Fatigue

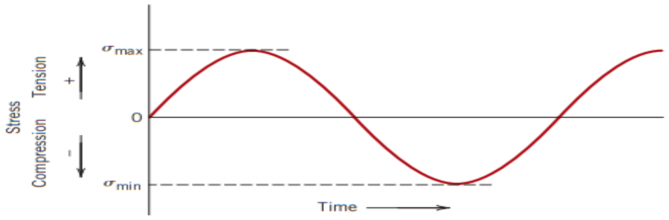
4th Lec

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.

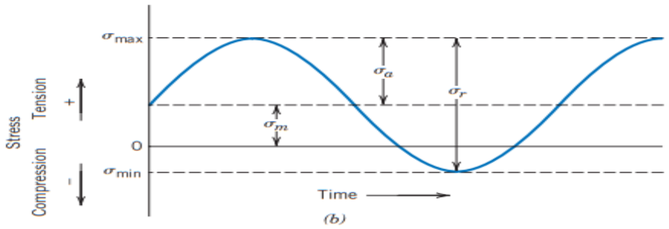
Fatigue is **important inasmuch as it is the single largest cause of failure** in metals, estimated to comprise approximately **90% of all metallic failures**; polymers and ceramics (except for glasses) are also susceptible to this type of failure. Furthermore, fatigue is occurring very **suddenly** and without warning. Fatigue failure is **brittle** like 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.

Cyclic Stresses

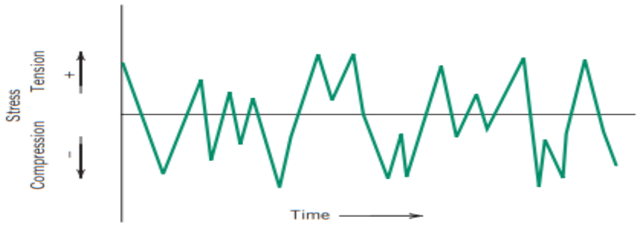
The applied stress may be **axial** (tension–compression), **flexural** (bending), or **torsional** (twisting) in nature. In general, three different fluctuating stress–time modes are possible. One is represented schematically by a regular and sinusoidal time dependence in Figure a, wherein the amplitude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



(a)



(b)



(c)

Another type, termed repeated stress cycle, is illustrated in Figure 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 c. Also indicated in Figure b are several parameters used to characterize the fluctuating stress cycle. The stress amplitude alternates about a **mean stress m, defined as the average of the maximum and minimum stresses in the cycle,** or:

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \qquad (8.14)$$

Furthermore, the *range of stress* σ_r is just the difference between $\sigma_{\max}$ and $\sigma_{\min}$—namely,

$$\sigma_r = \sigma_{\max} - \sigma_{\min} \qquad (8.15)$$

Stress amplitude σ_a is just one-half of this range of stress, or

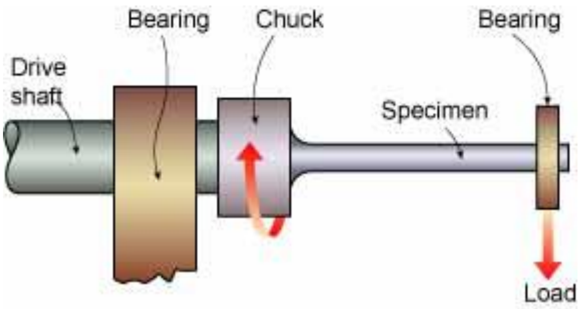
$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2} \qquad (8.16)$$

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

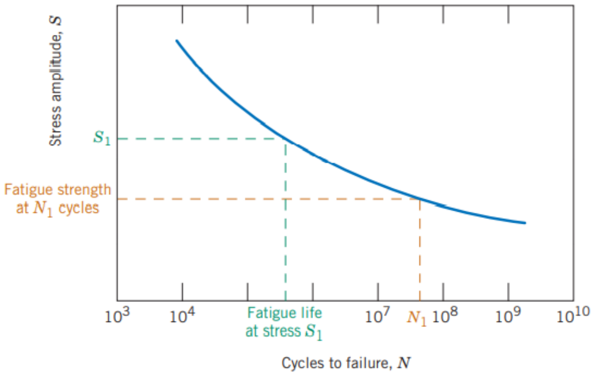
$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \qquad (8.17)$$

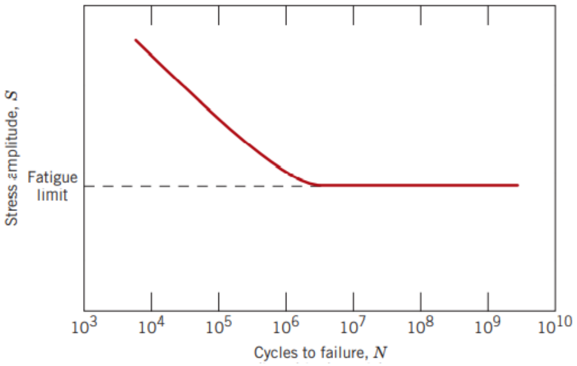
The S–N Curve

As with other mechanical characteristics, the fatigue properties of materials can be determined from laboratory simulation tests. A test apparatus should be designed to duplicate as nearly as possible the service stress conditions (stress level, time frequency, stress pattern, etc.). A schematic diagram of a rotating-bending test apparatus, commonly used for fatigue testing, is shown in Figure; the **compression and tensile stresses are imposed on the specimen as it is simultaneously bent and rotated**.



Tests are also frequently conducted using an alternating uniaxial tension–compression stress cycle. A series of tests are commenced by subjecting a specimen to the stress cycling at a relatively large maximum stress amplitude (max), usually on the order of **two-thirds of the static tensile strength**; the **<u>number of cycles to failure is counted</u>**. This procedure is **repeated on other specimens at progressively decreasing maximum stress amplitudes**. Data are plotted as stress **S** versus the logarithm of the number **N** of cycles to failure for each of the specimens. The values of S are normally taken as stress amplitudes; on occasion, max or min values may be used. Two distinct types of S–N behavior are observed, which are represented schematically in Figure.





As these plots indicate, the higher the magnitude of the stress, the smaller the number of cycles the material is capable of sustaining before failure. For some ferrous (iron base) and titanium alloys, the S–N curve becomes horizontal at higher N values; or there is a limiting stress level, called the **fatigue limit** (also sometimes the endurance limit), below which fatigue failure will not occur. This fatigue limit represents the **largest value of fluctuating stress** that will not cause failure for essentially an infinite number of cycles. For many steels, fatigue limits range between 35% and 60% of the tensile strength.

Most nonferrous alloys (e.g., aluminum, copper, magnesium) **do not have a fatigue limit,** in that the S–N curve continues its downward trend at increasingly greater N values . Thus, fatigue will ultimately occur regardless of the magnitude of the stress. For these materials, the fatigue response is specified as **fatigue strength**, which is defined as the stress level at which failure will occur for some **specified number** of cycles (e.g., 107 cycles).

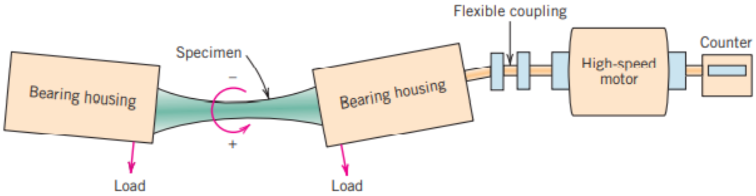


Figure 8.18 Schematic diagram of fatigue-testing apparatus for making rotating-bending tests. (From *KEYSER, MATERIALS SCIENCE IN ENGINEERING, 4th, © 1986.* Electronically reproduced by permission of Pearson Education, Inc., Upper Saddle River, New Jersey.)

Another important parameter that characterizes a material's fatigue behavior is **fatigue life** **(Nf)**. It is the number of cycles to cause failure at a specified stress level, as taken from the S–N plot. Unfortunately, there always exists considerable scatter in fatigue data that is, a variation in the measured N value for a number of specimens tested at the same stress level. This variation may lead to **significant design uncertainties** when fatigue life and/or fatigue limit (or strength) are being considered. The scatter in results is a consequence of the fatigue sensitivity to a number of test and material parameters that are impossible to control precisely. These parameters include specimen fabrication and surface preparation, metallurgical variables, specimen alignment in the apparatus, mean stress, and test frequency.

Fatigue S–N curves similar to those shown in Figure represent "best fit" curves that have been drawn through average-value data points. It is a little unsettling to realize that approximately one-half of the specimens tested actually failed at stress levels lying nearly 25% below the curve (as determined on the basis of statistical treatments).

Crack Initiation and Propagation

The process of fatigue failure is characterized by three distinct steps:

(1) crack initiation, wherein a small crack forms at some point of high stress concentration;

(2) crack propagation, during which this crack advances incrementally with each stress cycle; and

(3) final failure, which occurs very rapidly once the advancing crack has reached a critical size.

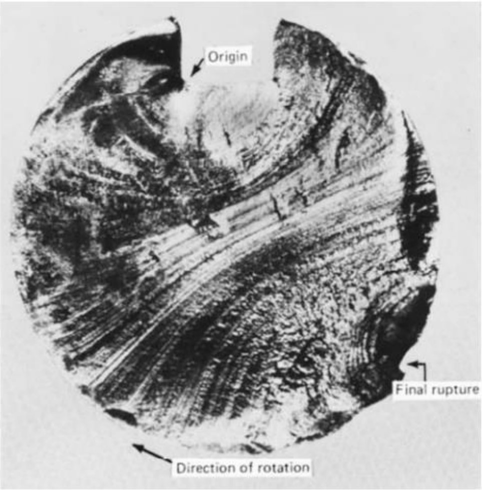


Figure 8.21 Fracture surface of a rotating steel shaft that experienced fatigue failure. Beachmark ridges are visible in the photograph. (Reproduced with permission from D. J. Wulpi, *Understanding How Components Fail,* American Society for Metals, Materials Park, OH, 1985.)

Figure 8.22 Transmission electron fractograph showing fatigue striations in aluminum. 9000×. (From V. J. Colangelo and F. A. Heiser, *Analysis of Metallurgical Failures,* 2nd edition. Copyright © 1987 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

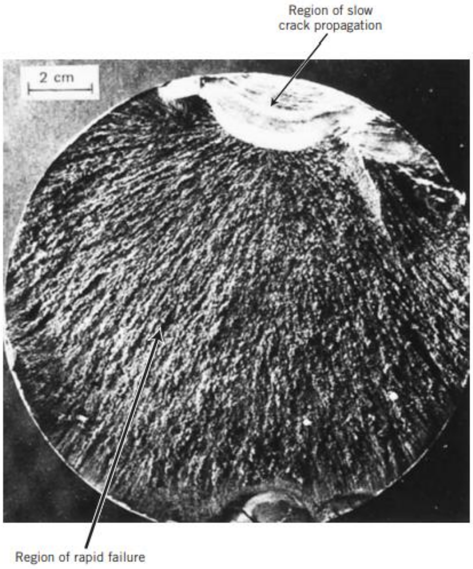


Figure 8.23 Fatigue failure surface. A crack formed at the top edge. The smooth region also near the top corresponds to the area over which the crack propagated slowly. Rapid failure occurred over the area having a dull and fibrous texture (the largest area). Approximately 0.5×. [Reproduced by permission from *Metals Handbook: Fractography and Atlas of Fractographs,* Vol. 9, 8th edition, H. E. Boyer (Editor), American Society for Metals, 1974.]

Cracks associated with fatigue failure almost always **initiate** (or nucleate) on the surface of a component at some point of **stress concentration**. Crack nucleation sites include surface scratches, sharp fillets, keyways, threads, dents, and the like. In addition, cyclic loading can produce microscopic surface discontinuities resulting from dislocation slip steps that may also act as stress raisers, and therefore as crack initiation sites.

The region of a fracture surface that formed during the crack propagation step may be characterized by two types of markings termed **beachmarks and striations**. Both of these features indicate the position of the crack tip at some point in time and appear as concentric ridges that expand away from the crack initiation site(s), frequently in a **circular or semicircular pattern**. Beachmarks are of macroscopic dimensions (Figure 8.21), and may be observed with the unaided eye. These markings are found for components that experienced interruptions during the crack propagation stage for example, a machine that operated only during normal work-shift hours. Each beachmark band represents a period of time over which crack growth occurred.

Factors That Affect Fatigue Life

The fatigue behavior of engineering materials is highly sensitive to a number of variables. Some of these factors include **mean stress level, geometrical design, surface effects, and metallurgical variables, as well as the environment**. This section is devoted to a discussion of these factors and, in addition, to measures that may be taken to improve the fatigue resistance of structural components.

Mean Stress

The dependence of fatigue life on stress amplitude is represented on the S–N plot. Such data are taken for a constant mean stress **m**, often for the reversed cycle situation (m). Mean stress, however, will also affect fatigue life; this influence may be represented by a series of S–N curves, each measured at a different m, as depicted schematically in Figure. As may be noted, **increasing the mean stress level leads to a decrease in fatigue life.**

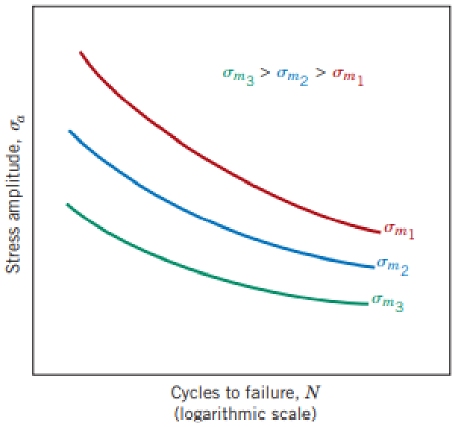


Figure 8.24 Demonstration of the influence of mean stress σ_m on S–N fatigue behavior.

Surface Effects

For many common loading situations, the maximum stress within a component or structure occurs at its surface. Consequently, most cracks leading to fatigue failure originate at surface positions, specifically at stress amplification sites. Therefore, it has been observed that fatigue life is especially sensitive to the condition and configuration of the component surface. Numerous factors influence fatigue resistance, the proper management of which will lead to an improvement in fatigue life. These include design criteria as well as **various surface treatments.**

Design Factors

The design of a component can have a significant influence on its fatigue characteristics. Any **notch** or geometrical discontinuity can act as a **stress raiser** and fatigue crack initiation site; these design features include grooves, holes, keyways, threads, and so on. **The sharper the discontinuity** (i.e., the smaller the radius of curvature), **the more severe the stress concentration**. The probability of fatigue failure may be reduced by **avoiding** (when possible) these structural irregularities, or by making design modifications whereby sudden contour changes leading to sharp corners are eliminated—for example, calling for **rounded fillets with large radii** of curvature at the point where there is a change in diameter for a rotating.

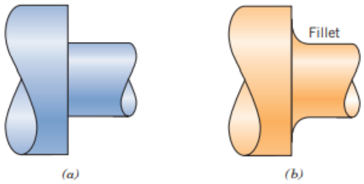


Figure 8.25 Demonstration of how design can reduce stress amplification. (*a*) Poor design: sharp corner. (*b*) Good design: fatigue lifetime improved by incorporating rounded fillet into a rotating shaft at the point where there is a change in diameter.

Surface Treatments

During machining operations, small scratches and grooves are invariably introduced into the workpiece surface by cutting tool action. These surface markings can limit the fatigue life. It has been observed that improving the surface finish by polishing will enhance fatigue life significantly. One of the most effective methods of increasing fatigue performance is by **imposing residual compressive stresses** within a thin outer surface layer. Thus, a surface tensile stress of external origin will be partially nullified and reduced in magnitude by the residual compressive stress. The net effect is that the likelihood of crack formation and therefore of fatigue failure is reduced.

Residual compressive stresses are commonly introduced into ductile metals mechanically by localized plastic deformation within the outer surface region. Commercially, this is often accomplished by a process termed **shot peening**. Small, hard particles (shot) having diameters within the range of 0.1 to 1.0 mm are projected at high velocities onto the surface to be treated. The resulting deformation induces compressive stresses to a depth of between one-quarter and one-half of the shot diameter. The influence of **shot peening** on the fatigue behavior of steel is demonstrated schematically in Figure 8.26.

Case hardening is a technique by which both surface hardness and fatigue life are enhanced for steel alloys. This is accomplished by a **carburizing** or **nitriding** process whereby a component is exposed to a carbonaceous or nitrogenous atmosphere at an elevated temperature. A carbon or nitrogen-rich outer surface layer (or "case") is introduced by atomic diffusion from the gaseous phase. The case is normally on the order of 1 mm deep and is harder than the inner core of material. The improvement of fatigue properties results from increased hardness

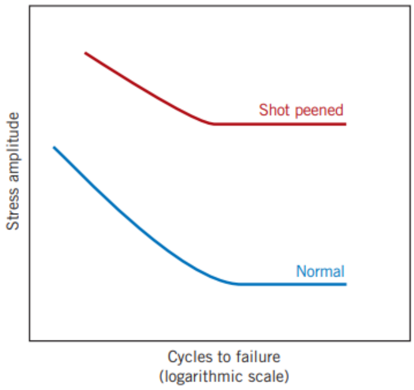


Figure 8.26 Schematic *S–N* fatigue curves for normal and shot-peened steel.

Environmental Effects

Environmental factors may also affect the fatigue behavior of materials. A few brief comments will be given relative to two types of environment-assisted fatigue failure: **thermal fatigue** and **corrosion fatigue**.

Thermal fatigue is normally induced at elevated temperatures by fluctuating thermal stresses; mechanical stresses from an external source need not be present. The origin of these thermal stresses is the restraint to the **dimensional expansion** and/or **contraction** that would normally occur in a structural member with variations in temperature. The magnitude of a thermal stress developed by a temperature change is dependent on the **coefficient of thermal expansion** and the modulus of elasticity E, thermal stresses will not arise if this mechanical restraint is absent. Therefore, one obvious way to prevent this type of fatigue is to eliminate, or at least reduce, the restraint source, thus allowing unhindered dimensional changes with temperature variations, or to choose materials with appropriate physical properties. Failure that occurs by the simultaneous action of a cyclic stress and chemical attack is termed **corrosion fatigue**.

Corrosive environments have a harmful influence and produce shorter fatigue lives. Even the normal ambient atmosphere will affect the fatigue behavior of some materials. **Small pits** may form as a result of chemical reactions (corrosion) between the environment and material, which serve as points of stress concentration and therefore as crack nucleation sites. In addition, crack propagation rate is enhanced as a result of the corrosive environment.