PROBLEMS

Section 12-1 Nucleation and Growth in Solid-State Reactions

12-1 How is the equation for nucleation of a phase in the solid state different from that for a liquid to solid transformation?

12-2 Determine the constants c and n in Equation 12-2 that describe the rate of crystallization of polypropylene at 140°C. (See Figure 12-26.)

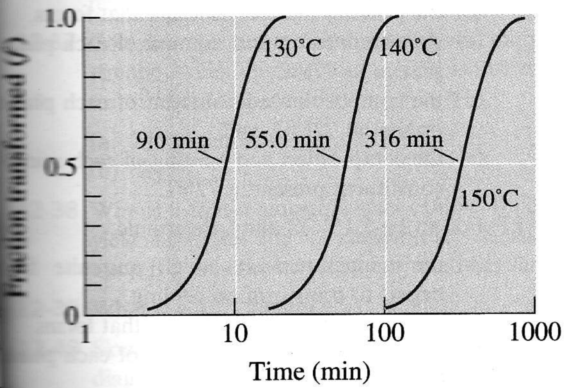


Figure 12-26 The effect of temperature on the crystallization of polypropylene (for Problem 12-2).

Section 12-2 Alloys Strengthened By Exceeding the Solubility Limit

12-3 What are the different ways by which a second phase can be made to precipitate in a two-phase microstructure?

12-4 Explain, when cooled slowly, why it is that the second phase in Al-4% Cu alloys nucleates and grows along the grain boundaries. Is this usually desirable?

12-5 What properties of the precipitate phase are needed for precipitation hardening? Why?

Section 12-3 Age or Precipitation Hardening

12-6 What is the principle of precipitation hardening?

12-7 What is a supersaturated solution? How do we obtain supersaturated solutions during precipitation hardening? Why is the formation of a supersaturated solution necessary?

12-8 Suppose that age hardening is possible in the Al-Mg system. (See Figure 12-8.)

(a) Recommend an artificial age-hardening heat treatment for each of the following alloys, and

(b) compare the amount of the β precipitate that forms from your treatment of each alloy.
(i) Al-4% Mg **(ii)** Al-6% Mg
(iii) Al-12% Mg

(c) Testing of the alloys after the heat treatment reveals that little strengthening occurs as a result of the heat treatment. Which of the requirements for age hardening is likely not satisfied?

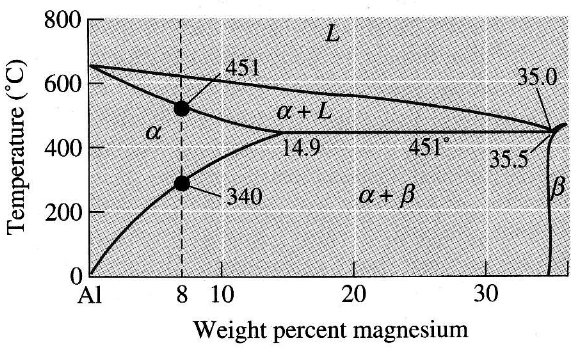


Figure 12-8 (Repeated for Problem 12-8) Portion of the aluminum-magnesium phase diagram.

12-9 An Al-2.5% Cu alloy is solution-treated, quenched, and overaged at 230°C to produce a stable microstructure. If the θ precipitates as spheres with a diameter of 9000 Å and a density of 4.26 g/cm^3, determine the number of precipitate particles per cm^3.

Section 12-4 Applications of Age-Hardened Alloys

12-10 Why is precipitation hardening an attractive mechanism of strengthening for aircraft materials?

12-11 Why are most precipitation-hardened alloys suitable only for relatively low-temperature applications?

Section 12-5 Microstructural Evolution in Age or Precipitation Hardening

12-12 Explain the three basic steps encountered during precipitation hardening.

Section 12-6 Effects of Aging Temperature and Time

12-13 What is aging? Why is this step needed in precipitation hardening?

12-14 What do the terms "natural aging" and "artificial aging" mean?

Stainless steels A group of ferrous alloys that contain at least 11% Cr, providing extraordinary corrosion resistance.

Tempered martensite The microconstituent of ferrite and cementite formed when martensite is tempered.

Tool steels A group of high-carbon steels that provide combinations of high hardness, toughness, or resistance to elevated temperatures.

Vermicular graphite The rounded, interconnected graphite that forms during the solidification of cast iron. This is the intended shape in compacted-graphite iron, but it is a defective shape in ductile iron.

White cast iron Cast iron that produces cementite rather than graphite during solidification. The white irons are hard and brittle.

PROBLEMS

Section 13-1 Designations and Classification of Steels

13-1 What is the difference between cast iron and steels?

13-2 What do A_1, A_3, and A_{cm} temperatures refer to? Are these temperatures constant?

13-3 Calculate the amounts of ferrite, cementite, primary microconstituent, and pearlite in the following steels:

(a) 1015 **(b)** 1035 **(c)** 1095 **(d)** 10130

13-4 Estimate the AISI-SAE number for steels having the following microstructures:

- **(a)** 38% pearlite-62% primary ferrite
- **(b)** 93% pearlite-7% primary cementite
- **(c)** 97% ferrite-3% cementite
- **(d)** 86% ferrite-14% cementite

13-5 Complete the following table:

	1035 Steel	10115 Steel
A_1 temperature		
A_3 or A_{cm} temperature		
Full annealing temperature		
Normalizing temperature		
Process annealing temperature		
Spheroidizing temperature		

13-6 What do the terms low-, medium-, and high-carbon steels mean?

Section 13-2 Simple Heat Treatments

Section 13-3 Isothermal Heat Treatments

13-7 Explain the following heat treatments: **(a)** process anneal, **(b)** austenitizing, **(c)** annealing, **(d)** normalizing, and **(e)** quenching.

13-8 Explain why, strictly speaking, TTT diagrams can be used for isothermal treatments only.

13-9 In a pearlitic 1080 steel, the cementite platelets are 4×10^{-5} cm thick, and the ferrite platelets are 14×10^{-5} cm thick. In a spheroidized 1080 steel, the cementite spheres are 4×10^{-3} cm in diameter. Estimate the total interface area between the ferrite and cementite in a cubic centimeter of each steel. Determine the percentage reduction in surface area when the pearlitic steel is spheroidized. The density of ferrite is 7.87 g/cm^3 and that of cementite is 7.66 g/cm^3.

13-10 Describe the microstructure present in a 1050 steel after each step in the following heat treatments:

- **(a)** heat at 820°C, quench to 650°C and hold for 90 s, and quench to 25°C
- **(b)** heat at 820°C, quench to 450°C and hold for 90 s, and quench to 25°C
- **(c)** heat at 820°C, and quench to 25°C
- **(d)** heat at 820°C, quench to 720°C and hold for 100 s, and quench to 25°C
- **(e)** heat at 820°C, quench to 720°C and hold for 100 s, quench to 400°C and hold for 500 s, and quench to 25°C

$$\text{Primary } \alpha = \left[\frac{(0.77 - 0.5)}{(0.77 - 0.0218)}\right] \times 100 = 36\%$$

$$\text{Pearlite} = \left[\frac{(0.5 - 0.0218)}{(0.77 - 0.0218)}\right] \times 100 = 64\%$$

3. Cool in air to room temperature, preserving the equilibrium amounts of primary ferrite and pearlite. The microstructure and hardness are uniform because of the isothermal anneal.

Interrupting the Isothermal Transformation Complicated microstructures are produced by interrupting the isothermal heat treatment. For example, we could austenitize the 1050 steel (Figure 13-8) 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! In practice, temperatures can not be changed instantaneously (i.e., we cannot go instantly from 800 to 650 or 650 to 350°C). This is why it is better to use the continuous cooling transformation (CCT) diagrams.

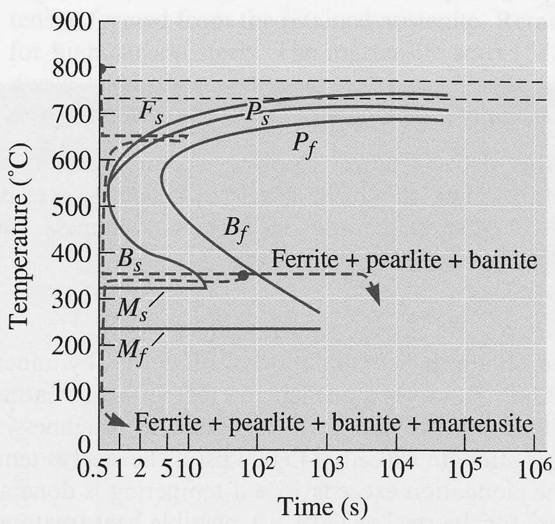


Figure 13-8 Producing complicated structures by interrupting the isothermal heat treatment of a 1050 steel.

13-4 Quench and Temper Heat Treatments

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 Fe_3C and ferrite (known as tempered martensite) if

(f) heat at 820°C, quench to 720°C and hold for 100 s, quench to 400°C and hold for 10 s, and quench to 25°C
(g) heat at 820°C, quench to 25°C, heat to 500°C and hold for 10^3 s, and air cool to 25°C

13-11 Describe the microstructure present in a 10110 steel after each step in the following heat treatments

(a) heat to 900°C, quench to 400°C and hold for 10^3 s, and quench to 25°C
(b) heat to 900°C, quench to 600°C and hold for 50 s, and quench to 25°C
(c) heat to 900°C, and quench to 25°C
(d) heat to 900°C, quench to 300°C and hold for 200 s, and quench to 25°C
(e) heat to 900°C, quench to 675°C and hold for 1 s, and quench to 25°C
(f) heat to 900°C, quench to 675°C and hold for 1 s, quench to 400°C and hold for 900 s, and slowly cool to 25°C
(g) heat to 900°C, quench to 675°C and hold for 1 s, quench to 300°C and hold for 10^3 s, and air cool to 25°C
(h) heat to 900°C, quench to 300°C and hold for 100 s, quench to 25°C, heat to 450°C for 3600 s, and cool to 25°C

13-12 Recommend appropriate isothermal heat treatments to obtain the following, including appropriate temperatures and times:

(a) an isothermally annealed 1050 steel with HRC 23,
(b) an isothermally annealed 10110 steel with HRC 40,
(c) an isothermally annealed 1080 steel with HRC 38,
(d) an austempered 1050 steel with HRC 40,
(e) an austempered 10110 steel with HRC 55, and
(f) an austempered 1080 steel with HRC 50.

13-13 Compare the minimum times required to isothermally anneal the following steels at 600°C. Discuss the effect of the carbon content of the steel on the kinetics of nucleation and growth during the heat treatment.

(a) 1050 **(b)** 1080 **(c)** 10110

Section 13-4 Quench and Temper Heat Treatments

13-14 Explain the following terms: **(a)** quenching, **(b)** tempering, **(c)** retained austenite, and **(d)** marquenching/martempering.

13-15 We wish to produce a 1050 steel that has a Brinell hardness of at least 330 and an elongation of at least 15%.

(a) Recommend a heat treatment, including appropriate temperatures, that permits this to be achieved. Determine the yield strength and tensile strength that are obtained by this heat treatment.
(b) What yield and tensile strength would be obtained in a 1080 steel by the same heat treatment?
(c) What yield strength, tensile strength and % elongation would be obtained in the 1050 steel if it were normalized?

13-16 We wish to produce a 1050 steel that has a tensile strength of at least 175,000 psi and a reduction in area of at least 50%.

(a) Recommend a heat treatment, including appropriate temperatures, that permits this to be achieved. Determine the Brinell hardness number, % elongation, and yield strength that are obtained by this heat treatment.
(b) What yield strength and tensile strength would be obtained in a 1080 steel by the same heat treatment?
(c) What yield strength, tensile strength, and % elongation would be obtained in the 1050 steel if it were annealed?

13-17 A 1030 steel is given an improper quench and temper heat treatment, producing a final structure composed of 60% martensite and 40% ferrite. Estimate the carbon content of the martensite and the austenitizing temperature that was used. What austenitizing temperature would you recommend?

13-18 A 1050 steel should be austenitized at 820°C, quenched in oil to 25°C, and tempered at 400°C for an appropriate time.

(a) What yield strength, hardness, and % elongation would you expect to obtain from this heat treatment?
(b) Suppose the actual yield strength of the steel is found to be 125,000 psi. What might have gone wrong in the heat treatment to cause this low strength?
(c) Suppose the hardness is found to be HB 525. What might have gone wrong in the heat treatment to cause this high hardness?

13-19 A part produced from a low-alloy, 0.2% C steel (Figure 13-15) has a microstructure containing ferrite, pearlite, bainite, and martensite after quenching. What microstructure would be obtained if we used a 1080 steel? What microstructure would be obtained if we used a 4340 steel?

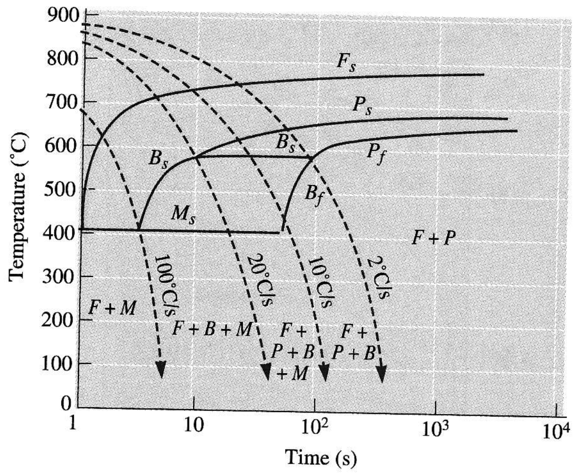


Figure 13-15 (Repeated for Problem 13-19.) The CCT diagram for a low-alloy, 0.2% C steel.

13-20 Fine pearlite and a small amount of martensite are found in a quenched 1080 steel. What microstructure would be expected if we used a low-alloy, 0.2% C steel? What microstructure would be expected if we used a 4340 steel?

Section 13-5 Effect of Alloying Elements

Section 13-6 Application of Hardenability

13-21 Explain the difference between hardenability and hardness. Explain using a sketch how hardenability of steels is measured.

13-22 We have found that a 1070 steel, when austenitized at 750°C, forms a structure containing pearlite and a small amount of grain-boundary ferrite that gives acceptable strength and ductility. What changes in the microstructure, if any, would be expected if the 1070 steel contained an alloying element such as Mo or Cr? Explain.

13-23 Using the TTT diagrams, compare the hardenabilities of 4340 and 1050 steels by determining the times required for the isothermal transformation of ferrite and pearlite (F_s, P_s, and P_f) to occur at 650°C.

13-24 We would like to obtain a hardness of HRC 38 to 40 in a quenched steel. What range of cooling rates would we have to obtain for the following steels? Are some steels inappropriate for achieving these levels of hardness?

(a) 4340 **(b)** 8640 **(c)** 9310
(d) 4320 **(e)** 1050 **(f)** 1080

13-25 A steel part must have an as-quenched hardness of HRC 35 in order to avoid excessive-wear rates during use. When the part is made from 4320 steel, the hardness is only HRC 32. Determine the hardness if the part were made under identical conditions, but with the following steels. Which, if any, of these steels would be better choices than 4320?

(a) 4340 **(b)** 8640 **(c)** 9310
(d) 1050 **(e)** 1080

13-26 A part produced from a 4320 steel has a hardness of HRC 35 at a critical location after quenching. Determine

(a) the cooling rate at that location, and
(b) the microstructure and hardness that would be obtained if the part were made of a 1080 steel.

13-27 A 1080 steel is cooled at the fastest possible rate that still permits all pearlite to form. What is this cooling rate? What Jominy distance, and hardness are expected for this cooling rate?

13-28 Determine the hardness and microstructure at the center of a 1.5-in.-diameter 1080 steel bar produced by quenching in

(a) unagitated oil,
(b) unagitated water, and
(c) agitated brine.

13-29 A 2-in.-diameter bar of 4320 steel is to have a hardness of at least HRC 35. What is the minimum severity of the quench (H coefficient)? What type of quenching medium would you recommend to produce the desired hardness with the least chance of quench cracking?

13-30 A steel bar is to be quenched in agitated water. Determine the maximum diameter of the bar that will produce a minimum hardness of HRC 40 if the bar is:

(a) 1050 **(b)** 1080 **(c)** 4320
(d) 8640 **(e)** 4340

13-31 The center of a 1-in.-diameter bar of 4320 steel has a hardness of HRC 40. Determine the hardness and microstructure at the center of a 2-in. bar of 1050 steel quenched in the same medium.

Section 13-7 Specialty Steels

Section 13-8 Surface Treatments

Section 13-9 Weldability of Steel

13-32 What is the principle of the surface hardening of steels using carburizing and nitriding?

13-33 A 1010 steel is to be carburized using a gas atmosphere that produces 1.0% C at the surface of the steel. The case depth is defined as the distance below the surface that contains at least 0.5% C. If carburizing is done at 1000°C, determine the time required to produce a case depth of 0.01 in. (See Chapter 5 for a review.)

13-34 A 1015 steel is to be carburized at 1050°C for 2 h using a gas atmosphere that produces 1.2% C at the surface of the steel. Plot the percent carbon versus the distance from the surface of the steel. If the steel is slowly cooled after carburizing, determine the amount of each phase and microconstituent at 0.002-in. intervals from the surface. (See Chapter 5.)

13-35 Why is it that the strength of the heat-affected zone is higher for low-carbon steels? What is the role of retained austenite, in this case?

13-36 Why is it easier to weld low-carbon steels, however, it is difficult to weld high-carbon steels?

13-37 A 1050 steel is welded. After cooling, hardnesses in the heat-affected zone are obtained at various locations from the edge of the fusion zone. Determine the hardnesses expected at each point if a 1080 steel were welded under the same conditions. Predict the microstructure at each location in the as-welded 1080 steel.

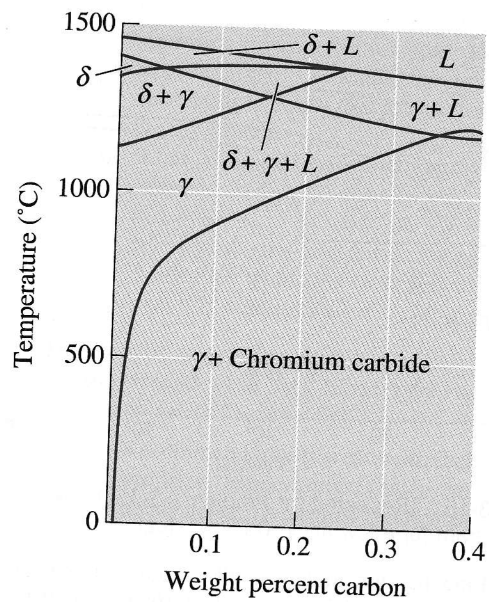
Distance from Edge of Fusion Zone	Hardness in 1050 Weld
0.05 mm	HRC 50
0.10 mm	HRC 40
0.15 mm	HRC 32
0.20 mm	HRC 28

Section 13-10 Stainless Steels

13-38 What is a stainless steel? Why are stainless steels stainless?

13-39 We wish to produce a martensitic stainless steel containing 17% Cr. Recommend a carbon content and austenitizing temperature that would permit us to obtain 100% martensite during the quench. What microstructure would be produced if the martensite were then tempered until the equilibrium phases formed?

13-40 Occasionally, when an austenitic stainless steel is welded, the weld deposit may be slightly magnetic. Based on the Fe-Cr-Ni-C phase diagram [Figure 13-28(b)], what phase would you expect is causing the magnetic behavior? Why might this phase have formed? What could you do to restore the nonmagnetic behavior?



(b)

Figure 13-28 (Repeated for Problem 13-40) (b) A section of the iron-chromium-nickel-carbon phase diagram at a constant 18% Cr-8% Ni. At low-carbon contents, austenite is stable at room temperature.

Section 13-11 Cast Irons

13-41 Define cast iron using the Fe-Fe_3C phase diagram.

13-42 What are the different types of cast irons? Explain using a sketch.

13-43 A tensile bar of a class 40 gray iron casting is found to have a tensile strength of 50,000 psi. Why is the tensile strength greater than that given by the class number? What do you think is the diameter of the test bar?

13-44 You would like to produce a gray iron casting that freezes with no primary austenite or graphite. If the carbon content in the iron is 3.5%, what percentage of silicon must you add?

Design Problems

13-45 We would like to produce a 2-in.-thick steel wear plate for a rock-crushing unit. To avoid frequent replacement of the wear plate, the hardness should exceed HRC 38 within 0.25 in. of the steel surface. However, the center of the plate should have a hardness of no more than HRC 32 to assure some toughness. We have only a water quench available to us. Design the plate, assuming that we only have the steels given in Figure 13-21 available to us.

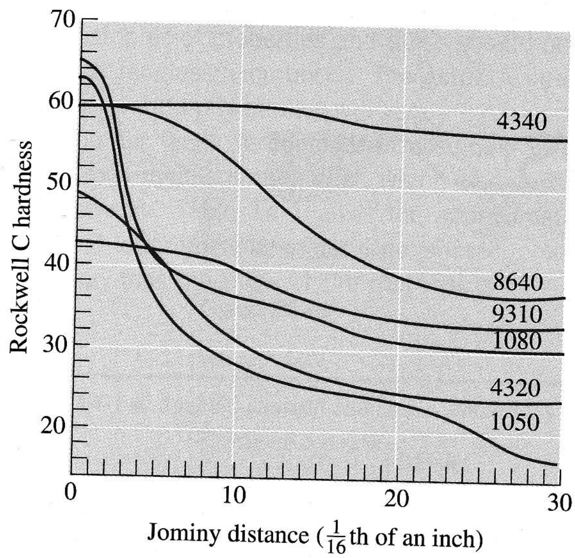


Figure 13-21 (Repeated for Problem 13-45.) The hardenability curves for several steels.

13-46 A quenched and tempered 10110 steel is found to have surface cracks that cause the heat-treated part to be rejected by the customer. Why did the cracks form? Design a heat treatment, including appropriate temperatures and times that will minimize these problems.

13-47 Design a corrosion-resistant steel to use for a pump that transports liquid helium (He) at 4 K in a superconducting magnet.

13-48 Design a heat treatment for a hook made of 1-in.-diameter steel rod having a microstructure containing a mixture of ferrite, bainite, and martensite after quenching. Estimate the mechanical properties of your hook.

13-49 Design an annealing treatment for a 1050 steel. Be sure to include details of temperatures, cooling rates, microstructures, and properties.

13-50 Design a process to produce a 0.5-cm-diameter steel shaft having excellent toughness, yet excellent wear and fatigue resistance. The surface hardness should be at least HRC 60, and the hardness 0.01 cm beneath the surface should be approximately HRC 50. Describe the process, including details of the heat-treating atmosphere, the composition of the steel, temperatures, and times.