

Chapter 9 / Failure



An oil tanker that fractured in a brittle manner by crack propagation around its girth. (Photography by Neal Boenzi. Reprinted with permission from *The New York Times*.)

Why Study Failure?

The design of a component or structure often calls upon the engineer to minimize the possibility of failure. Thus, it is important to understand the mechanics of the various failure modes—i.e., fracture, fatigue, and creep—and, in addition, be familiar with

appropriate design principles that may be employed to prevent in-service failures. {For example, we discuss in Section 20.5 material selection and processing issues relating to the fatigue of an automobile valve spring.}

Learning Objectives

After studying this chapter you should be able to do the following:

1. Describe the mechanism of crack propagation for both ductile and brittle modes of fracture.
2. Explain why the strengths of brittle materials are much lower than predicted by theoretical calculations.
3. Define fracture toughness in terms of (a) a brief statement, and (b) an equation; define all parameters in this equation.
4. Make distinctions between *stress intensity factor*, *fracture toughness*, and *plane strain fracture toughness*.
5. Briefly explain why there is normally significant scatter in the fracture strength for identical specimens of the same ceramic material.
6. Briefly describe the phenomenon of *crazing*.
7. Name and describe the two impact fracture testing techniques.
8. Define fatigue and specify the conditions under which it occurs.
9. From a fatigue plot for some material, determine (a) the fatigue lifetime (at a specified stress level), and (b) the fatigue strength (at a specified number of cycles).
10. Define creep and specify the conditions under which it occurs.
11. Given a creep plot for some material, determine (a) the steady-state creep rate, and (b) the rupture lifetime.

9.1 INTRODUCTION

The failure of engineering materials is almost always an undesirable event for several reasons; these include human lives that are put in jeopardy, economic losses, and the interference with the availability of products and services. Even though the causes of failure and the behavior of materials may be known, prevention of failures is difficult to guarantee. The usual causes are improper materials selection and processing and inadequate design of the component or its misuse. It is the responsibility of the engineer to anticipate and plan for possible failure and, in the event that failure does occur, to assess its cause and then take appropriate preventive measures against future incidents.

Topics to be addressed in this chapter are the following: simple fracture (both ductile and brittle modes), fundamentals of fracture mechanics, impact fracture testing, the ductile-to-brittle transition, fatigue, and creep. These discussions include failure mechanisms, testing techniques, and methods by which failure may be prevented or controlled.

FRACTURE

9.2 FUNDAMENTALS OF 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; the present discussion will be confined to fractures that result from uniaxial tensile loads. 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 7.13.

“Ductile” and “brittle” are relative terms; whether a particular fracture is one mode or the other depends on the situation. Ductility may be quantified in terms

of percent elongation (Equation 7.11) and percent reduction in area (Equation 7.12). Furthermore, ductility is a function of temperature of the material, the strain rate, and the stress state. The disposition of normally ductile materials to fail in a brittle manner is discussed in Section 9.8.

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 of 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. In addition, there will ordinarily be evidence of appreciable gross deformation at the fracture surfaces (e.g., twisting and tearing). 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.

9.3 DUCTILE FRACTURE

Ductile fracture surfaces will have their own distinctive features on both macroscopic and microscopic levels. Figure 9.1 shows schematic representations for two characteristic macroscopic fracture profiles. The configuration shown in Figure 9.1a 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 9.1b, which fracture is preceded by only a moderate amount

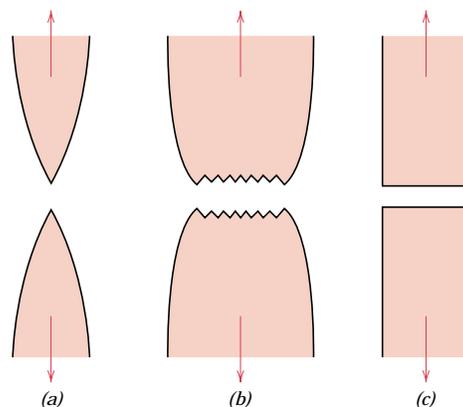


FIGURE 9.1 (a) Highly ductile fracture in which the specimen necks down to a point. (b) Moderately ductile fracture after some necking. (c) Brittle fracture without any plastic deformation.

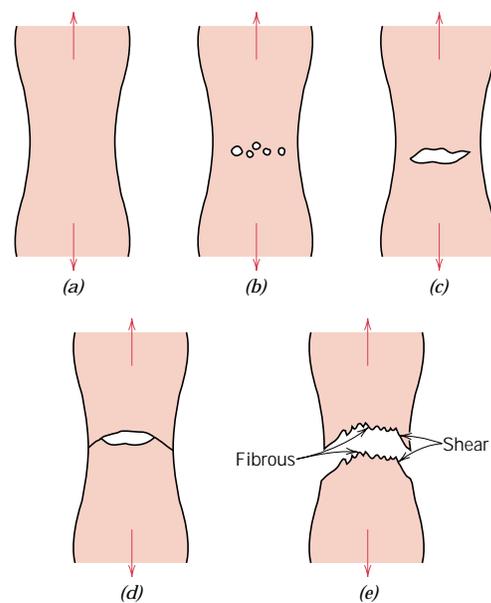


FIGURE 9.2 Stages in the cup-and-cone fracture. (a) Initial necking. (b) Small cavity formation. (c) Coalescence of cavities to form a crack. (d) Crack propagation. (e) Final shear fracture at a 45° angle relative to the tensile direction. (From K. M. Ralls, T. H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*, p. 468. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

of necking. The fracture process normally occurs in several stages (Figure 9.2). First, after necking begins, small cavities, or microvoids, form in the interior of the cross section, as indicated in Figure 9.2*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 9.2*c*). Finally, fracture ensues by the rapid propagation of a crack around the outer perimeter of the neck (Figure 9.2*d*), by shear deformation at an angle of about 45° 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 9.3*a*), the central

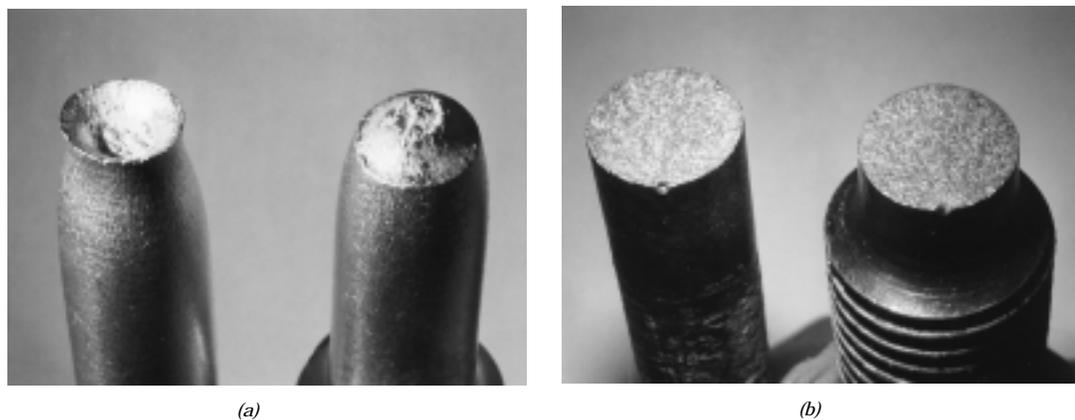


FIGURE 9.3 (a) Cup-and-cone fracture in aluminum. (b) Brittle fracture in a mild steel.

interior region of the surface has an irregular and fibrous appearance, which is indicative of plastic deformation.

FRACTOGRAPHIC STUDIES (CD-ROM)

9.4 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 9.1c.

Fracture surfaces of materials that failed in a brittle manner will have their own distinctive patterns; any signs of gross plastic deformation will be absent. For example, in some steel pieces, a series of V-shaped “chevron” markings may form near the center of the fracture cross section that point back toward the crack initiation site (Figure 9.5a). Other brittle fracture surfaces contain lines or ridges that radiate from the origin of the crack in a fanlike pattern (Figure 9.5b). Often, both of these marking patterns will be sufficiently coarse to be discerned with the naked eye. For very hard and fine-grained metals, there will be no discernible fracture pattern. Brittle fracture in amorphous materials, such as ceramic glasses, yields a relatively shiny and smooth surface.

For most brittle crystalline materials, crack propagation corresponds to the successive and repeated breaking of atomic bonds along specific crystallographic planes; such a process is termed *cleavage*. This type of fracture is said to be **transgranular** (or *transcrystalline*), because the fracture cracks pass through the grains. Macroscopically, the fracture surface may have a grainy or faceted texture (Figure 9.3b), as a result of changes in orientation of the cleavage planes from grain to grain. This feature is more evident in the scanning electron micrograph shown in Figure 9.6a.

In some alloys, crack propagation is along grain boundaries; this fracture is termed **intergranular**. Figure 9.6b is a scanning electron micrograph showing a typical intergranular fracture, in which the three-dimensional nature of the grains may be seen. This type of fracture normally results subsequent to the occurrence of processes that weaken or embrittle grain boundary regions.

9.5a PRINCIPLES OF FRACTURE MECHANICS [DETAILED VERSION (CD-ROM)]

9.5b PRINCIPLES OF FRACTURE MECHANICS (CONCISE VERSION)

Brittle fracture of normally ductile materials, such as that shown in the chapter-opening photograph of this chapter, has demonstrated the need for a better understanding of the mechanisms of fracture. Extensive research endeavors over the past several decades have led to the evolution of the field of **fracture mechanics**. This subject allows quantification of the relationships between material properties, stress level, the presence of crack-producing flaws, and crack propagation mechanisms. Design engineers are now better equipped to anticipate, and thus prevent, structural failures. The present discussion centers on some of the fundamental principles of the mechanics of fracture.