12

Dispersion Strengthening by Phase Transformations and Heat Treatment

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 12–30)

Solution: $f = 1 - \exp(-ct^n)$ $\quad T = 140°\text{C} = 413\text{ K}$

We can rearrange the equation and eliminate the exponential by taking natural logarithms of both sides of the rearranged equation. We can then note that $\ln(1 - f)$ versus t is a power equation; if these terms are plotted on a log-log plot, we should obtain a linear relationship, as the graph of the data below indicates. Note that in setting up the equation for plotting, we switch the minus sign from the right hand to the left hand side, since we don't have negative numbers on the log-log paper.

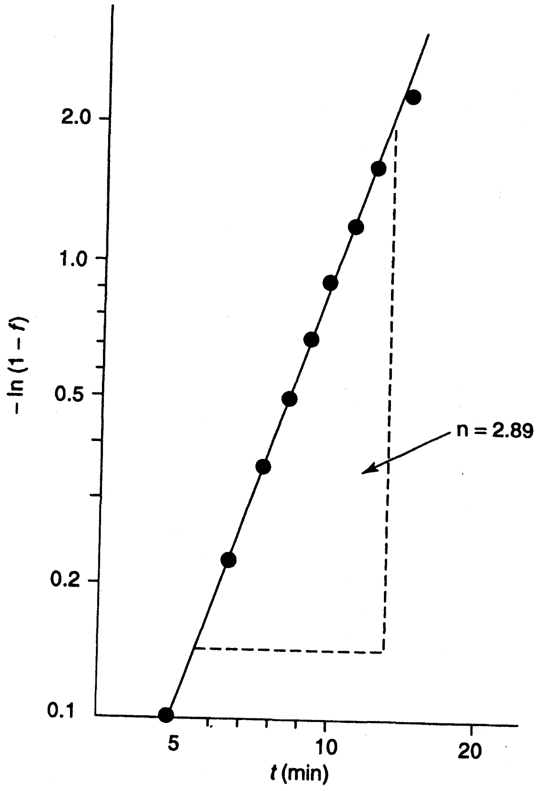
$$1 - f = \exp(-ct^n)$$
$$\ln(1 - f) = -ct^n$$
$$\ln[-\ln(1 - f)] = \ln(ct^n)$$
$$\ln[-\ln(1 - f)] = \ln(c) + n\ln(t)$$

A log-log plot of "$-\ln(1 - f)$" versus "t" is shown. From the graph, we find that the slope $n = 2.89$ and the constant c can be found from one of the points from the curve:

if $f = 0.5$, $t = 55$. Then

$$1 - 0.5 = \exp[-c(55)^{2.89}]$$
$$c = 6.47 \times 10^{-6}$$

f	t(min)	$-\ln(1 - f)$
0.1	28	0.1
0.2	37	0.22
0.3	44	0.36
0.4	50	0.51
0.5	55	0.69
0.6	60	0.92
0.7	67	1.20
0.8	73	1.61
0.9	86	2.302


2.0
1.0
0.5
0.2
0.1
−ln (1 − f)
n = 2.89
5
10
20
t (min)

12–4 Determine the activation energy for crystallization of polypropylene, using the curves in Figure 12–30.

Solution: We can determine how the rate (equal to $1/\tau$) changes with temperature:

$$\text{rate} = 1/\tau = c\exp(-Q/RT)$$

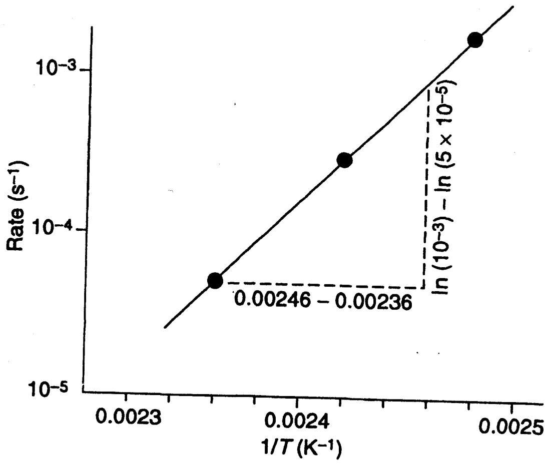
$1/\tau\ (\mathrm{s}^{-1})$	$1/T\ (\mathrm{K}^{-1})$
$1/(9\ \mathrm{min})(60\ \mathrm{s/min}) = 1.85 \times 10^{-3}$	$1/(130 + 273) = 2.48 \times 10^{-3}$
$1/(55\ \mathrm{min})(60\ \mathrm{s/min}) = 3.03 \times 10^{-4}$	$1/(140 + 273) = 2.42 \times 10^{-3}$
$1/(316\ \mathrm{min})(60\ \mathrm{s/min}) = 5.27 \times 10^{-5}$	$1/(150 + 273) = 2.36 \times 10^{-3}$

From the semilog graph of rate versus reciprocal temperature, we find that the slope is:

$$Q/R = \frac{\ln(10^{-3}) - \ln(5 \times 10^{-5})}{0.00246 - 0.00236}$$

$$Q/R = 29{,}957$$

$$Q = 59{,}525\ \text{cal/mol}$$



12–17 Suppose that age hardening is possible in the Al–Mg system (see Figure 12–10). (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?

Solution: (a) The heat treatments for each alloy might be:

	Al–4% Mg	Al–6% Mg	Al–12% Mg
T_{Eutectic} =	451°C	451°C	451°C
T_{Solvus} =	210°C	280°C	390°C
Solution Treat at:	210–451°C	280–451°C	390–451°C
	Quench	Quench	Quench
Age at:	<210°C	<280°C	<390°C

(b) Answers will vary depending on aging temperature selected. If all three are aged at 200°C, as an example, the tie line goes from about 3.8 to 35% Mg:

Al–4% Mg: $\% \beta = (4 - 3.8)/(35 - 3.8) \times 100 = 0.6\%$

Al–6% Mg: $\% \beta = (6 - 3.8)/(35 - 3.8) \times 100 = 7.1\%$

Al–12% Mg: $\% \beta = (12 - 3.8)/(35 - 3.8) \times 100 = 26.8\%$

(c) Most likely, a coherent precipitate is not formed; simple dispersion strengthening, rather than age hardening, occurs.

12–33 Figure 12–31 shows a hypothetical phase diagram. Determine whether each of the following alloys might be good candidates for age hardening and explain your answer. For those alloys that might be good candidates, describe the heat treatment required, including recommended temperatures.

(a) A–10% B (b) A–20% B (c) A–55% B
(d) A–87% B (e) A–95% B

Solution: (a) A–10% B is a good candidate: Solution Treatment @ $T = 290$ to 400°C
Quench
Age @ $T < 290$°C

(b) A–20% B: Some age hardening effect may occur when alloy is solution treated below 400°C and quenched. However, eutectic is also present and the strengthening effect will not be as dramatic as in (a).

(c) A–55% B: almost all θ is formed. The alloy is expected to be very brittle.

(d) A–87% B: the alloy cools from a two-phase ($\beta + \theta$) region to a one-phase (β) region, opposite of what we need for age hardening.

(e) A–95% B: the alloy is single phase (β) at all temperatures and thus cannot be age hardened.

12–56 Determine the eutectoid temperature, the composition of each phase in the eutectoid reaction, and the amount of each phase present in the eutectoid microconstituent for the following systems. For the metallic systems, comment on whether you expect the eutectoid microconstituent to be ductile or brittle.

(a) ZrO_2–CaO (See Figure 12–32)
(b) Cu–Al at 11.8%Al (See Figure 12–33(c))
(c) Cu–Zn at 47%Zn (See Figure 12–33(a))
(d) Cu–Be (See Figure 12–33(d))

Solution: (a) @900°C: $\text{Tetragonal}_{12\%\text{ CaO}} \rightarrow \text{Monoclinic}_{3\%\text{ CaO}} + \text{Cubic}_{14\%\text{ CaO}}$

$$\%\text{ Monoclinic} = \frac{14 - 12}{14 - 3} \times 100 = 18\% \quad \%\text{ Cubic} = 82\%$$

The eutectoid microconstituent (and the entire material, for that matter) will be brittle because the materials are ceramics

(b) @565°C: $\beta_{11.8\%\text{ Al}} \rightarrow \alpha_{9.4\%\text{ Al}} + \gamma_{2\ 15.6\%\text{ Al}}$

$$\%\,\alpha = \frac{15.6 - 11.8}{15.6 - 9.4} \times 100 = 61.3\% \quad \%\,\beta = 38.7\%$$

Most of the eutectoid microconstituent is α (solid solution strengthened copper) and is expected to be ductile.

(c) @250°C: $\beta'_{47\%\text{ Zn}} \rightarrow \alpha_{36\%\text{ An}} + \gamma_{59\%\text{ Zn}}$

$$\%\,\alpha = \frac{59 - 47}{59 - 36} \times 100 = 52.2\% \quad \%\,\gamma = 47.8\%$$

Slightly more than half of the eutectoid is the copper solid solution; there is a good chance that the eutectoid would be ductile.

(d) @605°C: $\gamma_{1\ 6\%\text{ Be}} \rightarrow \alpha_{1.5\%\text{ Be}} + \gamma_{2\ 11\%\text{ Be}}$

$$\%\,\alpha = \frac{11 - 6}{11 - 1.5} \times 100 = 52.6\% \quad \%\,\beta = 47.4\%$$

Slightly more than half of the eutectoid is the copper solid solution; we might then expect the eutectoid to be ductile.

12–72 A steel containing 0.3% C is heated to various temperatures above the eutectoid temperature, held for 1 h, and then quenched to room temperature. Using Figure 12–34, determine the amount, composition, and hardness of any martensite that forms when the heating temperature is

(a) 728°C (b) 750°C (c) 790°C (d) 850°C

Solution: (a) γ: 0.77% C $\quad \% M = \dfrac{0.3 - 0.0218}{0.77 - 0.0218} \times 100\% = 37.2\%$ HRC 65

(b) γ: 0.60% C $\quad \% M = \dfrac{0.3 - 0.02}{0.6 - 0.02} \times 100\% = 48.3\%$ HRC 65

(c) γ: 0.35% C $\quad \% M = \dfrac{0.3 - 0.02}{0.35 - 0.02} \times 100\% = 84.8\%$ HRC 58

(d) γ: 0.3% C $\quad \% M = 100\%$ HRC 55

12–80 A steel containing 0.95% C is heated to various temperatures above the eutectoid temperature, held for 1 h, and then quenched to room temperature. Using Figure 12–34, determine the amount and composition of any martensite that forms when the heating temperature is

(a) 728°C (b) 750°C (c) 780°C (d) 850°C

Solution: (a) $\gamma = 0.77\%$ C $\quad \% M = \dfrac{6.67 - 0.95}{6.67 - 0.77} \times 100\% = 96.9\%$ HRC 65

(b) $\gamma = 0.82\%$ C $\quad \% M = \dfrac{6.67 - 0.95}{6.67 - 0.82} \times 100\% = 97.8\%$ HRC 65

(c) $\gamma = 0.88\%$ C $\quad \% M = \dfrac{6.67 - 0.95}{6.67 - 0.88} \times 100\% = 98.8\%$ HRC 65

(d) $\gamma = 0.95\%$ C $\quad \% M = 100\%$ HRC 65

12–81 A steel microstructure contains 75% martensite and 25% ferrite; the composition of the martensite is 0.6% C. Using Figure 12–34, determine (a) the temperature from which the steel was quenched and (b) the carbon content of the steel.

Solution: In order for γ (and therefore martensite) to contain 0.6% C, the austenitizing $T = 750°\text{C}$. Then:

$$M = \gamma = 0.25 = \frac{0.6 - x}{0.6 - 0.02} \qquad x = 0.455\% \text{ C}$$