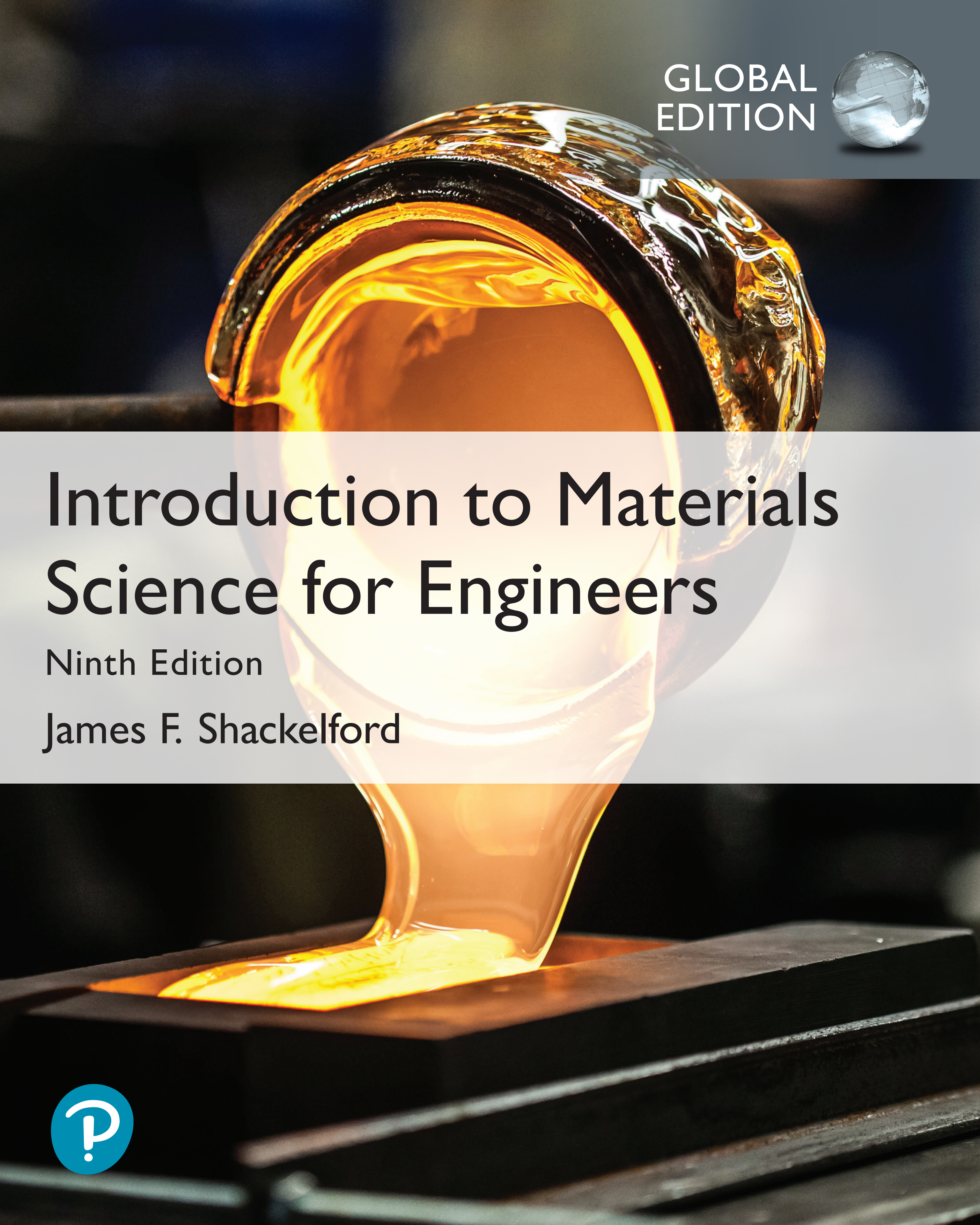

GLOBAL
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Introduction to Materials Science for Engineers

Ninth Edition

James F. Shackelford

NINTH EDITION
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Introduction to MATERIALS SCIENCE FOR ENGINEERS

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Pearson

where C is a preexponential constant, Q is the activation energy (per mole) for viscous flow, R is the universal gas constant, and T is the absolute temperature.

EXAMPLE 6.10

In a laboratory creep experiment at 1,000°C, a steady-state creep rate of 5×10^{-1} % per hour is obtained in a metal alloy. The creep mechanism for this alloy is known to be dislocation climb with an activation energy of 200 kJ/mol. Predict the creep rate at a service temperature of 600°C. (Assume that the laboratory experiment duplicated the service stress.)

SOLUTION

Using the laboratory experiment to determine the preexponential constant in Equation 6.16, we obtain

$$\begin{aligned} C &= \dot{\epsilon} e^{+Q/RT} \\ &= (5 \times 10^{-1}\ \%\ \text{per hour}) e^{+(2 \times 10^{5}\ \text{J/mol})/[8.314\ \text{J/molK})](1{,}273\text{K})} \\ &= 80.5 \times 10^{6}\ \%\ \text{per hour}. \end{aligned}$$

Applying this amount to the service temperature yields

$$\begin{aligned} \dot{\epsilon} &= (80.5 \times 10^{6}\ \%\ \text{per hour}) e^{-(2 \times 10^{5})/(8.314)(873)} \\ &= 8.68 \times 10^{-5}\ \%\ \text{per hour}. \end{aligned}$$

Note. We have assumed that the creep mechanism remains the same between 1,000 and 600°C.

D EXAMPLE 6.11

Starting at this point and continuing throughout the remainder of the book, problems that deal with materials in the engineering design process will be identified with a design icon, **D**.

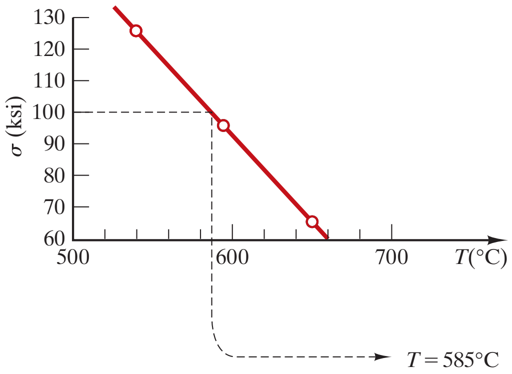
In designing a pressure vessel for the petrochemical industry, an engineer must estimate the temperature to which Inconel 718 could be subjected and still provide a service life of 10,000 h under a service stress of 690 MPa (100,000 psi) before failing by creep rupture. What is the service temperature?

SOLUTION

Using Figure 6.37, we must re-plot the data, noting that the failure stress for a rupture time of 10^4 h varies with temperature as follows:

σ(ksi)	T(°C)
125	540
95	595
65	650

Plotting gives



EXAMPLE 6.12

The relaxation time for a rubber band at 25°C is 60 days.

(a) If it is stressed to 2 MPa initially, how many days will be required before the stress relaxes to 1 MPa?

(b) If the activation energy for the relaxation process is 30 kJ/mol, what is the relaxation time at 35°C?

SOLUTION

(a) From Equation 6.17,

$$\sigma = \sigma_0 e^{-t/\tau}$$

and

$$1 \text{ MPa} = 2 \text{ MPa} e^{-t/(60 \text{ d})}.$$

Rearranging the terms yields

$$t = -(60 \text{ days})(\ln \tfrac{1}{2}) = 41.5 \text{ days}.$$

(b) From Equation 6.18,

$$\frac{1}{\tau} = Ce^{-Q/RT},$$

or

$$\frac{1/\tau_{25^\circ\text{C}}}{1/\tau_{35^\circ\text{C}}} = \frac{e^{-Q/R(298 \text{ K})}}{e^{-Q/R(308 \text{ K})}},$$

or

$$\tau_{35^\circ\mathrm{C}} = \tau_{25^\circ\mathrm{C}}\exp\left[\frac{Q}{R}\left(\frac{1}{308\ \mathrm{K}} - \frac{1}{298\ \mathrm{K}}\right)\right],$$

giving, finally,

$$\begin{aligned}\tau_{35^\circ\mathrm{C}} &= (60\ \mathrm{days})\exp\left[\frac{30\times10^3\mathrm{J/mol}}{8.314\ \mathrm{J/(mol\cdot K)}}\left(\frac{1}{308\ \mathrm{K}} - \frac{1}{298\ \mathrm{K}}\right)\right]\\ &= 40.5\ \mathrm{days}.\end{aligned}$$

Practice Problem 6.10

Using an Arrhenius equation, we are able to predict the creep rate for a given alloy at 600°C in Example 6.10. For the same system, calculate the creep rate at **(a)** 700°C, **(b)** 800°C, and **(c)** 900°C. **(d)** Plot the results on an Arrhenius plot similar to that shown in Figure 6.35.

Practice Problem 6.11

In Example 6.11, we are able to estimate a maximum service temperature for Inconel 718 in order to survive a stress of 690 MPa (100,000 psi) for 10,000 h. What is the maximum service temperature for this pressure-vessel design that will allow this alloy to survive **(a)** 100,000 h and **(b)** 1,000 h at the same stress?

Practice Problem 6.12

In Example 6.12(a), the time for relaxation of stress to 1 MPa at 25°C is calculated. **(a)** Calculate the time for stress to relax to 0.5 MPa at 25°C. **(b)** Repeat part (a) for 35°C using the result of Example 6.12b.

6.6 Viscoelastic Deformation

We shall see in the next chapter on thermal behavior that materials generally expand upon heating. This thermal expansion is monitored as an incremental increase in length, ΔL, divided by its initial length, L_0. Two unique mechanical responses are found in measuring the thermal expansion of an inorganic glass or an organic polymer (Figure 6.39). First, there is a distinct break in the expansion curve at the temperature T_g. There are two different thermal-expansion coefficients (slopes) above and below T_g. The thermal-expansion coefficient below T_g is comparable to that of a crystalline solid of the same composition. The thermal-expansion coefficient above T_g is comparable to that for a liquid. As a result, T_g is referred to as the **glass transition temperature**. Below T_g, the material is a true glass (a rigid solid), and above T_g it is a supercooled liquid (see Section 4.5). In terms of mechanical behavior, elastic deformation occurs below T_g, while

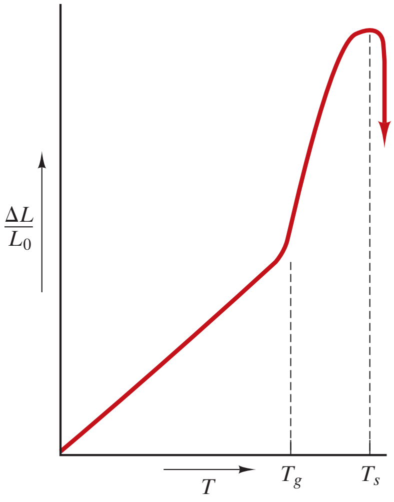


FIGURE 6.39 *Typical thermal-expansion measurement of an inorganic glass or an organic polymer indicates a glass transition temperature, T_g, and a softening temperature, T_s.*

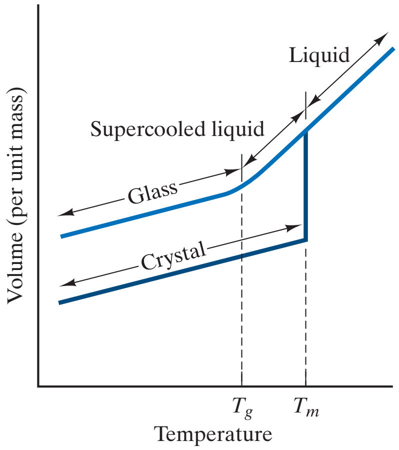


FIGURE 6.40 *Upon heating, a crystal undergoes modest thermal expansion up to its melting point (T_m), at which a sharp increase in specific volume occurs. Upon further heating, the liquid undergoes a greater thermal expansion. Slow cooling of the liquid would allow crystallization abruptly at T_m and a retracing of the melting plot. Rapid cooling of the liquid can suppress crystallization producing a supercooled liquid. In the vicinity of the glass transition temperature (T_g), gradual solidification occurs. A true glass is a rigid solid with thermal expansion similar to the crystal, but an atomic-scale structure similar to the liquid (see Figure 4.19).*

viscous (liquidlike) **deformation** occurs above T_g. Continuing to measure thermal expansion above T_g leads to a precipitous drop in the data curve at the temperature T_s. This **softening temperature** marks the point where the material has become so fluid that it can no longer support the weight of the length-monitoring probe (a small refractory rod). A plot of specific volume versus temperature is given in Figure 6.40. This plot is closely related to the thermal-expansion curve of Figure 6.39. The addition of data for the crystalline material (of the same composition as the glass) gives a pictorial definition of a glass in comparison to a supercooled liquid and a crystal.

The viscous behavior of glasses (organic or inorganic) can be described by the **viscosity**, η, which is defined as the proportionality constant between a shearing force per unit area (F/A) and velocity gradient (dv/dx),

$$\frac{F}{A} = \eta \frac{dv}{dx}, \tag{6.19}$$

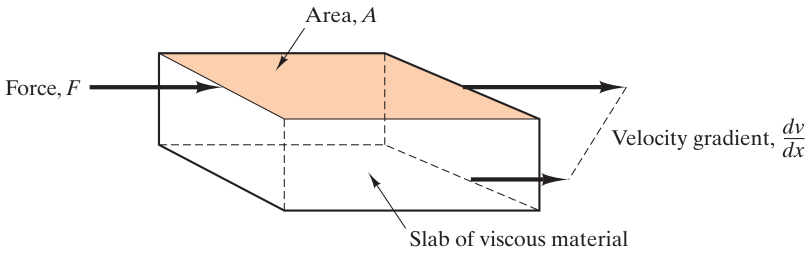


FIGURE 6.41 *Illustration of terms used to define viscosity, η, in Equation 6.19.*

with the terms illustrated in Figure 6.41. The units for viscosity are traditionally the poise $[= 1\ g/(cm \cdot s)]$, which is equal to 0.1 $Pa \cdot s$.

INORGANIC GLASSES

The viscosity of a typical soda–lime–silica glass from room temperature to 1,500°C is summarized in Figure 6.42, which serves as an example of **viscoelastic deformation** in that the plot goes from room temperature where the glass is elastic to above the glass transition temperature where it is viscous in nature. A good deal of useful processing information is contained in Figure 6.42 relative to the manufacture of glass products. The **melting range** is the temperature range (between about 1,200 and 1,500°C for soda–lime–silica glass), where η is between 50 and 500 P. This relatively low magnitude of viscosity represents a very fluid material for a silicate liquid. Water and liquid metals, however, have viscosities of only about 0.01 P. The forming of product shapes is practical in the viscosity range of 10^4 to 10^8 P, the **working range** (between about 700 and 900°C for soda–lime–silica glass). The **softening point** is formally defined at an η value of $10^{7.6}$ P (~700°C for soda–lime–silica glass) and is at the lower temperature end of the working range. After a glass product is formed, residual stresses can be relieved by holding in the *annealing range* of η from $10^{12.5}$ to $10^{13.5}$ P. The **annealing point** is defined as the temperature at which $\eta = 10^{13.4}$ P and internal stresses can be relieved in about 15 minutes (~450°C for soda–lime–silica glass). The glass transition temperature (of Figures 6.39 and 6.40) occurs around the annealing point.

Above the glass transition temperature, the viscosity data follow an Arrhenius form with

$$\eta = \eta_0 e^{+Q/RT}, \tag{6.20}$$

where η_0 is the preexponential constant, Q is the activation energy for viscous deformation, R is the universal gas constant, and T is the absolute temperature. Note that the exponential term has a positive sign rather than the usual negative sign associated with diffusivity data. The reason for this difference is simply the nature of the definition of viscosity, which decreases rather than increases with temperature. Fluidity, which could be defined as $1/\eta$, would, by definition, have a negative exponential sign comparable to the case for diffusivity.

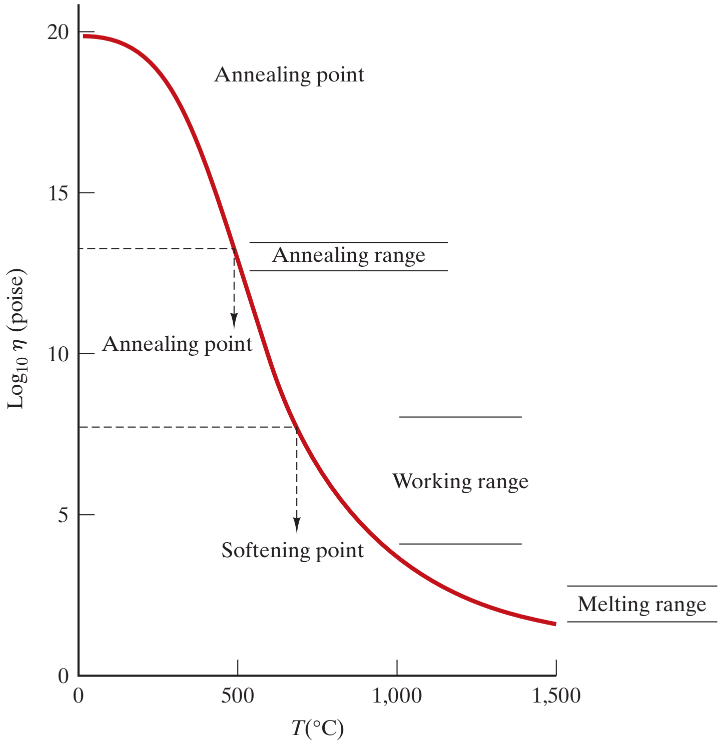


FIGURE 6.42 *Viscosity of a typical soda–lime–silica glass from room temperature to* 1,500°C. *Above the glass transition temperature* (~450°C *in this case), the viscosity decreases in the Arrhenius fashion (see Equation 6.20).*

A creative application of viscous deformation is **tempered glass**. Figure 6.43 shows how the glass is first equilibrated above the glass transition temperature, T_g, followed by a surface quench that forms a rigid surface "skin" at a temperature below T_g. Because the interior is still above T_g, interior compressive stresses are largely relaxed, although a modest tensile stress is present in the surface "skin." Slow cooling to room temperature allows the interior to contract considerably more than the surface, causing a net compressive residual stress on the surface balanced by a smaller tensile residual stress in the interior. This situation is ideal for a brittle ceramic. Susceptible to surface Griffith flaws, the material must be subjected to a significant tensile load before the residual compressive load can be neutralized. An additional tensile load is necessary to fracture the material. The breaking strength becomes the normal (untempered) breaking strength plus the magnitude of the surface residual stress. A chemical rather than thermal technique to achieve the same result is to chemically exchange larger radius K^+ ions for the Na^+ ions in the surface of a sodium-containing silicate glass. The compressive stressing of the silicate network produces a product known as **chemically strengthened glass**. (Recall that chemical strengthening plays a central role in the production of cover glass for smartphones and tablets, as introduced in Chapter 1.3.)