Fracture

Simple fracture is the separation of a body into two or more pieces in response to an imposed stress that is static (i.e., constant or slowly changing with time) and at temperatures that are low relative to the melting temperature of the material. The applied stress may be tensile, compressive, shear, or torsional. For engineering materials, two fracture modes are possible: **ductile** and **brittle.** Classification is based on the ability of a material to experience plastic deformation. Ductile materials typically exhibit substantial plastic deformation with high energy absorption before fracture. On the other hand, there is normally little or no plastic deformation with low energy absorption accompanying a brittle fracture. The tensile stress–strain behaviors of both fracture types may be reviewed in Figure 4-1.

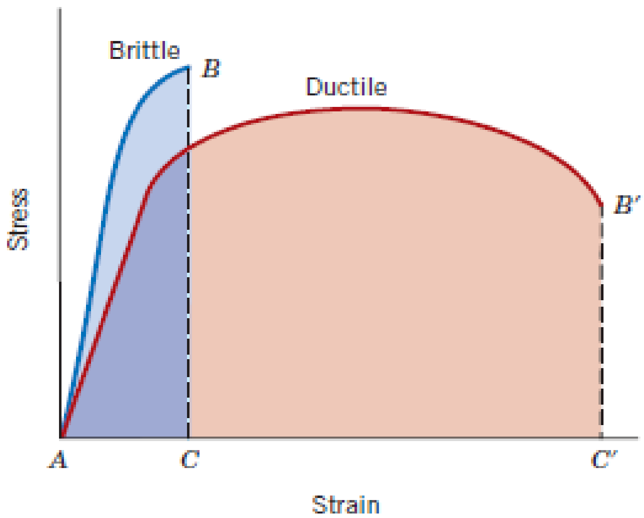

Figure 4-1 Schematic representations of tensile stress–strain behavior for brittle and ductile materials loaded to fracture.

Any fracture process involves two steps—crack formation and propagation—in response to an imposed stress. The mode of fracture is highly dependent on the mechanism f crack propagation. Ductile fracture is characterized by extensive plastic deformation in the vicinity of an advancing crack. Furthermore, the process proceeds relatively slowly as the crack length is extended. Such a crack is often said to be *stable*. That is, it resists any further extension unless there is an increase in the applied stress. On the other hand, for brittle fracture, cracks may spread extremely rapidly, with very little accompanying plastic deformation.
Such cracks may be said to be *unstable*, and crack propagation, once started, will continue spontaneously without an increase in magnitude of the applied stress.

Ductile fracture is almost always preferred for two reasons. First, brittle fracture occurs suddenly and catastrophically without any warning; this is a consequence of the spontaneous and rapid crack propagation. On the other hand, for ductile fracture, the presence of plastic deformation gives warning that fracture is imminent, allowing preventive measures to be taken. Second, more strain energy is required to induce ductile fracture inasmuch as ductile materials are generally tougher. Under the action of an applied tensile stress, most metal alloys are ductile, whereas ceramics are notably brittle, and polymers may exhibit both types of fracture.

DUCTILE FRACTURE

Ductile fracture surfaces will have their own distinctive features on both macroscopic and microscopic levels. Figure 4-2 shows schematic representations for two characteristic macroscopic fracture profiles. The configuration shown in Figure 4-2*a* is found for extremely soft metals, such as pure gold and lead at room temperature, and other metals, polymers, and inorganic glasses at elevated temperatures. These highly ductile materials neck down to a point fracture, showing virtually 100% reduction in area.
The most common type of tensile fracture profile for ductile metals is that represented in Figure 4-3*b*, where fracture is preceded by only a moderate amount of necking. The fracture process normally occurs in several stages (Figure 4-3).

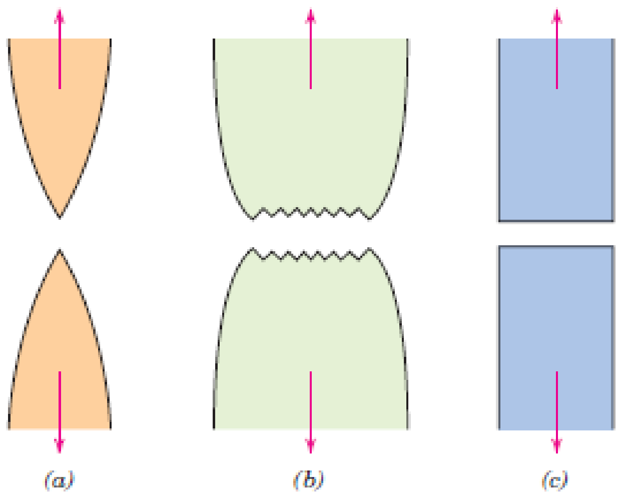

Figure 4-2 (*a*) Highly ductile fracture in which the specimen necks down to a point. (*b*) Moderately ductile fracture after some necking. (*c*) Brittle fracture without any plastic deformation.

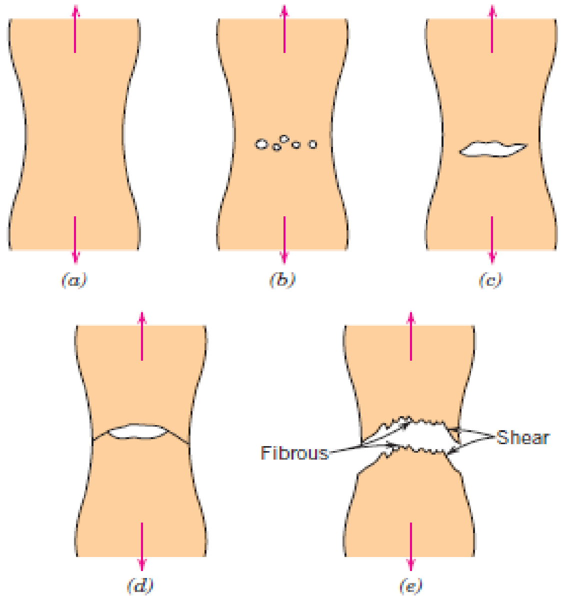

Figure 4-3 Stages in the cup-and-cone fracture. (*a*) Initial necking. (*b*) Small cavity formation. (*c*) Coalescence of cavities to form a crack. (*d*) Crack propagation. (*e*) Final shear fracture at a 45^o angle relative to the tensile direction.

First, after necking begins, small cavities, or microvoids, form in the interior of the cross section, as indicated in Figure 4-3*b*. Next, as deformation continues, these microvoids enlarge, come together, and coalesce to form an elliptical crack, which has its long axis perpendicular to the stress direction. The crack continues to grow in a direction parallel to its major axis by this microvoid coalescence process (Figure 4-3*c*). Finally, fracture ensues by the rapid propagation of a crack around the outer perimeter of the neck (Figure 4-3*d*), by shear deformation at an angle of about 45^o with the tensile axis—this is the angle at which the shear stress is a maximum. Sometimes a fracture having this characteristic surface contour is termed a *cup-and-cone fracture* because one of the mating surfaces is in the form of a cup, the other like a cone. In this type of fractured specimen (Figure 4-4*a*), the central interior region of the surface has an irregular and fibrous appearance, which is indicative of plastic deformation.

Figure 4-4 (*a*) Cup-and-cone fracture in aluminum. (*b*) Brittle fracture in a mild steel.

BRITTLE FRACTURE

Brittle fracture takes place without any appreciable deformation, and by rapid crack propagation. The direction of crack motion is very nearly perpendicular to the direction of the applied tensile stress and yields a relatively flat fracture surface, as indicated in Figure 4-2*c*.

PRINCIPLES OF FRACTURE MECHANICS

Stress Concentration

The measured fracture strengths for most brittle materials are significantly lower than those predicted by theoretical calculations based on atomic bonding energies. This discrepancy is explained by the presence of very small, microscopic flaws or cracks that always exist under normal conditions at the surface and within the interior of a body of material. These flaws are a detriment to the fracture strength because an applied stress may be amplified or concentrated at the tip, the magnitude of this amplification depending on crack orientation and geometry. When a tensile stress σ is applied, the actual stress at the crack tip is:

$$\sigma_m = 2\sigma_o \left(\frac{a}{p_t}\right)^{\frac{1}{2}}$$

Where σ_o is the magnitude of the nominal applied tensile stress, p_t is the radius of curvature of the crack tip (Figure 4-5*a*), and *a* represents the length of a surface crack, or half of the length of an internal crack. For a relatively long microcrack that has a small tip radius of curvature, the factor $(a/p_t)^{1/2}$ may be very large. This will yield a value of σ_m that is many times the value of σ_o.

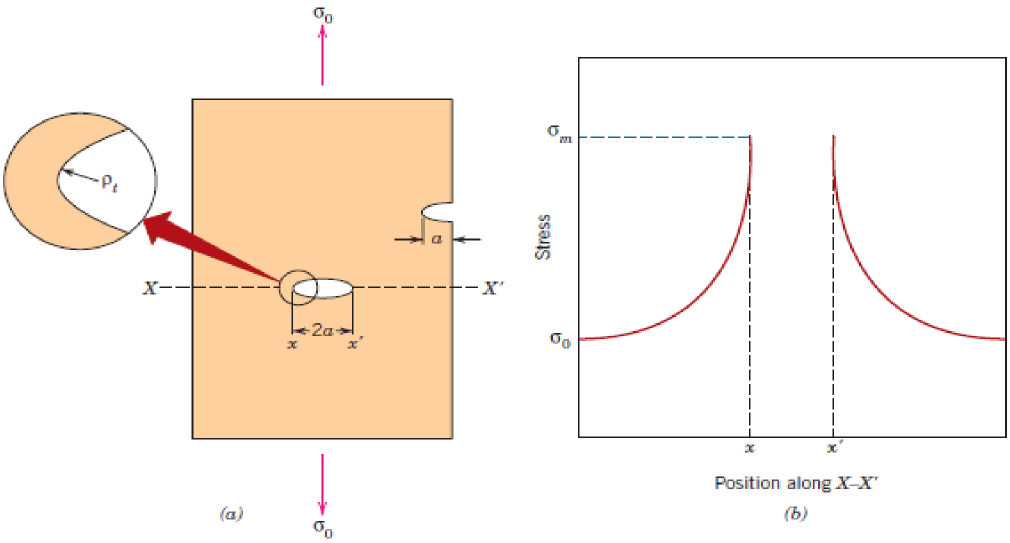

Figure 4-5 (*a*) The geometry of surface and internal cracks.
(*b*) Schematic stress profile along the line *X*–*X*′ in (*a*),
demonstrating stress amplification at crack tip positions.

Sometimes the ratio σ_m/σ_o is denoted as the *stress concentration factor* K_t

$$K_t = \frac{\sigma_m}{\sigma_o} = 2\left(\frac{a}{p_t}\right)^{\frac{1}{2}}$$

Using principles of fracture mechanics, it is possible to show that the critical stress required for crack propagation in a brittle material is described by the expression:

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{\frac{1}{2}}$$

Where

E = modulus of elasticity
a = one half the length of an internal crack
γ_s = specific surface energy

All brittle materials contain a population of small cracks and flaws that have a variety of sizes, geometries, and orientations. When the magnitude of a tensile stress at the tip of one of these flaws exceeds the value of this critical stress, a crack forms and then propagates, which results in fracture.

Example

Maximum Flaw Length Computation

A relatively large plate of a glass is subjected to a tensile stress of 40 MPa. If the specific surface energy and modulus of elasticity for this glass are 0.3 J/m^2 and 69 GPa, respectively, determine the maximum length of a surface flaw that is possible without fracture.

Solution

To solve this problem it is necessary to employ Equation 8.3. Rearrangement of this expression such that a is the dependent variable, and realizing that $\sigma = 40$ MPa, $\gamma_s = 0.3$ J/m^2, and $E = 69$ GPa leads to

$$a = \frac{2E\gamma_s}{\pi\sigma^2}$$

$$= \frac{(2)(69 \times 10^9 \text{ N/m}^2)(0.3 \text{ N/m})}{\pi(40 \times 10^6 \text{ N/m}^2)^2}$$

$$= 8.2 \times 10^{-6} \text{ m} = 0.0082 \text{ mm} = 8.2\ \mu\text{m}$$

Fracture Toughness

Furthermore, using fracture mechanical principles, an expression has been developed that relates this critical stress for crack propagation (σ_c) and crack length (a) as:

$$K_c = Y\sigma_c\sqrt{\pi a}$$

In this expression K_c is the **fracture toughness,** a property that is a measure of a material's resistance to brittle fracture when a crack is present. Worth noting is that K_c has the unusual units of MPa$\sqrt{m}$. Furthermore, Y is a dimensionless parameter or function that depends on both crack and specimen sizes and geometries, as well as the manner of load application.

Fatigue

Fatigue is a form of failure that occurs in structures subjected to dynamic and fluctuating stresses (e.g., bridges, aircraft, and machine components). Under these circumstances it is possible for failure to occur at a stress level considerably lower than the tensile or yield strength for a static load. The term "fatigue" is used because this type of failure normally occurs after a lengthy period of repeated stress or strain cycling. Fatigue is important inasmuch as it is the single largest cause of failure in metals, estimated to comprise approximately 90% of all metallic failures; polymers and ceramics (except for glasses) are also susceptible to this type of failure. Furthermore, fatigue is catastrophic and insidious, occurring very suddenly and without warning.

Fatigue failure is brittlelike in nature even in normally ductile metals, in that there is very little, if any, gross plastic deformation associated with failure. The process occurs by the initiation and propagation of cracks, and ordinarily the fracture surface is perpendicular to the direction of an applied tensile stress.

Fatigue failures typically occur in three stages. First, a tiny crack initiates or nucleates often at a time well after loading begins. Normally, nucleation sites are located at or near the surface, where the stress is at a maximum, and include surface defects such as scratches or pits, sharp corners due to poor design or manufacture, inclusions, grain boundaries, or dislocation concentrations. Next, the crack gradually propagates as the load continues to cycle. Finally, a sudden fracture of the material occurs when the remaining cross-section of the material is too small to support the applied load.

CYCLIC STRESSES

The applied stress may be axial (tension-compression), flexural (bending), or torsional (twisting) in nature. In general, three different fluctuating stress–time modes are possible. One is represented schematically by a regular and sinusoidal time dependence in Figure 4-6*a*, wherein the amplitude is symmetrical about a mean zero stress level, for example, alternating from a maximum tensile stress (σ_{max}) to a minimum compressive stress (σ_{min}) of equal magnitude; this is referred to as a *reversed stress cycle*.

Another type, termed *repeated stress cycle*, is illustrated in Figure 4-6*b*; the maxima and minima are asymmetrical relative to the zero stress level. Finally, the stress level may vary randomly in amplitude and frequency, as exemplified in Figure 4-6*c*.

Also indicated in Figure 4-6*b* are several parameters used to characterize the fluctuating stress cycle. The stress amplitude alternates about a *mean stress* σ_m, defined as the average of the maximum and minimum stresses in the cycle, or

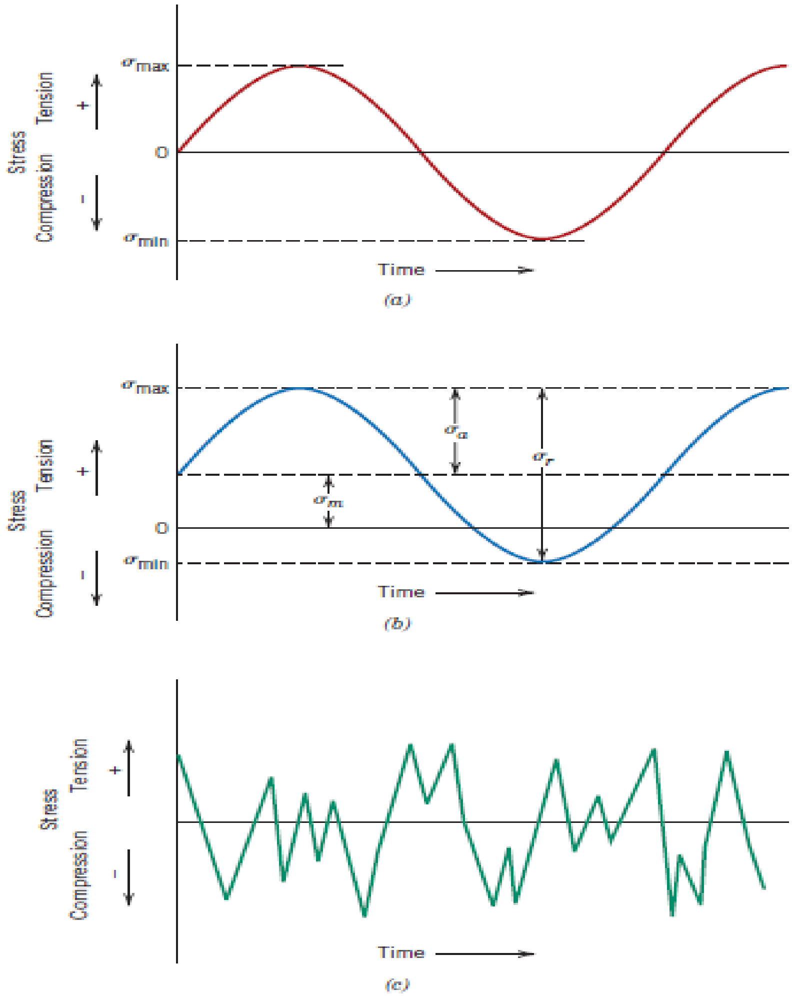

Figure 4-6 Variation of stress with time that accounts for fatigue failures. (*a*) Reversed stress cycle, in which the stress alternates from a maximum tensile stress (+) to a maximum compressive stress (-) of equal magnitude. (*b*) Repeated stress cycle, in which maximum and minimum stresses are asymmetrical relative to the zero-stress level; mean stress (**σ_m**) range of stress (**σ_r**) and stress amplitude (**σ_a**) are indicated. (*c*) Random stress cycle.

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \qquad \text{… ….} \quad (1)$$

Furthermore, the *range of stress* (**σ_r**) is just the difference between (**σ_{max}**) and (**σ_{min}**) namely,

$$\sigma_r = \sigma_{max} - \sigma_{min} \quad \text{… … .} (2)$$

Stress amplitude (**σ_a**) is just one half of this range of stress, or

$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{max} - \sigma_{min}}{2} \qquad \dots \dots \quad (3)$$

Finally, the *stress ratio R* is just the ratio of minimum and maximum stress amplitudes:

$$R = \frac{\sigma_{min}}{\sigma_{max}} \qquad \dots \dots \quad (4)$$

By convention, tensile stresses are positive and compressive stresses are negative. For example, for the reversed stress cycle, the value of *R* is -1