8.4 Nondestructive Testing

Nondestructive testing is the evaluation of engineering materials without impairing their usefulness. A central focus of many of the nondestructive testing techniques is the identification of potentially critical flaws, such as surface and internal cracks. As with fracture mechanics, nondestructive testing can serve to analyze an existing failure or it can be used to prevent future failures. The dominant techniques of this field are x-radiography and ultrasonics.

Although diffraction allows dimensions on the order of the x-ray wavelength (typically < 1 nm) to be measured, **x-radiography** produces a *shadowgraph* of the internal structure of a part with a much coarser resolution, typically on the order of 1 mm (Figure 8.22). The medical chest x-ray is a common example. Industrial x-radiography is widely used for inspecting castings and weldments. For a given material being inspected by a given energy x-ray beam, the intensity of the beam, I, transmitted through a thickness of material, x, is given by Beer's* law,

$$I = I_0 e^{-\mu x}, \tag{8.4}$$

*August Beer (1825–1863), German physicist. Beer graduated from the University of Bonn, where he was to remain as a teacher for the remainder of his relatively short life. He is primarily remembered for the law first stated relative to his observations on the absorption of visible light.

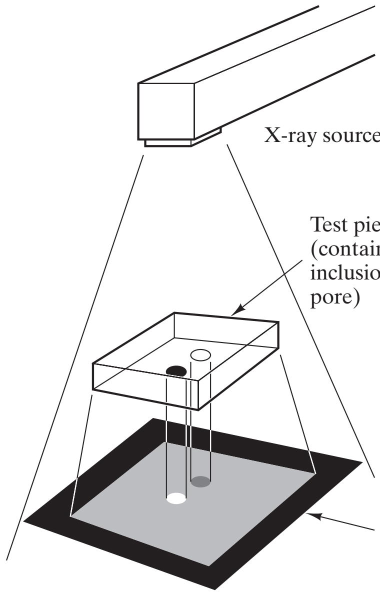

FIGURE 8.22 *A schematic of x-radiography.*

where I_0 is the incident beam intensity and μ is the linear absorption coefficient for the material. The intensity is proportional to the number of photons in the beam and is distinct from the energy of photons in the beam. The absorption coefficient is a function of the beam energy and of the elemental composition of the material. Experimental values for the μ of iron as a function of energy are given in Table 8.5. There is a general drop in the magnitude of μ with increasing beam energy primarily due to mechanisms of photon absorption and scattering. The dependence of the linear absorption coefficient on elemental composition is illustrated by the data of Table 8.6. Note that μ for a given beam energy generally increases with atomic number, causing low-atomic-number metals such as aluminum to be relatively transparent and high-atomic-number metals such as lead to be relatively opaque.

While x-radiography is based on a portion of the electromagnetic spectrum with relatively short wavelengths in comparison with the visible region, **ultrasonic testing** is based on a portion of the acoustic spectrum (typically 1 to 25 MHz)

TABLE 8.5

Linear Absorption Coefficient of Iron as a Function of X-Ray Beam Energy

Energy (MeV)	μ(mm^{-1})
0.05	1.52
0.10	0.293
0.50	0.0662
1.00	0.0417
2.00	0.0334
4.00	0.0260

Source: Selected data from D. E. Bray and R. K. Stanley, *Nondestructive Evaluation*, McGraw-Hill Book Co., New York, 1989.

TABLE 8.6

Linear Absorption Coefficient of Various Elements for an X-Ray Beam with Energy = 100 keV(=0.1 MeV)

Element	Atomic number	μ(mm^{-1})
Aluminum	13	0.0459
Titanium	22	0.124
Iron	26	0.293
Nickel	28	0.396
Copper	29	0.410
Zinc	30	0.356
Tungsten	74	8.15a
Lead	82	6.20

Source: Selected data from D. E. Bray and R. K. Stanley, *Nondestructive Evaluation,* McGraw-Hill Book Co., New York, 1989.

with frequencies well above those of the audible range (20 to 20,000 Hz). An important distinction between x-radiography and ultrasonic testing is that the ultrasonic waves are mechanical in nature, requiring a transmitting medium, while electromagnetic waves can be transmitted in a vacuum. A typical ultrasonic source involving a piezoelectric transducer is shown in Section 4 of Chapter 13.

X-ray attenuation is a dominant factor in x-radiography, but typical engineering materials are relatively transparent to ultrasonic waves. The key factor in ultrasonic testing is the reflection of the ultrasonic waves at interfaces of dissimilar materials. The high degree of reflectivity by a typical flaw, such as an internal crack, is the basis for defect inspection. Figure 8.23 illustrates a typical *pulse echo* ultrasonic inspection. This technique is not suitable for use on complex-shaped parts, and there is a tendency for ultrasonic waves to scatter due to microstructural features such as porosity and precipitates.

EXAMPLE 8.6

Calculate the fraction of x-ray beam intensity transmitted through a 10-mm-thick plate of low-carbon steel. Take the beam energy to be 100 keV. Because of the small amount of carbon and its inherently low absorption of x-rays, the steel can be approximated as elemental iron.

SOLUTION

Using Equation 8.4 and the attenuation coefficient from Table 8.6,

$$I = I_0 e^{-\mu x},$$

or

$$\begin{aligned} I/I_0 &= e^{-\mu x} \\ &= e^{-(0.293\ \text{mm}^{-1})(10\ \text{mm})} \\ &= e^{-2.93} = 0.0534. \end{aligned}$$

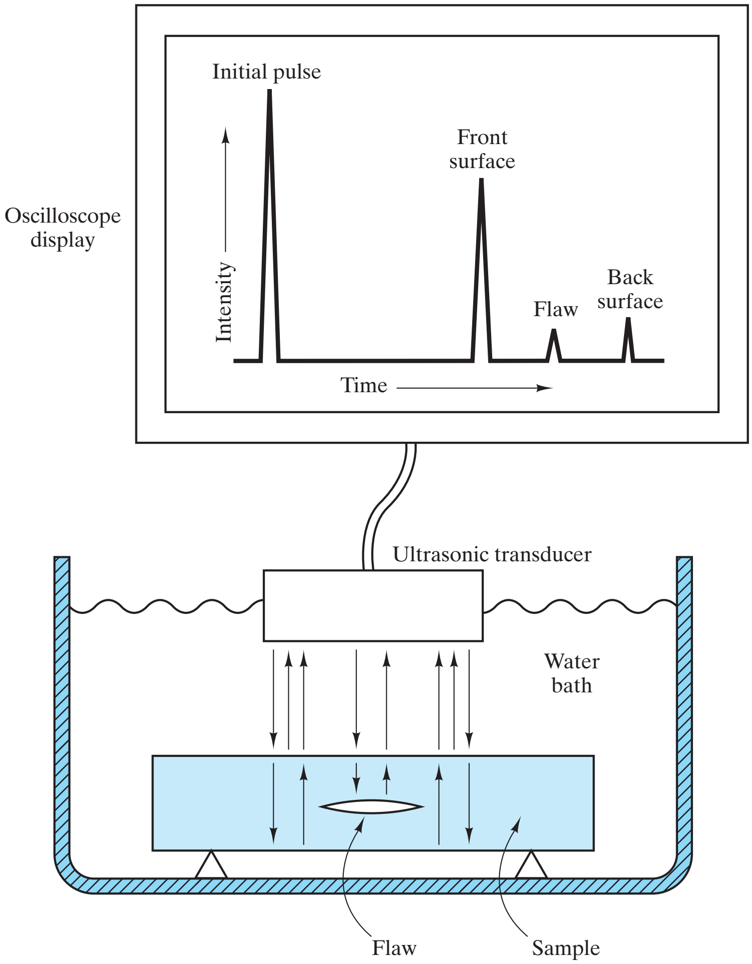

FIGURE 8.23 *A schematic of a pulse echo ultrasonic test.*

POWERS OF 10

Note that a common goal of nondestructive tests is to find millimeter scale flaws such as the one shown here. Even careful visual inspections can sometimes find these flaws when present on the surface of a structure.

PRACTICE PROBLEM 8.6

For a 100-keV x-ray beam, calculate the fraction of beam intensity transmitted through a 10-mm-thick plate of **(a)** titanium and **(b)** lead. (See Example 8.6.)