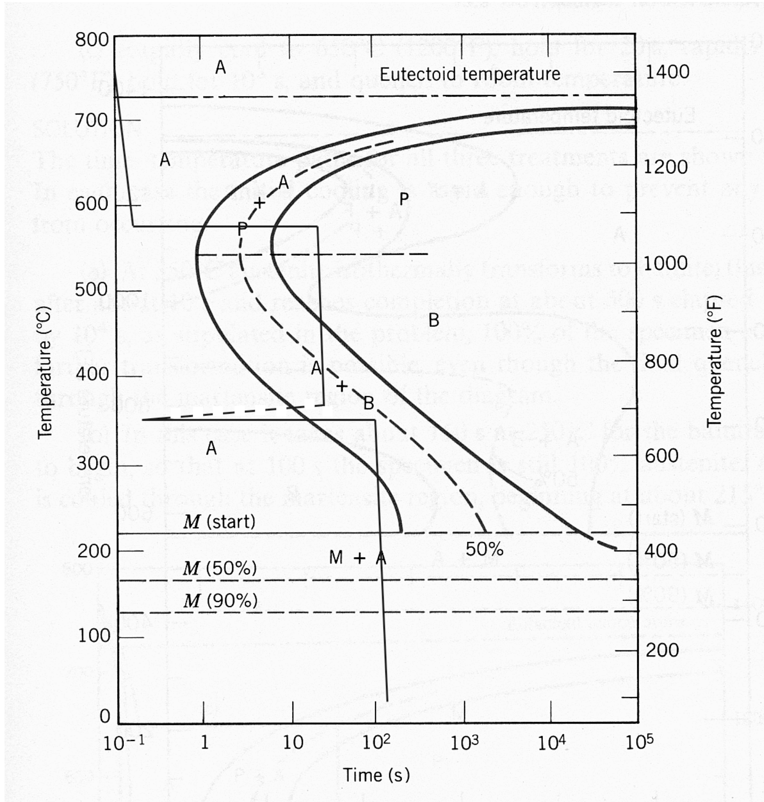


After cooling and holding at 400°C for 200 s, the entire specimen has transformed to bainite. Therefore, during the cooling to room temperature no additional transformations will occur. Hence, the final microstructure consists of 100% bainite.

(g) Rapidly cool to 575°C (1065°F), hold for 20 s, rapidly cool to 350°C (660°F), hold for 100 s, then quench to room temperature.

Solution

Below is Figure 10.22 upon which is superimposed the above heat treatment.

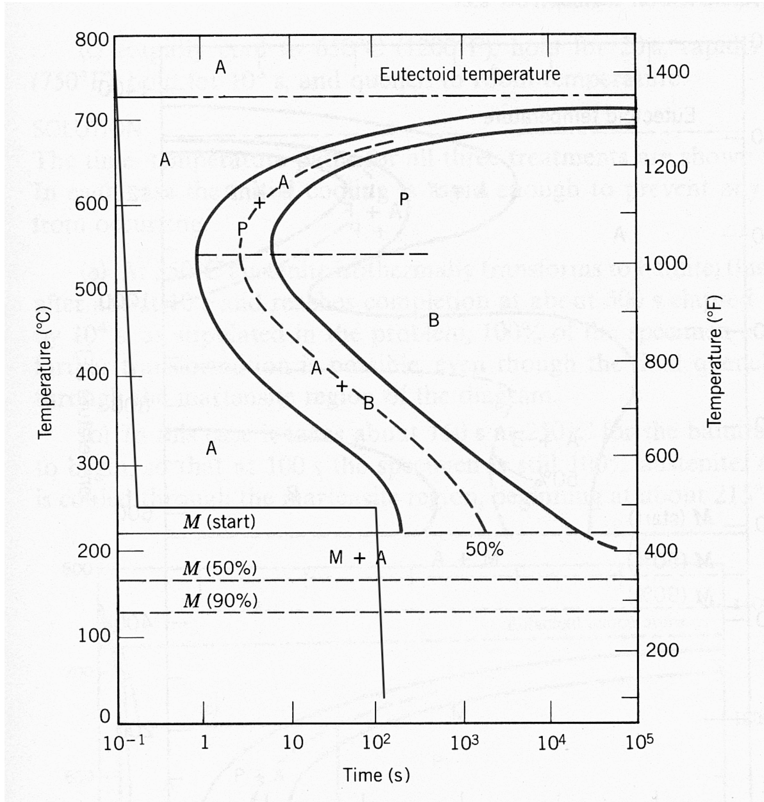


After cooling and holding at 575°C for 20 s, the entire specimen has transformed to fine pearlite. Therefore, during the second heat treatment at 350°C no additional transformations will occur. Hence, the final microstructure consists of 100% fine pearlite.

(h) Rapidly cool to 250°C (480°F), hold for 100 s, then quench to room temperature in water. Reheat to 315°C (600°F) for 1 h and slowly cool to room temperature.

<u>Solution</u>

Below is Figure 10.22 upon which is superimposed the above heat treatment.



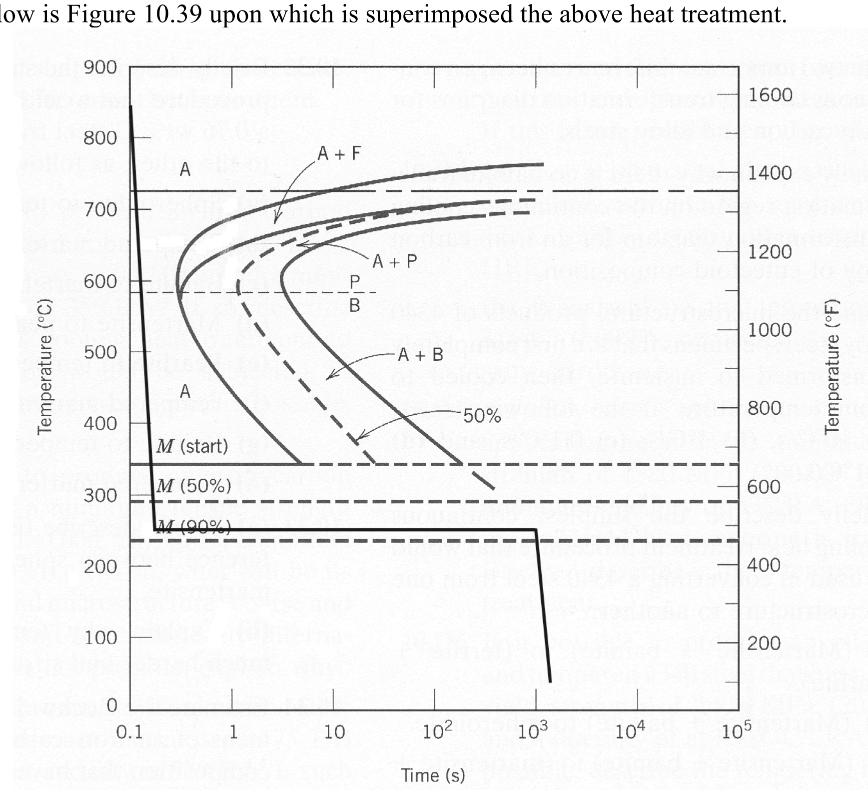
After cooling and holding at 250°C for 100 s, no transformations will have occurred—at this point, the entire specimen is still austenite. Upon rapidly cooling to room temperature in water, the specimen will completely transform to martensite. The second heat treatment (at 315°C for 1 h)—not shown on the above plot—will transform the material to tempered martensite. Hence, the final microstructure is 100% tempered martensite.

10.20 *Using the isothermal transformation diagram for a 0.45 wt% C steel alloy (Figure 10.39), determine the final microstructure (in terms of just the microconstituents present) of a small specimen that has been subjected to the following time-temperature treatments. In each case assume that the specimen begins at 845°C (1550°F), and that it has been held at this temperature long enough to have achieved a complete and homogeneous austenitic structure.*

(a) Rapidly cool to 250°C (480°F), hold for 10^3 s, then quench to room temperature.

Solution

Below is Figure 10.39 upon which is superimposed the above heat treatment.

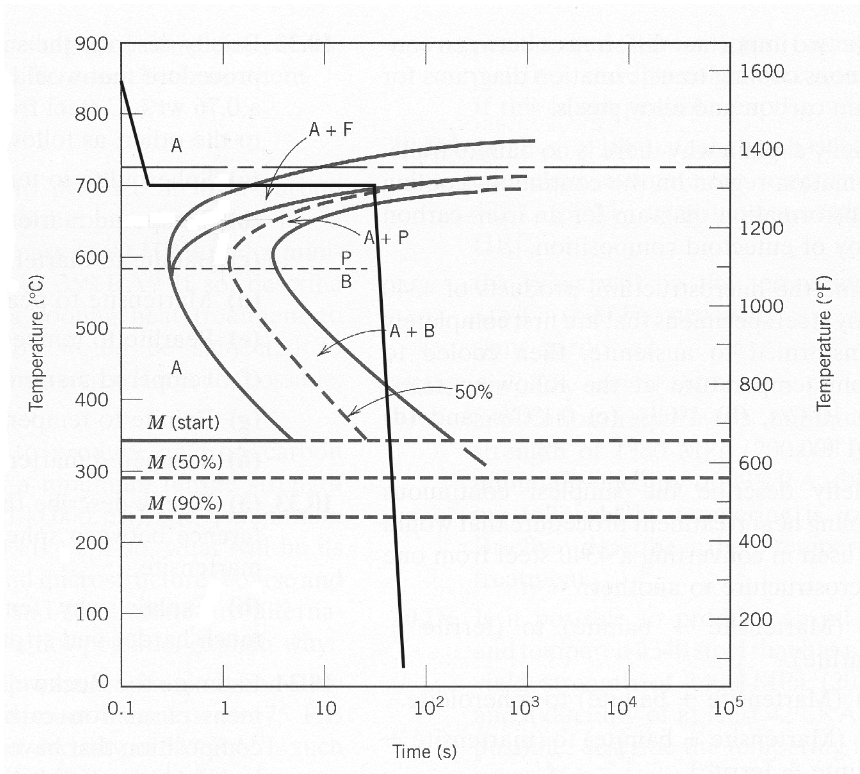


While rapidly cooling to 250°C about 80% of the specimen transforms to martensite; during the 1000 s isothermal treatment at 250°C no additional transformations occur. During the final cooling to room temperature, the untransformed austenite also transforms to martensite. Hence, the final microstructure consists of 100% martensite.

(b) Rapidly cool to 700°C (1290°F), hold for 30 s, then quench to room temperature.

Solution

Below is Figure 10.39 upon which is superimposed the above heat treatment.

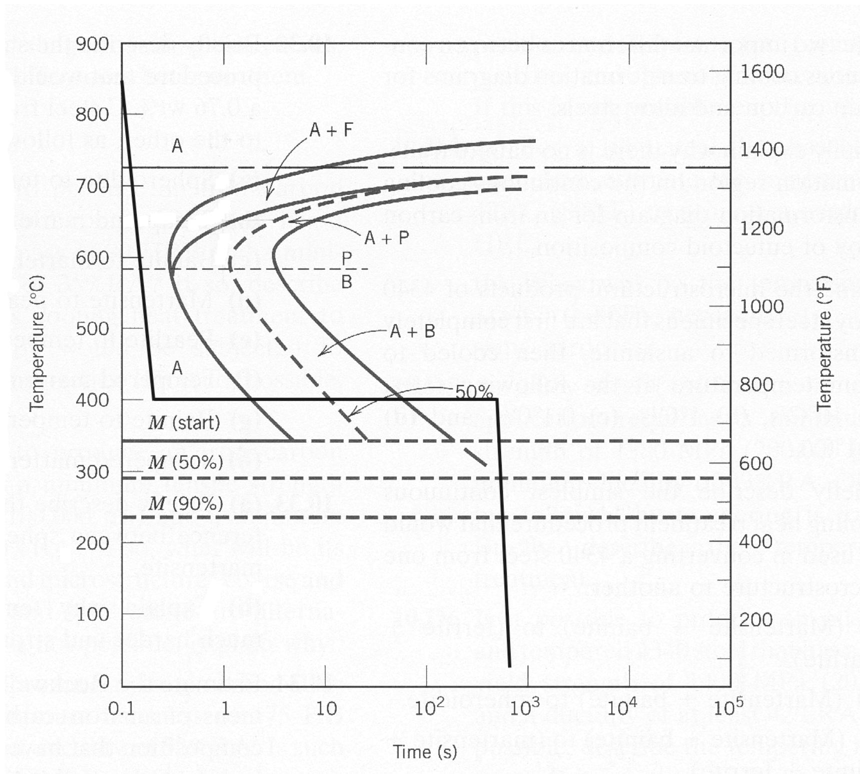


After cooling to and holding at 700°C for 30 s, a portion of specimen has transformed to proeutectoid ferrite. While cooling to room temperature, the remainder of the specimen transforms to martensite. Hence, the final microstructure consists proeutectoid ferrite and martensite.

(c) Rapidly cool to 400°C (750°F), hold for 500 s, then quench to room temperature.

<u>Solution</u>

Below is Figure 10.39 upon which is superimposed the above heat treatment.

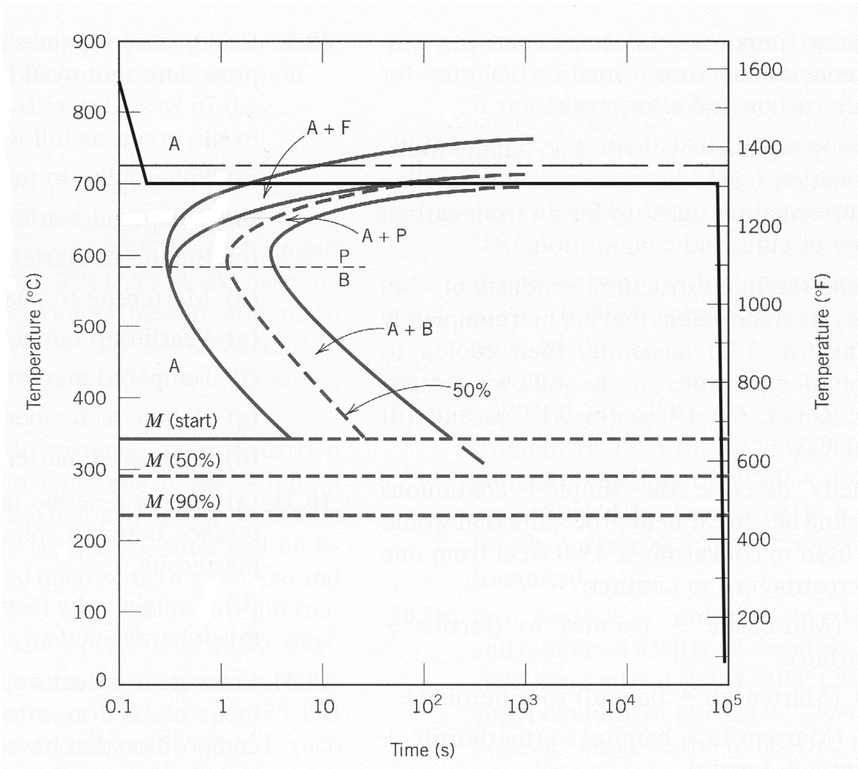


After cooling to and holding at 400°C for 500 s, all of the specimen has transformed to bainite. Hence, the final microstructure consists of 100% bainite.

(d) Rapidly cool to 700°C (1290°F), hold at this temperature for 10^5 s, then quench to room temperature.

<u>Solution</u>

Below is Figure 10.39 upon which is superimposed the above heat treatment.

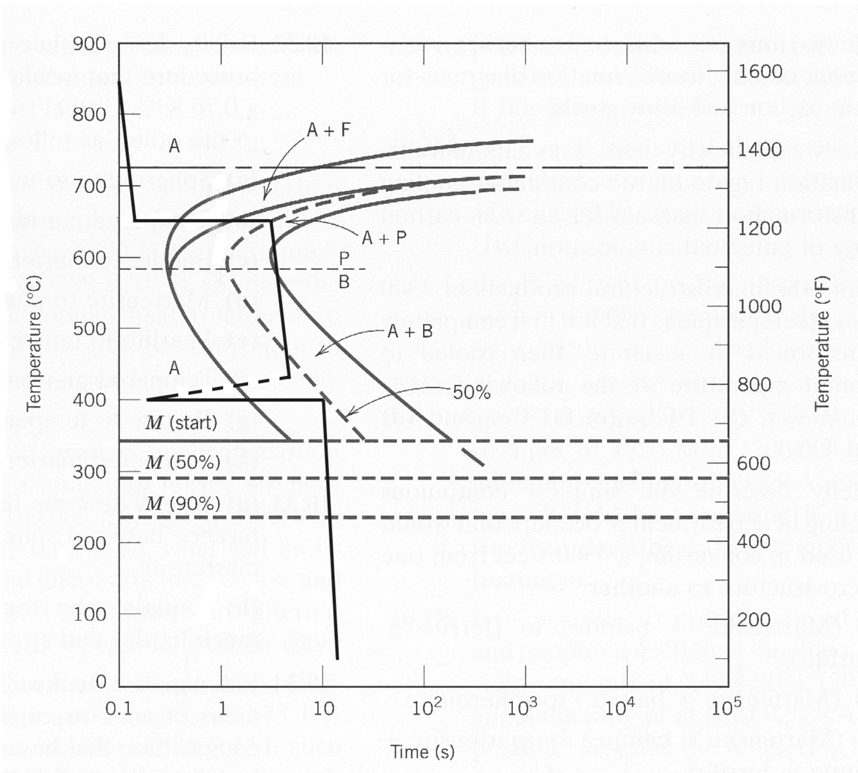


After cooling to and while holding at 700°C the specimen first transforms to proeutectoid ferrite and coarse pearlite. Continued heat treating at 700°C for 10^5 s results in a further transformation into spheroidite. Hence, the final microstructure consists of 100% spheroidite.

(e) Rapidly cool to 650°C (1200°F), hold at this temperature for 3 s, rapidly cool to 400°C (750°F), hold for 10 s, then quench to room temperature.

Solution

Below is Figure 10.39 upon which is superimposed the above heat treatment.

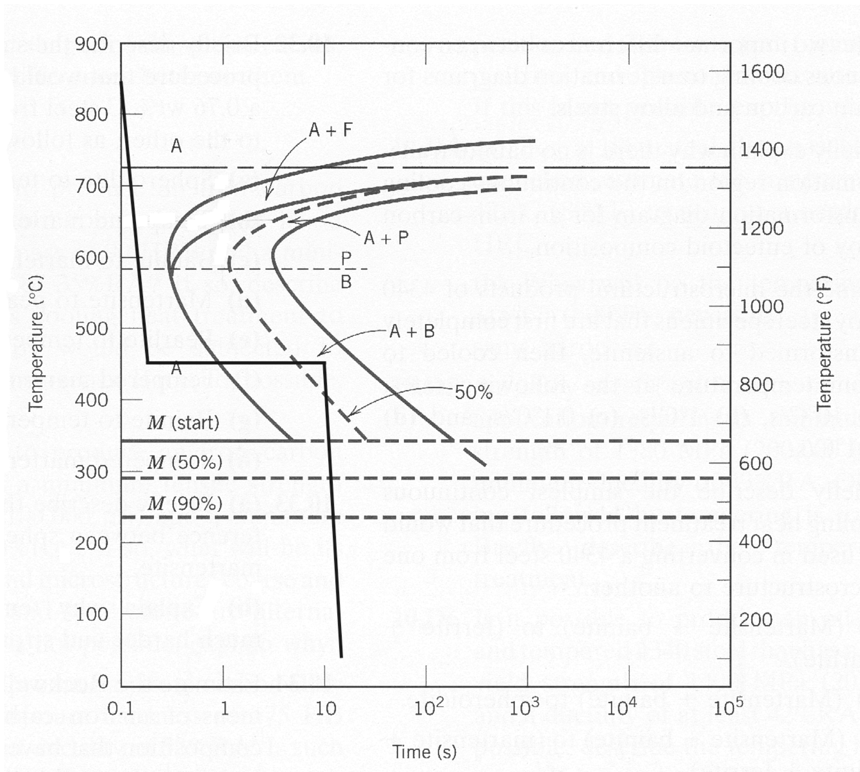


After cooling to and holding at 650°C for 3 s, some of the specimen first transformers to proeutectoid ferrite and then to pearlite (medium). During the second stage of the heat treatment at 400°C, some (but not all) of the remaining unreacted austenite transforms to bainite. As a result of the final quenching, all of the remaining austenite transforms to martensite. Hence, the final microstructure consists of ferrite, pearlite (medium), bainite, and martensite.

(f) Rapidly cool to 450°C (840°F), hold for 10 s, then quench to room temperature.

<u>Solution</u>

Below is Figure 10.39 upon which is superimposed the above heat treatment.

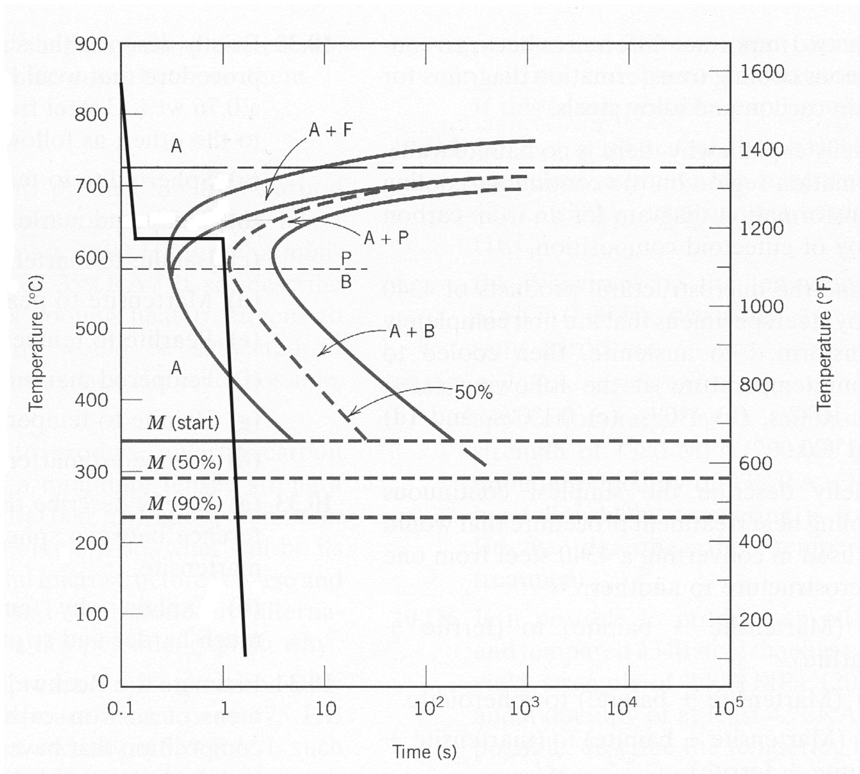


After cooling to and holding at 450°C for 10 s, a portion of the specimen first transformers to bainite. During the quenching to room temperature, the remainder of the specimen transforms to martensite. Hence, the final microstructure consists of bainite and martensite.

(g) Rapidly cool to 625°C (1155°F), hold for 1 s, then quench to room temperature.

<u>Solution</u>

Below is Figure 10.39 upon which is superimposed the above heat treatment.

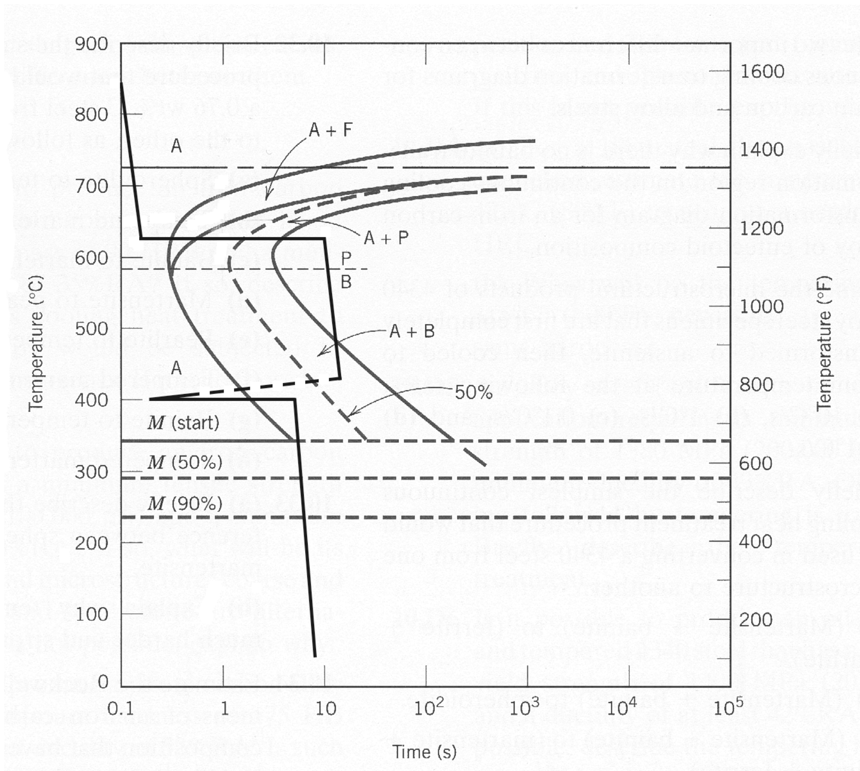


After cooling to and holding at 625°C for 1 s, a portion of the specimen first transformers to proeutectoid ferrite and pearlite. During the quenching to room temperature, the remainder of the specimen transforms to martensite. Hence, the final microstructure consists of ferrite, pearlite, and martensite.

(h) Rapidly cool to 625°C (1155°F), hold at this temperature for 10 s, rapidly cool to 400°C (750°F), hold at this temperature for 5 s, then quench to room temperature.

Solution

Below is Figure 10.39 upon which is superimposed the above heat treatment.



After cooling to and holding at 625°C for 10 s, all of the specimen transformers to proeutectoid ferrite and pearlite. During the second part of the heat treatment at 400°C no additional transformation will occur. Hence, the final microstructure consists of ferrite and pearlite.

10.22 *Make a copy of the isothermal transformation diagram for a 0.45 wt% C iron-carbon alloy (Figure 10.39), and then sketch and label on this diagram the time-temperature paths to produce the following microstructures:*

(a) 42% proeutectoid ferrite and 58% coarse pearlite

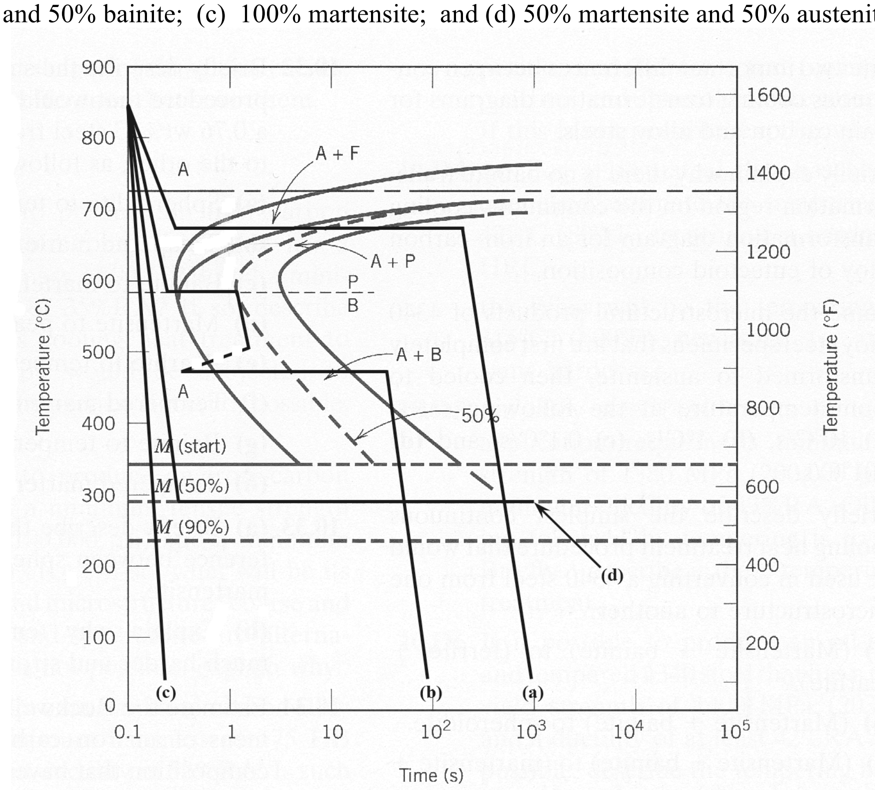
(b) 50% fine pearlite and 50% bainite

(c) 100% martensite

(d) 50% martensite and 50% austenite

Solution

Below is shown an isothermal transformation diagram for a 0.45 wt% C iron-carbon alloy, with time-temperature paths that will produce (a) 42% proeutectoid ferrite and 58% coarse pearlite; (b) 50% fine pearlite and 50% bainite; (c) 100% martensite; and (d) 50% martensite and 50% austenite.



10.23 *Name the microstructural products of eutectoid iron–carbon alloy (0.76 wt% C) specimens that are first completely transformed to austenite, then cooled to room temperature at the following rates:*

(a) 200°C/s,

(b) 100°C/s, and

(c) 20°C/s.

Solution

We are called upon to name the microstructural products that form for specimens of an iron-carbon alloy of eutectoid composition that are continuously cooled to room temperature at a variety of rates. Figure 10.27 is used in these determinations.

(a) At a rate of 200°C/s, only martensite forms.

(b) At a rate of 100°C/s, both martensite and pearlite form.

(c) At a rate of 20°C/s, only fine pearlite forms.

10.26 *Briefly explain why there is no bainite transformation region on the continuous cooling transformation diagram for an iron–carbon alloy of eutectoid composition.*

Solution

There is no bainite transformation region on the continuous cooling transformation diagram for an iron-carbon alloy of eutectoid composition (Figure 10.25) because by the time a cooling curve has passed into the bainite region, the entirety of the alloy specimen will have transformed to pearlite.

10.28 *Briefly describe the simplest continuous cooling heat treatment procedure that would be used in converting a 4340 steel from one microstructure to another.*

(a) (Martensite + bainite) to (ferrite + pearlite)

(b) (Martensite + bainite) to spheroidite

(c) (Martensite + bainite) to (martensite + bainite + ferrite)

Solution

This problem asks that we briefly describe the simplest continuous cooling heat treatment procedure that would be used in converting a 4340 steel from one microstructure to another. Solutions to this problem require the use of Figure 10.28.

(a) In order to convert from (martensite + bainite) to (ferrite + pearlite) it is necessary to heat above about 720°C, allow complete austenitization, then cool to room temperature at a rate slower than 0.006°C/s.

(b) To convert from (martensite + bainite) to spheroidite the alloy must be heated to about 700°C for several hours.

(c) In order to convert from (martensite + bainite) to (martensite + bainite + ferrite) it is necessary to heat to above about 720°C, allow complete austenitization, then cool to room temperature at a rate between 0.3°C/s and 0.02°C/s.

10.32 *Rank the following iron–carbon alloys and associated microstructures from the highest to the lowest tensile strength:*

(a) 0.25 wt%C with spheroidite,

(b) 0.25 wt%C with coarse pearlite,

(c) 0.60 wt%C with fine pearlite, and

(d) 0.60 wt%C with coarse pearlite.

Justify this ranking.

Solution

This problem asks us to rank four iron-carbon alloys of specified composition and microstructure according to hardness. This ranking is as follows:

0.60 wt% C, fine pearlite
0.60 wt% C, coarse pearlite
0.25 wt% C, coarse pearlite
0.25 wt% C, spheroidite

The 0.25 wt% C, coarse pearlite is stronger than the 0.25 wt% C, spheroidite since coarse pearlite is stronger than spheroidite; the composition of the alloys is the same. The 0.60 wt% C, coarse pearlite is stronger than the 0.25 wt% C, coarse pearlite, since increasing the carbon content increases the strength. Finally, the 0.60 wt% C, fine pearlite is stronger than the 0.60 wt% C, coarse pearlite inasmuch as the strength of fine pearlite is greater than coarse pearlite because of the many more ferrite-cementite phase boundaries in fine pearlite.

10.34 *Briefly describe the simplest heat treatment procedure that would be used in converting a 0.76 wt% C steel from one microstructure to the other, as follows:*

(a) Spheroidite to tempered martensite

(b) Tempered martensite to pearlite

(c) Bainite to martensite

(d) Martensite to pearlite

(e) Pearlite to tempered martensite

(f) Tempered martensite to pearlite

(g) Bainite to tempered martensite

(h) Tempered martensite to spheroidite

Solution

In this problem we are asked to describe the simplest heat treatment that would be required to convert a eutectoid steel from one microstructure to another. Figure 10.27 is used to solve the several parts of this problem.

(a) For spheroidite to tempered martensite, austenitize at a temperature of about 760°C, quench to room temperature at a rate greater than about 140°C/s, then isothermally heat at a temperature between 250 and 650°C.

(b) For tempered martensite to pearlite, austenitize at a temperature of about 760°C, then cool to room temperature at a rate less than about 35°C/s.

(c) For bainite to martensite, first austenitize at a temperature of about 760°C, then quench to room temperature at a rate greater than about 140°C/s.

(d) For martensite to pearlite, first austenitize at a temperature of about 760°C, then cool to room temperature at a rate less than about 35°C/s.

(e) For pearlite to tempered martensite, first austenitize at a temperature of about 760°C, then rapidly quench to room temperature at a rate greater than about 140°C/s, then isothermally heat treat (temper) at a temperature between 250 and 650°C.

(f) For tempered martensite to pearlite, first austenitize at a temperature of about 760°C, then cool to room temperature at a rate less than about 35°C/s.

(g) For bainite to tempered martensite, first austenitize at a temperature of about 760°C, then rapidly quench to room temperature at a rate greater than about 140°C/s, then isothermally heat treat (temper) at a temperature between 250 and 650°C.

(h) For tempered martensite to spheroidite simply heat at about 700°C for approximately 20 h.

10.35 *(a) Briefly describe the microstructural difference between spheroidite and tempered martensite.*

(b) Explain why tempered martensite is much harder and stronger.

Solution

(a) Both tempered martensite and spheroidite have sphere-like cementite particles within a ferrite matrix; however, these particles are much larger for spheroidite.

(b) Tempered martensite is harder and stronger inasmuch as there is much more ferrite-cementite phase boundary area for the smaller particles; thus, there is greater reinforcement of the ferrite phase, and more phase boundary barriers to dislocation motion.

10.36 *Estimate the Rockwell hardnesses for specimens of an iron–carbon alloy of eutectoid composition that have been subjected to the heat treatments described in parts (b), (d), (f), (g), and (h) of Problem 10.18.*

Solution

This problem asks for estimates of Rockwell hardness values for specimens of an iron-carbon alloy of eutectoid composition that have been subjected to some of the heat treatments described in Problem 10.18.

(b) The microstructural product of this heat treatment is 100% spheroidite. According to Figure 10.30*a*, the hardness of a 0.76 wt% C alloy with spheroidite is about 87 HRB.

(d) The microstructural product of this heat treatment is 100% martensite. According to Figure 10.32, the hardness of a 0.76 wt% C alloy consisting of martensite is about 64 HRC.

(f) The microstructural product of this heat treatment is 100% bainite. From Figure 10.31, the hardness of a 0.76 wt% C alloy consisting of bainite is about 385 HB. And, conversion from Brinell to Rockwell hardness using Figure 6.18 leads to a hardness of 36 HRC.

(g) The microstructural product of this heat treatment is 100% fine pearlite. According to Figure 10.30*a*, the hardness of a 0.76 wt% C alloy consisting of fine pearlite is about 27 HRC.

(h) The microstructural product of this heat treatment is 100% tempered martensite. According to Figure 10.35, the hardness of a water-quenched eutectoid alloy that was tempered at 315°C for one hour is about 57 HRC.

10.D2 *Is it possible to produce an iron-carbon alloy that has a minimum tensile strength of 690 MPa (100,000 psi) and a minimum ductility of 40%RA? If so, what will be its composition and microstructure (coarse and fine pearlites and spheroidite are alternatives)? If this is not possible, explain why.*

Solution

This problem asks if it is possible to produce an iron-carbon alloy that has a minimum tensile strength of 690 MPa (100,000 psi) and a minimum ductility of 40%RA. If such an alloy is possible, its composition and microstructure are to be stipulated.

From Equation 6.20a, this tensile strength corresponds to a Brinell hardness of

$$\mathrm{HB} = \frac{TS\ (\mathrm{MPa})}{3.45} = \frac{690\ \mathrm{MPa}}{3.45} = 200$$

According to Figures 10.30*a* and *b*, the following is a tabulation of the composition ranges for fine and coarse pearlites and spheroidite that meet the stipulated criteria.

Microstructure	Compositions for HB ≥ 200	Compositions for %RA ≥ 40%
Fine pearlite	> 0.45 %C	< 0.47 %C
Coarse pearlite	> 0.7 %C	< 0.54 %C
Spheroidite	not possible	0-1.0 %C

Therefore, only fine pearlite has a composition range overlap for both of the hardness and ductility restrictions; the fine pearlite would necessarily have to have a carbon content between 0.45 and 0.47 wt% C.

10.D4 *(a) For a 1080 steel that has been water quenched, estimate the tempering time at 425°C (800°F) to achieve a hardness of 50 HRC.*

(b) What will be the tempering time at 315°C (600°F) necessary to attain the same hardness?

Solution

This problem asks us to consider the tempering of a water-quenched 1080 steel to achieve a hardness of 50 HRC. It is necessary to use Figure 10.35.

(a) The time necessary at 425°C is about 500 s.

(b) At 315°C, the time required (by extrapolation) is approximately 4×10^6 s (about 50 days).