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QUESTIONS AND PROBLEMS

The Kinetics of Phase Transformations

10.1 Name the two stages involved in the formation of particles of a new phase. Briefly describe each.

10.2 **(a)** Rewrite the expression for the total free energy change for nucleation (Equation 10.1) for the case of a cubic nucleus of edge length a (instead of a sphere of radius r). Now differentiate this expression with respect to a (per Equation 10.2) and solve for both the critical cube edge length, a^*, and also ΔG^*.

(b) Is ΔG^* greater for a cube or a sphere? Why?

10.3 If ice homogeneously nucleates at −40°C, calculate the critical radius given values of -3.1×10^8 J/m^3 and 25×10^{-3} J/m^2, respectively, for the latent heat of fusion and the surface free energy.

10.4 **(a)** For the solidification of nickel, calculate the critical radius r^* and the activation free energy ΔG^* if nucleation is homogeneous. Values for the latent heat of fusion and surface free energy are -2.53×10^9 J/m^3 and 0.255 J/m^2, respectively. Use the supercooling value found in Table 10.1.

(b) Now calculate the number of atoms found in a nucleus of critical size. Assume a lattice parameter of 0.360 nm for solid nickel at its melting temperature.

10.5 **(a)** Assume for the solidification of nickel (Problem 10.4) that nucleation is homogeneous, and the number of stable nuclei is 10^6 nuclei per cubic meter. Calculate the critical radius and the number of stable nuclei that exist at the following degrees of supercooling: 200 K and 300 K.

(b) What is significant about the magnitudes of these critical radii and the numbers of stable nuclei?

10.6 For some transformation having kinetics that obey the Avrami equation (Equation 10.17), the parameter n is known to have a value of 1.5. If, after 125 s, the reaction is 25% complete, how long (total time) will it take the transformation to go to 90% completion?

10.7 Compute the rate of some reaction that obeys Avrami kinetics, assuming that the constants n and k have values of 2.0 and 5×10^{-4}, respectively, for time expressed in seconds.

10.8 It is known that the kinetics of recrystallization for some alloy obey the Avrami equation, and that the value of n in the exponential is 5.0. If, at some temperature, the fraction recrystallized is 0.30 after 100 min, determine the rate of recrystallization at this temperature.

10.9 The kinetics of the austenite-to-pearlite transformation obey the Avrami relationship.

Using the fraction transformed–time data given here, determine the total time required for 95% of the austenite to transform to pearlite:

Fraction Transformed	*Time (s)*
0.2	280
0.6	425

10.10 The fraction recrystallized–time data for the recrystallization at 350°C of a previously deformed aluminum are tabulated here. Assuming that the kinetics of this process obey the Avrami relationship, determine the fraction recrystallized after a total time of 116.8 min.

Fraction Recrystallized	*Time (min)*
0.30	95.2
0.80	126.6

10.11 **(a)** From the curves shown in Figure 10.11 and using Equation 10.18, determine the rate of recrystallization for pure copper at the several temperatures.

(b) Make a plot of ln(rate) versus the reciprocal of temperature (in K^{-1}), and determine the activation energy for this recrystallization process. (See Section 5.5.)

(c) By extrapolation, estimate the length of time required for 50% recrystallization at room temperature, 20°C (293 K).

10.12 Determine values for the constants n and k (Equation 10.17) for the recrystallization of copper (Figure 10.11) at 119°C.

Metastable Versus Equilibrium States

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

10.14 **(a)** Briefly describe the phenomena of superheating and supercooling.

(b) Why do these phenomena occur?

Isothermal Transformation Diagrams

10.15 Suppose that a steel of eutectoid composition is cooled to 675°C (1250°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.

10.16 Briefly cite the differences between pearlite, bainite, and spheroidite relative to microstructure and mechanical properties.

10.17 What is the driving force for the formation of spheroidite?

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 350°C (660°F), hold for 10^3 s, then quench to room temperature.

(b) Rapidly cool to 625°C (1160°F), hold for 10 s, then quench to room temperature.

(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.

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

(e) Rapidly cool to 300°C (570°F), hold for 20 s, then quench to room temperature in water. Reheat to 425°C (800°F) for 10^3 s and slowly cool to room temperature.

(f) Cool rapidly to 665°C (1230°F), hold for 10^3 s, then quench to room temperature.

(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.

(h) Rapidly cool to 350°C (660°F), hold for 150 s, then quench to room temperature.

10.19 Make a copy of the isothermal transformation diagram for an iron–carbon alloy of eutectoid composition (Figure 10.22) and then sketch and label time–temperature paths on this diagram to produce the following microstructures:

(a) 100% coarse pearlite

(b) 50% martensite and 50% austenite

(c) 50% coarse pearlite, 25% bainite, and 25% martensite

10.20 Using the isothermal transformation diagram for a 1.13 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 920°C (1690°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.

(b) Rapidly cool to 775°C (1430°F), hold for 500 s, then quench to room temperature.

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

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

(e) Rapidly cool to 650°C (1200°F), hold at this temperature for 3 s, rapidly cool to 400°C (750°F), hold for 25 s, then quench to room temperature.

(f) Rapidly cool to 350°C (660°F), hold for 300 s, then quench to room temperature.

(g) Rapidly cool to 675°C (1250°F), hold for 7 s, then quench to room temperature.

(h) Rapidly cool to 600°C (1110°F), hold at this temperature for 7 s, rapidly cool to 450°C (840°F), hold at this temperature for 4 s, then quench to room temperature.

10.21 For parts a, c, d, f, and h of Problem 10.20, determine the approximate percentages of the microconstituents that form.

10.22 Make a copy of the isothermal transformation diagram for a 1.13 wt% C iron–carbon alloy (Figure 10.39), and then on this diagram sketch and label time–temperature paths to produce the following microstructures:

(a) 6.2% proeutectoid cementite and 93.8% coarse pearlite

(b) 50% fine pearlite and 50% bainite

(c) 100% martensite

(d) 100% tempered martensite

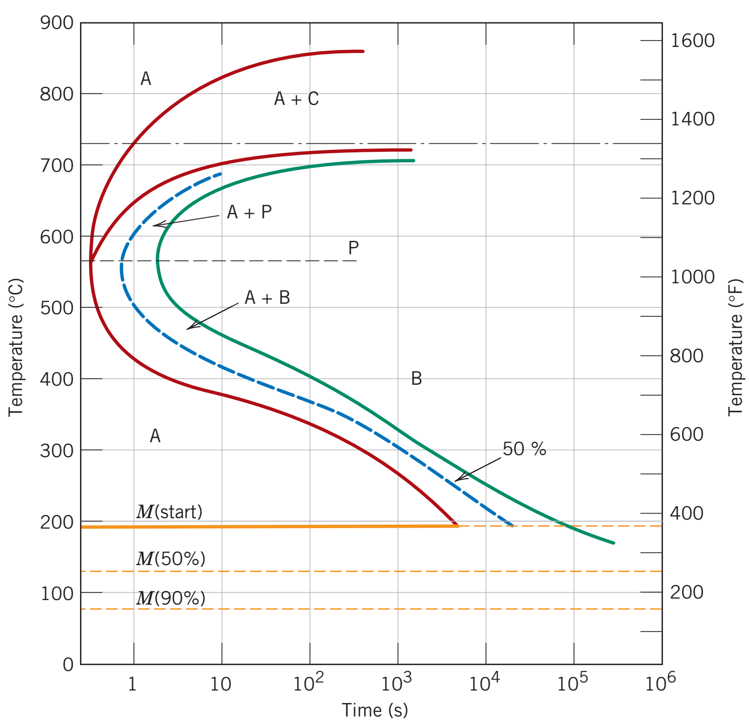

Figure 10.39 Isothermal transformation diagram for a 1.13 wt% C iron–carbon alloy: A, austenite; B, bainite; C, proeutectoid cementite; M, martensite; P, pearlite. [Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams,* American Society for Metals, 1977, p. 33.]

Continuous Cooling Transformation Diagrams

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)** 1°C/s, **(b)** 20°C/s, **(c)** 50°C/s, and **(d)** 175°C/s.

10.24 Figure 10.40 shows the continuous cooling transformation diagram for a 0.35 wt% C iron–carbon alloy. Make a copy of this figure and then sketch and label continuous cooling curves to yield the following microstructures:

(a) Fine pearlite and proeutectoid ferrite

(b) Martensite

(c) Martensite and proeutectoid ferrite

(d) Coarse pearlite and proeutectoid ferrite

(e) Martensite, fine pearlite, and proeutectoid ferrite

10.25 Cite two important differences between continuous cooling transformation diagrams for plain carbon and alloy steels.

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.

10.27 Name the microstructural products of 4340 alloy steel specimens that are first completely transformed to austenite, then cooled to room temperature at the following rates: **(a)** 0.005°C/s, **(b)** 0.05°C/s, **(c)** 0.5°C/s, and **(d)** 5°C/s.

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 + ferrite + bainite) to (martensite + ferrite + pearlite + bainite)

(b) (Martensite + ferrite + bainite) to spheroidite

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

10.29 On the basis of diffusion considerations, explain why fine pearlite forms for the moderate cooling of austenite through the eutectoid temperature, whereas coarse pearlite is the product for relatively slow cooling rates.

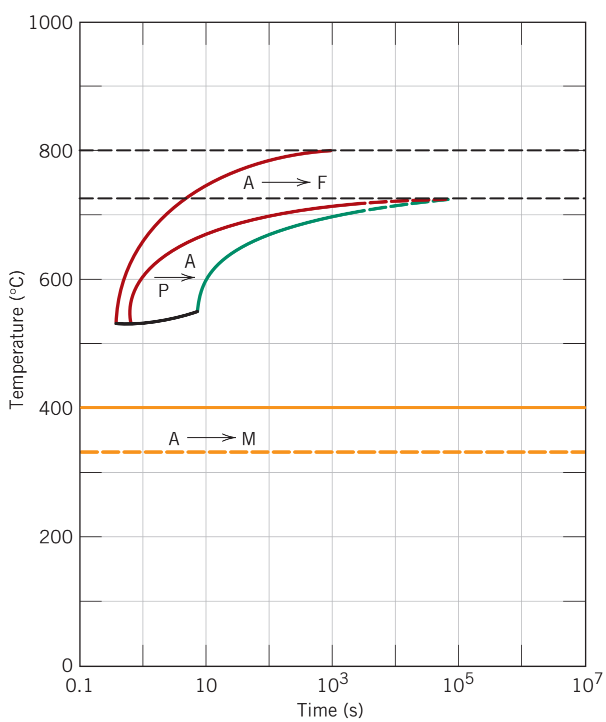

Figure 10.40 Continuous cooling transformation diagram for a 0.35 wt% C iron–carbon alloy.

Mechanical Behavior of Iron–Carbon Alloys
Tempered Martensite

10.30 Briefly explain why fine pearlite is harder and stronger than coarse pearlite, which in turn is harder and stronger than spheroidite.

10.31 Cite two reasons why martensite is so hard and brittle.

10.32 Rank the following iron–carbon alloys and associated microstructures from the hardest to the softest: **(a)** 0.25 wt% C with coarse pearlite, **(b)** 0.80 wt% C with spheroidite, **(c)** 0.25 wt% C with spheroidite, and **(d)** 0.80 wt% C with fine pearlite. Justify this ranking.

10.33 Briefly explain why the hardness of tempered martensite diminishes with tempering time (at constant temperature) and with increasing temperature (at constant tempering time).

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) Martensite to spheroidite

(b) Spheroidite to martensite

(c) Bainite to pearlite

(d) Pearlite to bainite

(e) Spheroidite to pearlite

(f) Pearlite to spheroidite

(g) Tempered martensite to martensite

(h) Bainite to spheroidite

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

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

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 (d), (e), (f), (g), and (h) of Problem 10.18.

10.37 Estimate the Brinell hardnesses for specimens of a 1.13 wt% C iron–carbon alloy that have been subjected to the heat treatments described in parts (a), (d), and (h) of Problem 10.20.

10.38 Determine the approximate tensile strengths for specimens of a eutectoid iron–carbon alloy that have experienced the heat treatments described in parts (a), (b), and (d) of Problem 10.23.

10.39 For a eutectoid steel, describe isothermal heat treatments that would be required to yield specimens having the following Brinell hardnesses: **(a)** 180 HB, **(b)** 220 HB, and **(c)** 500 HB.

DESIGN PROBLEMS

Continuous Cooling Transformation Diagrams
Mechanical Behavior of Iron–Carbon Alloys

10.D1 Is it possible to produce an iron–carbon alloy of eutectoid composition that has a minimum hardness of 200 HB and a minimum ductility of 25% RA? If so, describe the continuous cooling heat treatment to which the alloy would be subjected to achieve these properties. If it is not possible, explain why.

10.D2 Is it possible to produce an iron–carbon alloy that has a minimum tensile strength of 620 MPa (90,000 psi) and a minimum ductility of 50% 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.

10.D3 It is desired to produce an iron–carbon alloy that has a minimum hardness of 200 HB and a minimum ductility of 35% RA. Is such an alloy possible? If so, what will be its composition and microstructure (coarse and fine pearlites and spheroidite are alternatives)? If this is not possible, explain why.

Tempered Martensite

10.D4 (a) For a 1080 steel that has been water quenched, estimate the tempering time at 535°C (1000°F) to achieve a hardness of 45 HRC.

(b) What will be the tempering time at 425°C (800°F) necessary to attain the same hardness?

10.D5 An alloy steel (4340) is to be used in an application requiring a minimum tensile strength of 1515 MPa (220,000 psi) and a minimum ductility of 40% RA. Oil quenching followed by tempering is to be used. Briefly describe the tempering heat treatment.

10.D6 Is it possible to produce an oil-quenched and tempered 4340 steel that has a minimum yield strength of 1240 MPa (180,000 psi) and a ductility of at least 50% RA? If this is possible, describe the tempering heat treatment. If it is not possible, then explain why.