CHAPTER THREE

Failure of Engineering Materials

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.

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.

Types of Failure :

- Simple fracture :-
  - Ductile fracture
  - Brittle fracture
- Fatigue Failure
- Creep

1. Simple Fracture :

Simple fracture can be defined as 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). The applied stress may be tensile, compressive, shear, or torsional .

- Any fracture process involves two steps :-
  a. crack formation and
  b. crack propagation

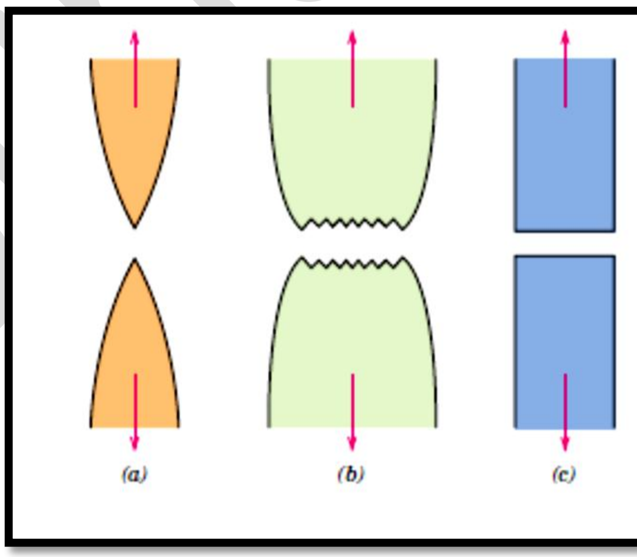
The mode of fracture is highly dependent on the mechanism of crack propagation.

- 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 in as much 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 (3.1) shows schematic representations for two characteristic macroscopic fracture profiles. The configuration shown in Figure (3.1*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.

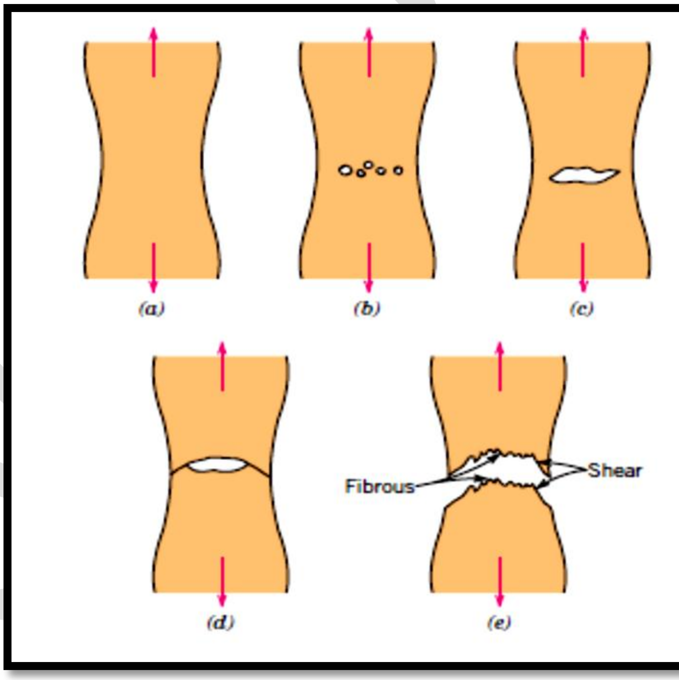
Figure(3.1) : (*a*) Highly ductile fracture in which the specimen necks down to a point.
(*b*) Moderately ductile fracture after some necking.
(*c*) Brittle fracture without any plastic deformation.

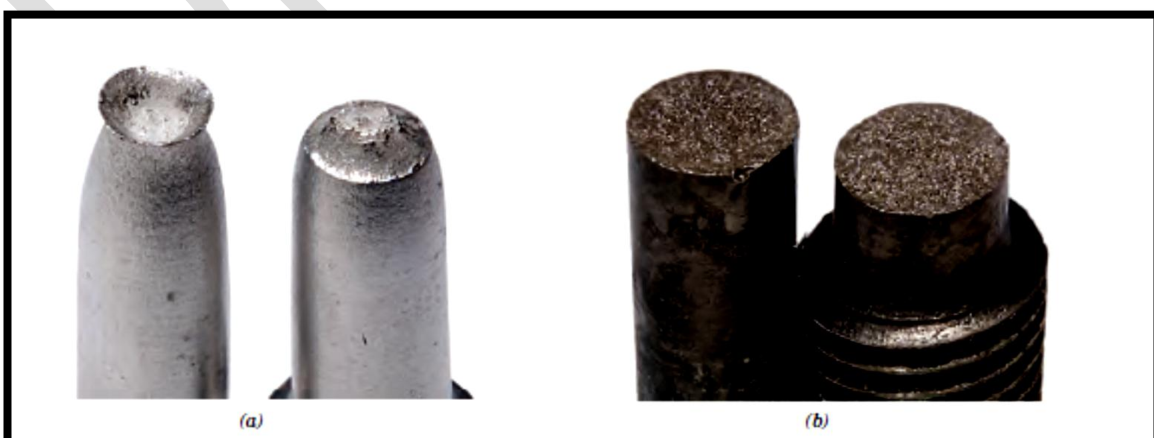


The most common type of tensile fracture profile for ductile metals is that represented in Figure 3.1b, where fracture is preceded by only a moderate amount of necking. The fracture process normally occurs in several stages (Figure 3.2). First, after necking begins, small cavities, or micro voids, form in the interior of the cross section, as indicated in Figure (3.2b). Next, as deformation continues, these micro voids 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 micro void coalescence process (Figure 3.2*c*).

Finally, fracture ensues by the rapid propagation of a crack around the outer perimeter of the neck (Figure 3.2*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 3.3a), the central interior region of the surface has an irregular and fibrous appearance, which is indicative of plastic deformation.

Figure(3.2): 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.





Figure(3.3): (*a*) Cup-and-cone fracture in aluminum. (*b*) Brittle fracture in a mild steel.

Ductility is strongly dependent on the inclusion content of the material. With increasing numbers of inclusions , the distance between the voids decreases, so it easier for them to link together and lower the ductility .

The characteristics of the surface of ductile fracture :

A ductile fracture surface has a dull, fibrous appearance and often resembles a " cup and cone " configuration .

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 (3.1*c*.).

Characterization of brittle fracture :

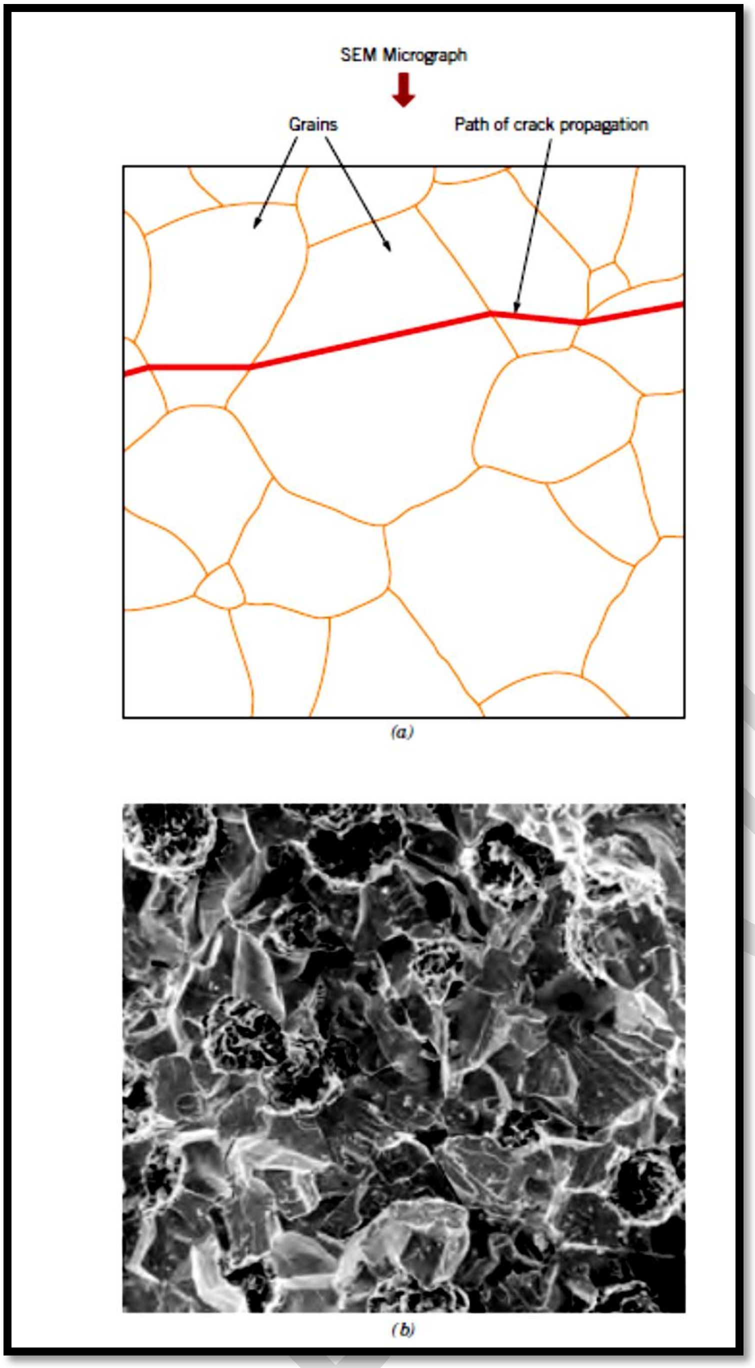
1. Rapid rate of crack propagation with no gross deformation and very little micro deformation .
2. It is a kin to cleavage in ionic.
3. A brittle fracture surface typically appears shiny with flat facets.

Brittle fracture in amorphous materials , such as ceramic glasses , are relatively shiny and smooth surfaces .

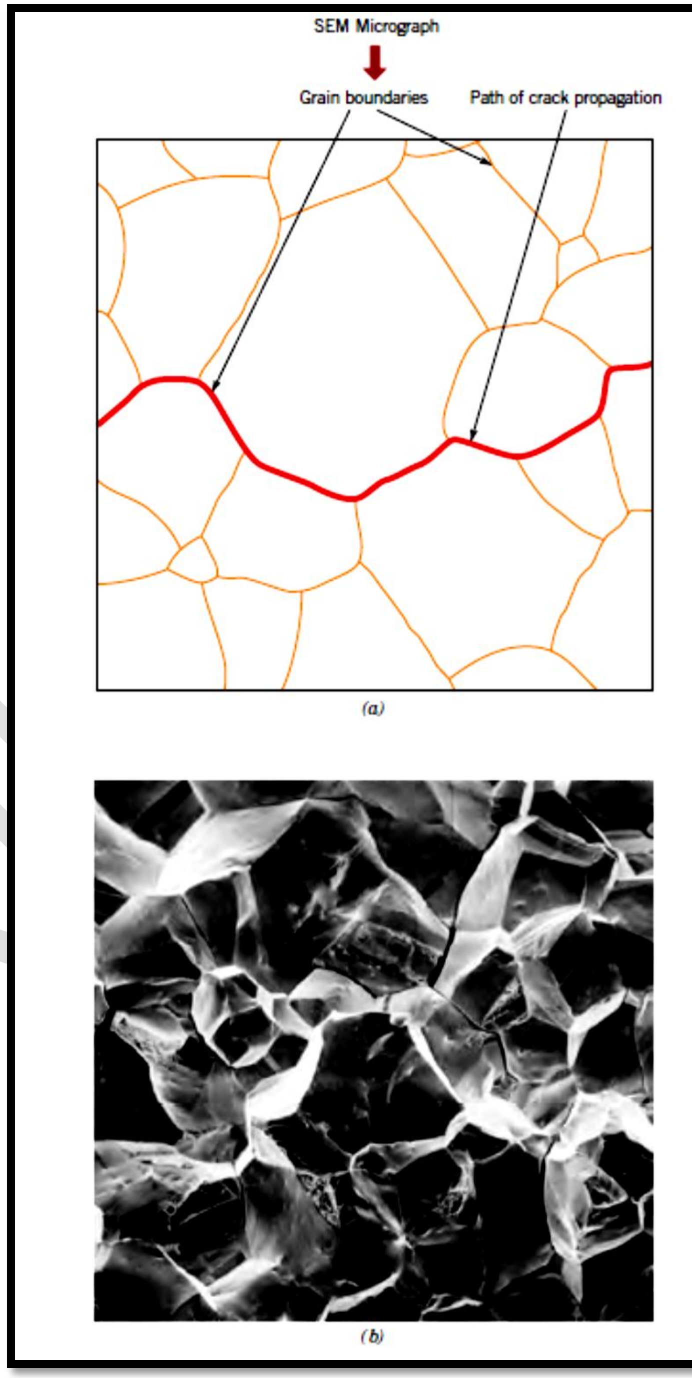
Transgranular & Intergranular Fracture :

For most brittle crystalline materials, crack propagation corresponds to the successive and repeated breaking of atomic bonds along specific crystallographic planes (Figure 3.4a). 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 3.3*b*), as a result of changes in orientation of the cleavage planes from grain to grain. This cleavage feature is shown at a higher magnification in the scanning electron micrograph of Figure 3.4*b*.

In some alloys, crack propagation is along grain boundaries (Figure 3.5a); this fracture is termed **intergranular.** Figure 3.5b is a scanning electron micrograph showing a typical intergranular fracture.



Figure(3.4): a) Schematic cross-section profile showing crack propagation through the interior of grains for transgranular fracture.
(*b*) Scanning electron fractograph of ductile cast iron showing a transgranular fracture surfac

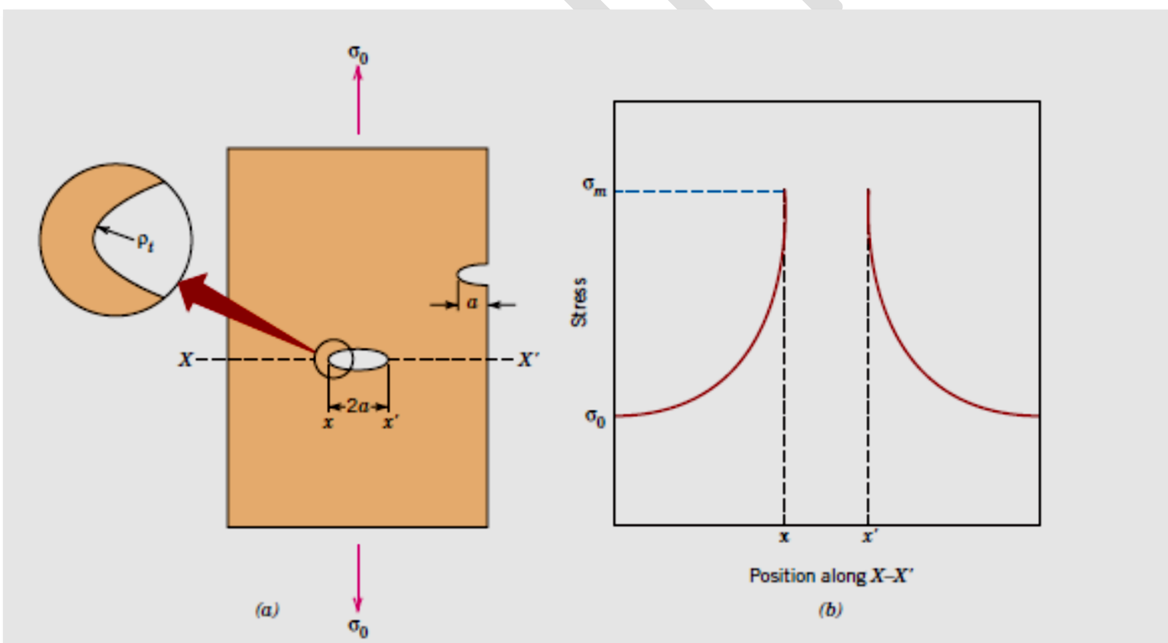


Figure(3.5): (*a*) Schematic cross-section profile showing crack propagation along grain boundaries for intergranular fracture.
(*b*) Scanning electron fractograph showing an intergranular fracture surface. 50x

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. This phenomenon is demonstrated in Figure 3.6, a stress profile across a cross section containing an internal crack. As indicated by this profile, the magnitude of this localized stress diminishes with distance away from the crack tip. At positions far removed, the stress is just the nominal stress or the applied load divided by the specimen cross-sectional area (perpendicular to this load). Due to their ability to amplify an applied stress in their locale, these flaws are sometimes called **stress raisers.**



Figure(3.6) : (*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.

If it is assumed that a crack is similar to an elliptical hole through a plate, and is oriented perpendicular to the applied stress, the maximum stress, occurs at the crack tip and may be approximated by

$$\sigma_m = 2\sigma_0\left(\frac{a}{\rho_t}\right)^{1/2}$$

where

σ_0 : is the magnitude of the nominal applied tensile stress,

ρ_t : is the radius of curvature of the crack tip (Figure 3.6*a*),

and a : represents the length of a surface crack, or half of the length of an internal crack.

Sometimes the ratio is denoted as the *stress concentration factor* (K_t)

$$K_t = \frac{\sigma_m}{\sigma_0} = 2\left(\frac{a}{\rho_t}\right)^{1/2}$$

which is simply a measure of the degree to which an external stress is amplified at the tip of a crack.

Critical stress for crack propagation in a brittle material

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

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

Where:

E = modulus of elasticity

γ_s = specific surface energy

a =one half the length of an internal crack

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 PROBLEM 8.1

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 σ = 40 MPa, γ_s = 0.3 J/m^2, and E = 69 GPa leads to

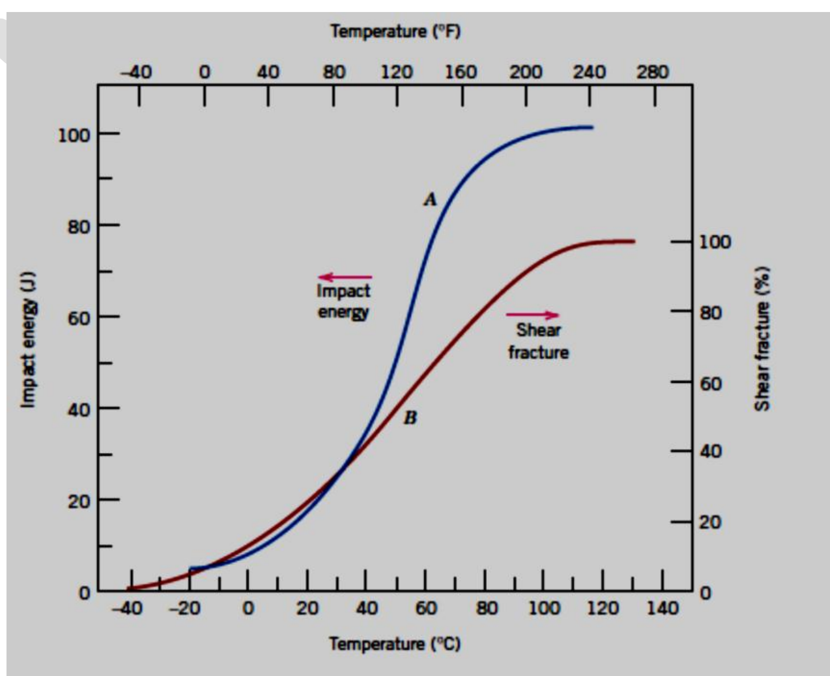
$$a = \frac{2E\gamma_s}{\pi\sigma^2}$$

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

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

Ductile-to-Brittle Transition:

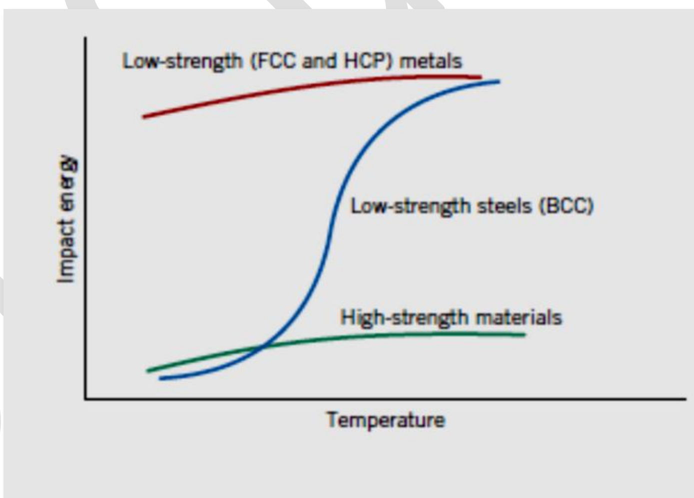
One of the primary functions of Charpy and Izod tests is to determine whether or not a material experiences a **ductile-to-brittle transition** with decreasing temperature and, if so, the range of temperatures over which it occurs.



Figure(3.7): Temperature dependence of the Charpy V-notch impact energy (curve *A*) and percent shear fracture (curve *B*) for an A283 steel.

The ductile-to-brittle transition is related to the temperature dependence of the measured impact energy absorption. This transition is represented for a steel by curve *A* in Figure 3.7 At higher temperatures the CVN energy is relatively large, in correlation with a ductile mode of fracture. As the temperature is lowered, the impact energy drops suddenly over a relatively narrow temperature range, below which the energy has a constant but small value; that is, the mode of fracture is brittle.

Structures constructed from alloys that exhibit this ductile-to-brittle behavior should be used only at temperatures above the transition temperature, to avoid brittle and catastrophic failure. Classic examples of this type of failure occurred, with disastrous consequences, during World War II when a number of welded transport ships, away from combat, suddenly and precipitously split in half. The vessels were constructed of a steel alloy that possessed adequate ductility according to room-temperature tensile tests. The brittle fractures occurred at relatively low ambient temperatures, at about 4°C.



Figure(3.8): Schematic curves for the three general types of impact energy-versus-temperature behavior

From figure (3.8) , may be noted that low-strength FCC metals (some aluminum and copper alloys) and most HCP metals do not experience a ductile-to-brittle transition (corresponding to the upper curve of Figure 3.8), and retain high impact energies (i.e., remain ductile) with decreasing temperature. For high-strength materials (e.g., high-strength steels and titanium alloys), the impact energy is also relatively insensitive to temperature (the lower curve of Figure 3.8); however, these materials are also very brittle, as reflected by their low impact energy values. And, of course, the characteristic ductile-to-brittle transition is represented by the middle curve of Figure 3.8. As noted, this behavior is typically found in low-strength steels that have the BCC crystal structure.

For these low-strength steels, the transition temperature is sensitive to both alloy composition and microstructure. For example, decreasing the average grain size results in a lowering of the transition temperature. Hence, refining the grain size both strengthens and toughens steels. In contrast, increasing the carbon content, while increasing the strength of steels, also raises the CVN transition of steels, as indicated in Figure 3.9.

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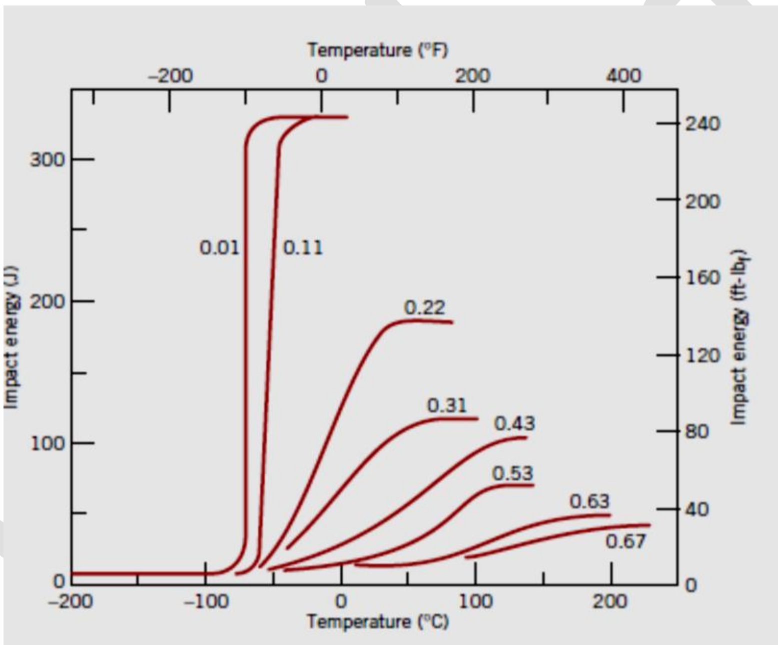


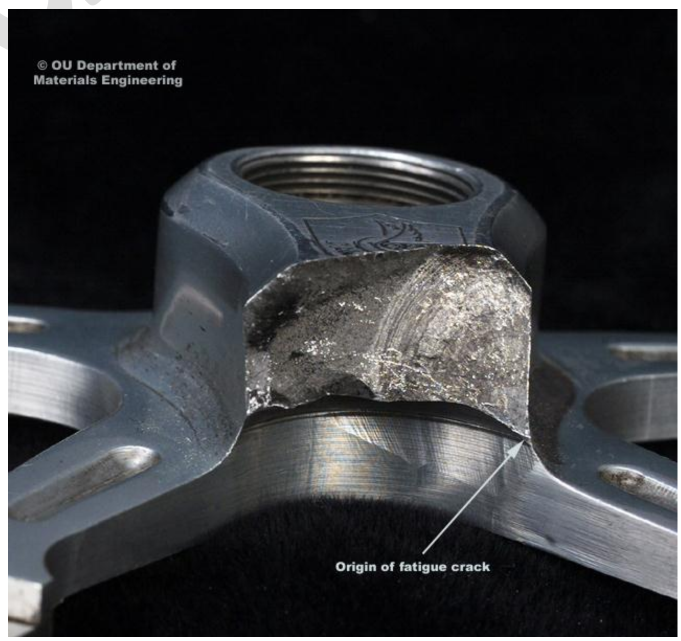
Figure(3.9) : Influence of carbon content on the Charpy V-notch energy-versus temperature behavior for steel.

2. Fatigue Failure :

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 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.

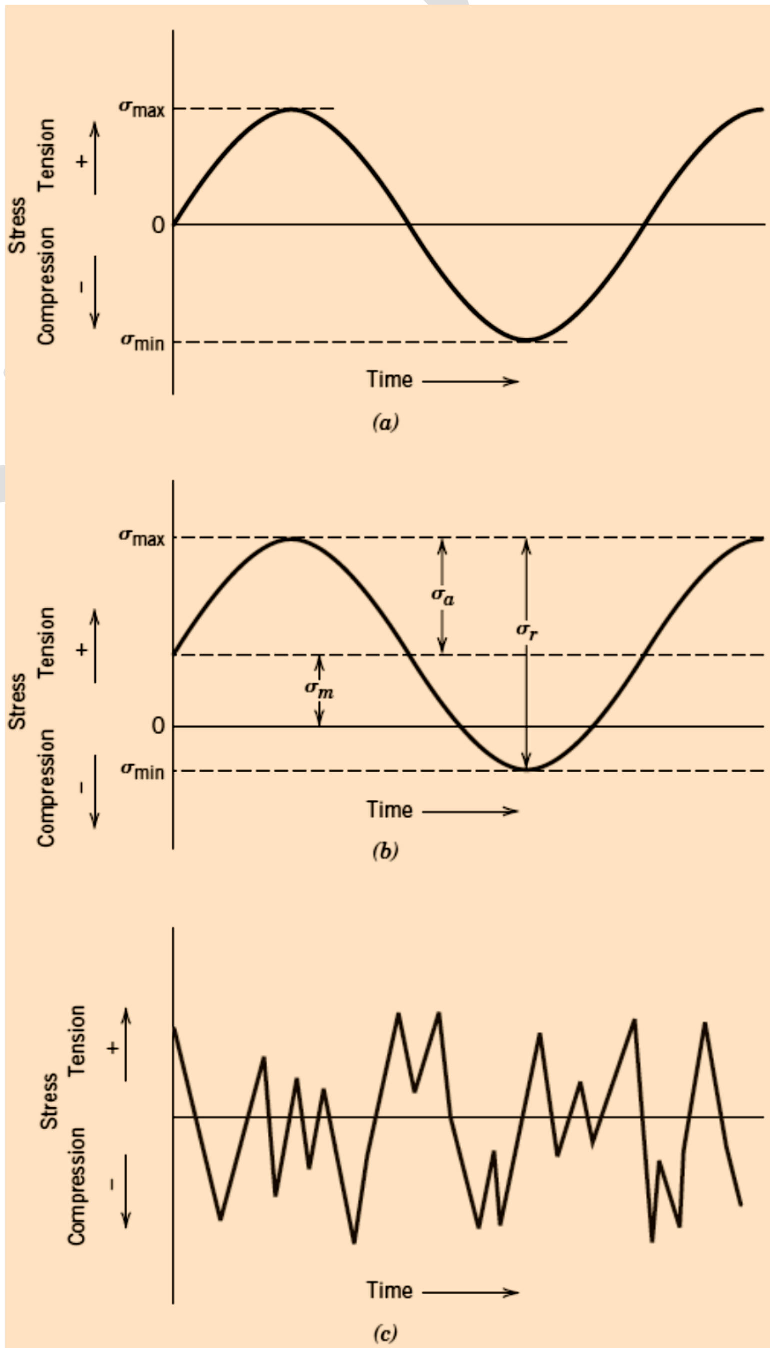


CYCLIC STRESSES

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 3.10 *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*.

Figure 3.10 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.



Another type, termed *repeated stress cycle*, is illustrated in Figure 3.10*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 3.10*c*.

Also indicated in Figure 3.10*b* are several parameters used to characterize the fluctuating stress cycle. The stress amplitude alternates about a *mean stress* defined as the average of the maximum and minimum stresses in the cycle, or

Mean stress for cyclic loading—dependence on maximum and minimum stress levels

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

Computation of range of stress for cyclic loading

$$\sigma_r = \sigma_{max} - \sigma_{min}$$

Stress amplitude ($\boldsymbol{\sigma_a}$) is just one half of this range of stress, or

Computation of stress amplitude for cyclic loading

$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{max} - \sigma_{min}}{2}$$

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

Computation of stress ratio

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$

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

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.).

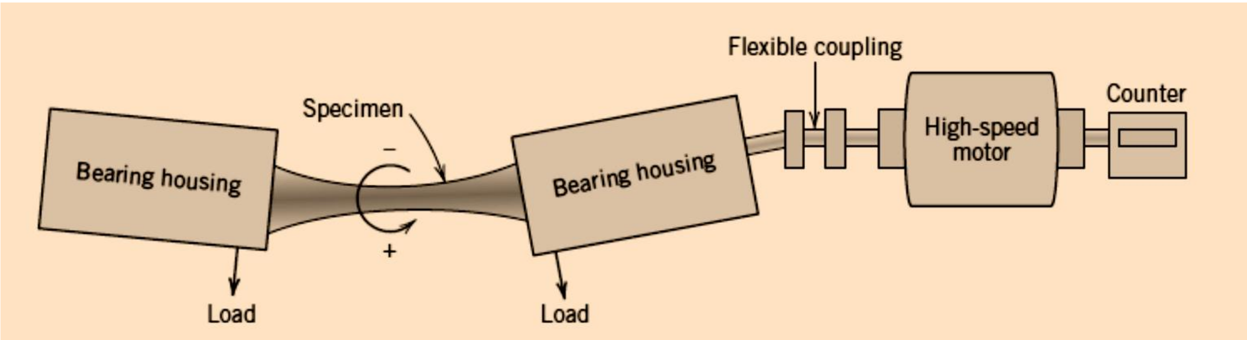


Figure 3.11 Schematic diagram of fatigue-testing apparatus for making rotating bending tests.

A schematic diagram of a rotating-bending test apparatus, commonly used for fatigue testing, is shown in Figure 3.11; 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 (σ_{max}), usually on the order of two thirds of the static tensile strength; the number of cycles to failure is counted. 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, σ_{max} or σ_{min} values may be used.

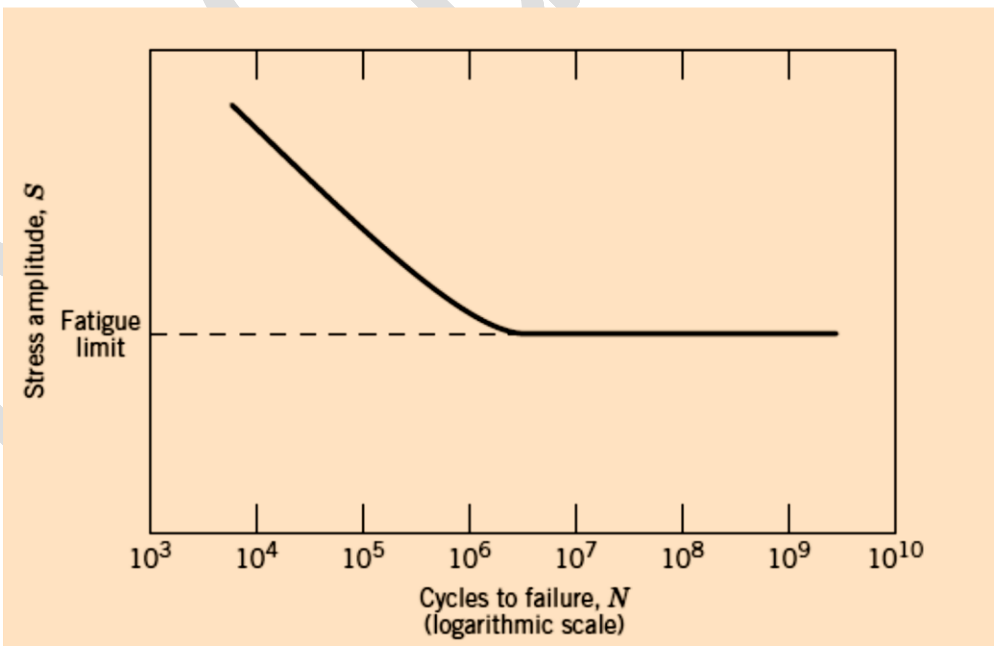
Two distinct types of *S–N* behavior are observed, which are represented schematically in Figure 3.11. As these plots indicate, the higher the magnitude of the stress, the smaller the number of cycles the material is capable of sustaining before failure. For some ferrous (iron base) and titanium alloys, the *S–N* curve (Figure 3.11) 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.

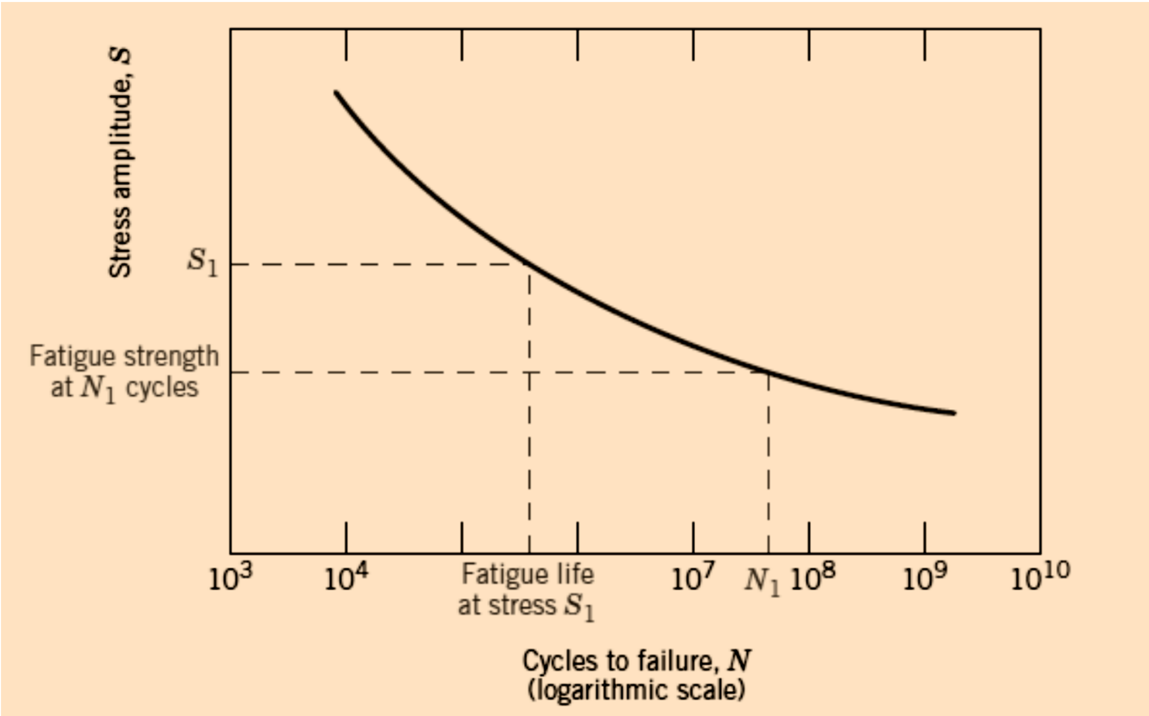
This fatigue limit represents the largest value of fluctuating stress that will *not* cause failure for essentially an infinite number of cycles.

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 (Figure 3.12). 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., 10^7cycles).** The determination of fatigue strength is also demonstrated in Figure 3.12.

Another important parameter that characterizes a material's fatigue behavior **is fatigue life It is the number of cycles to cause failure at a specified stress level, as taken from the *S*–*N* plot (Figure 3.12).**



Figure(3.11):Stress amplitude (*S*) versus logarithm of the number of cycles to fatigue failure (*N*). a material that displays a fatigue limit



Figure(3.12): Stress amplitude (*S*) versus logarithm of the number of cycles to fatigue failure (*N*) a material that does not display a fatigue limit.

Low & High cycle Fatigue

The fatigue behaviors represented in Figures 3.11 and 3.12 may be classified into two domains:

One is associated with relatively high loads that produce not only elastic strain but also some plastic strain during each cycle. Consequently, fatigue lives are relatively short; this domain is termed ***low-cycle fatigue*** and occurs at less than about 10^4 to 10^5 cycles.

For lower stress levels wherein deformations are totally elastic, longer lives result. This is called ***high-cycle fatigue*** inasmuch as relatively large numbers of cycles are required to produce fatigue failure. High-cycle fatigue is associated with fatigue lives greater than about 10^4 to 10^5 cycles.

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;

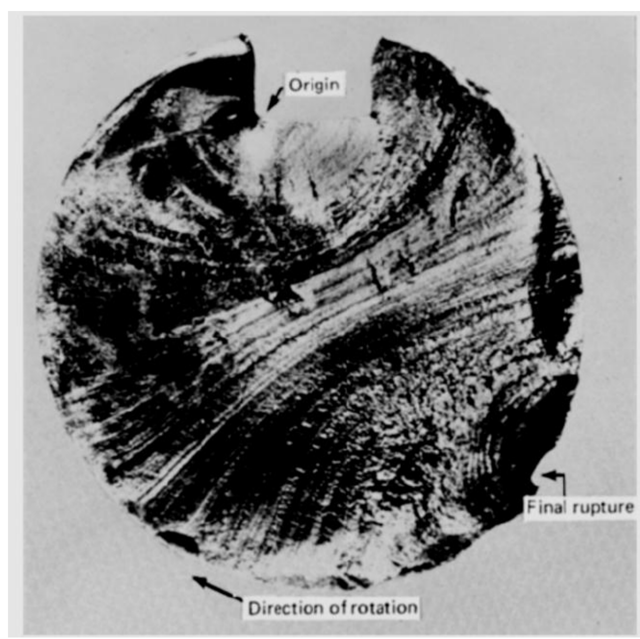
(2) crack propagation, during which this crack advances incrementally with each stress cycle; and

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

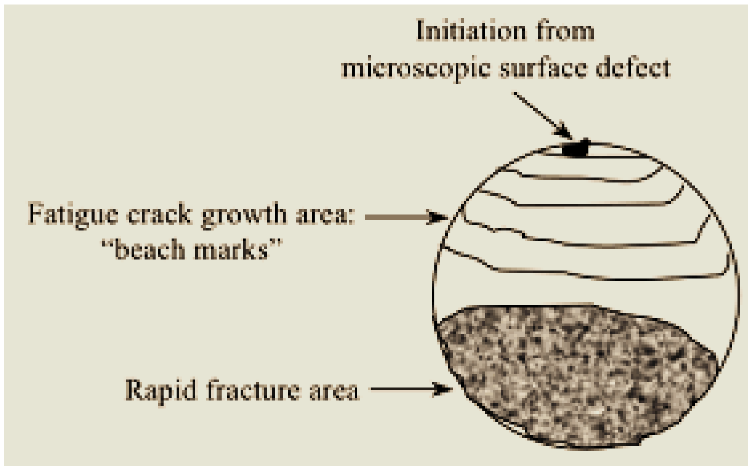
The region of a fracture surface that formed during the crack propagation step may be characterized by two types of markings termed ***beach marks*** and ***striations*.**

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. Beach marks are of macroscopic dimensions (Figure 3.13), 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 beach mark band represents a period of time over which crack growth occurred.



Figure(3.13):Fracture surface of a rotating steel shaft that experienced fatigue failure.
Beachmark ridges are visible in the photograph.

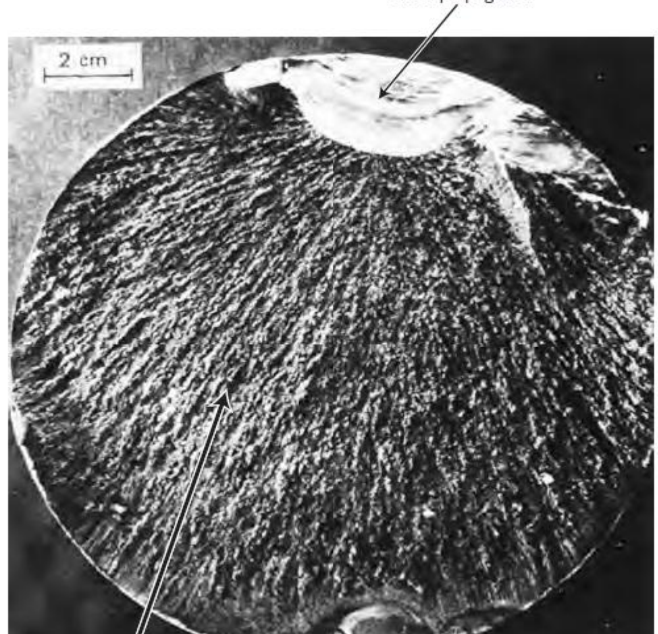
Often the cause of failure may be deduced after examination of the failure surfaces. The presence of beach marks and/or striations on a fracture surface confirms that the cause of failure was fatigue. Nevertheless, the absence of either or both does not exclude fatigue as the cause of failure.
We can recognize the beach mark and rapid fracture area from figure (3.14)



Figure(3.14): Surface of a Fatigue fracture

Rapid failure may be either ductile or brittle; evidence of plastic deformation will be present for ductile, and absent for brittle, failure. This region of failure may be noted in Figure 3.15.

Fatigue (3.15):
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).



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 σ_m, often for the reversed cycle situation ($\sigma_m = 0$). 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 as depicted schematically in Figure 3.16 As may be noted, increasing the mean stress level leads to a decrease in fatigue life.

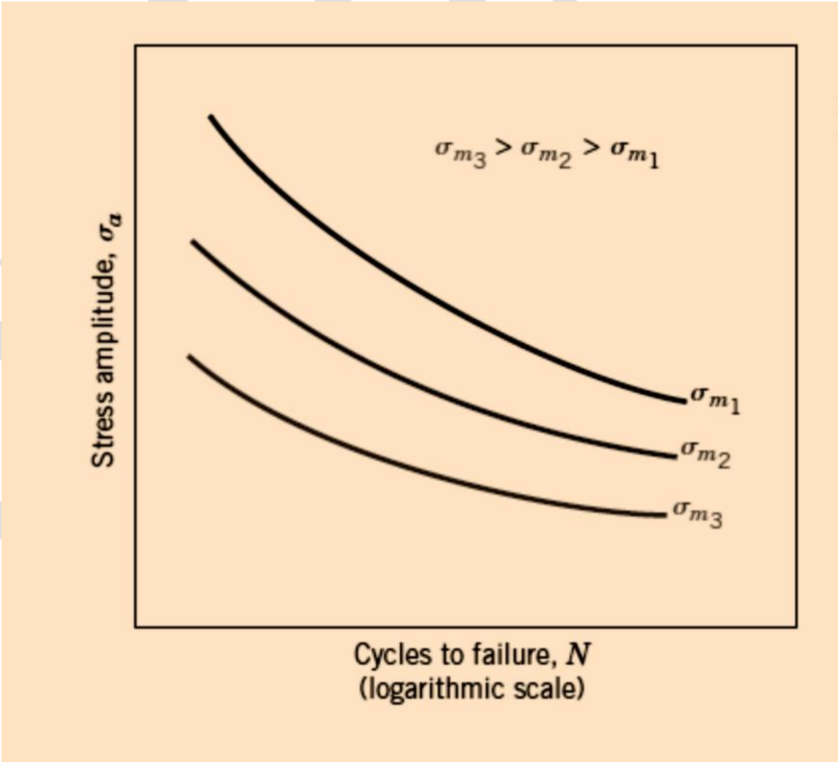


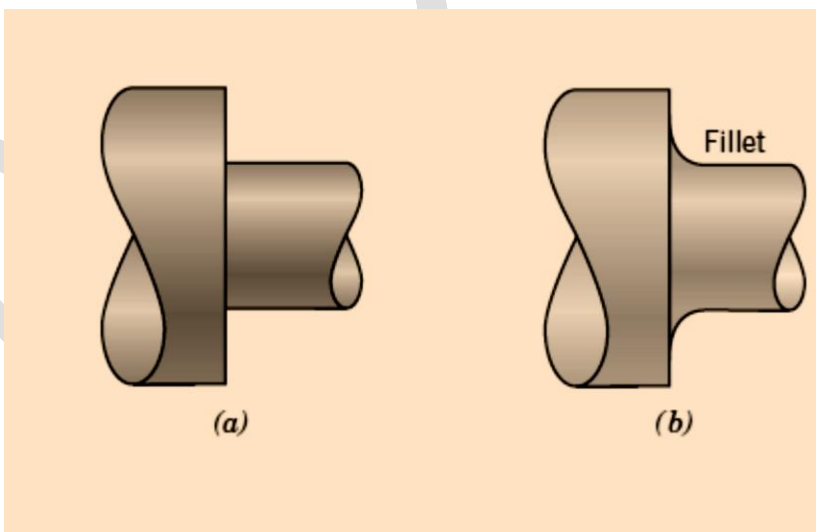
Figure 3.16: Demonstration of the influence of mean stress on *S–N* fatigue behavior.

❖ 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 shaft (Figure 3.17).



Figure(3.17): 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 work piece 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 3.18.

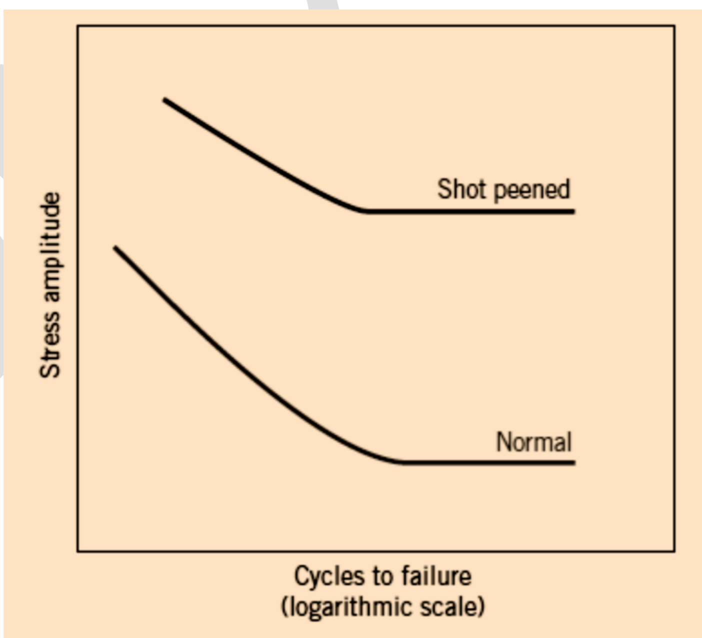


Figure 3.18: Schematic *S–N* fatigue curves for normal and shot-peened steel.

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 within the case, as well as the desired residual compressive stresses the formation of which attends the carburizing or nitriding process.

The increase in case hardness is demonstrated in the photomicrograph appearing in Figure 3.19. The dark and elongated diamond shapes are Knoop micro hardness indentations. The upper indentation, lying within the carburized layer, is smaller than the core indentation.

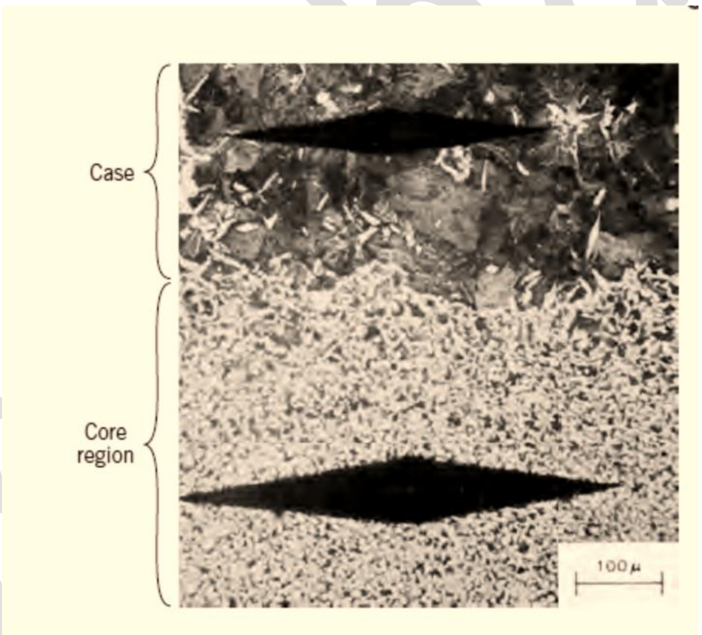


Figure 3.19: Photomicrograph showing both core (bottom) and carburized outer case (top) regions of a casehardened steel. The case is harder as attested by the smaller micro hardness indentation.

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 .
Of course, 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.(have low thermal expansion coefficient).

Corrosion Fatigue :

Failure that occurs by the simultaneous action of a cyclic stress and chemical attack is termed **corrosion fatigue.** Corrosive environments have a deleterious 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 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. The nature of the stress cycles will influence the fatigue behavior; for example, lowering the load application frequency leads to longer periods during which the opened crack is in contact with the environment and to a reduction in the fatigue life.
Several approaches to corrosion fatigue prevention exist. On one hand, we can take measures to reduce the rate of corrosion by some of the techniques for example, apply protective surface coatings, select a more corrosion-resistant material, and reduce the corrosiveness of the environment. And/or it might be advisable to take actions to minimize the

probability of normal fatigue failure, as outlined above—for example, reduce the applied tensile stress level and impose residual compressive stresses on the surface of the member.

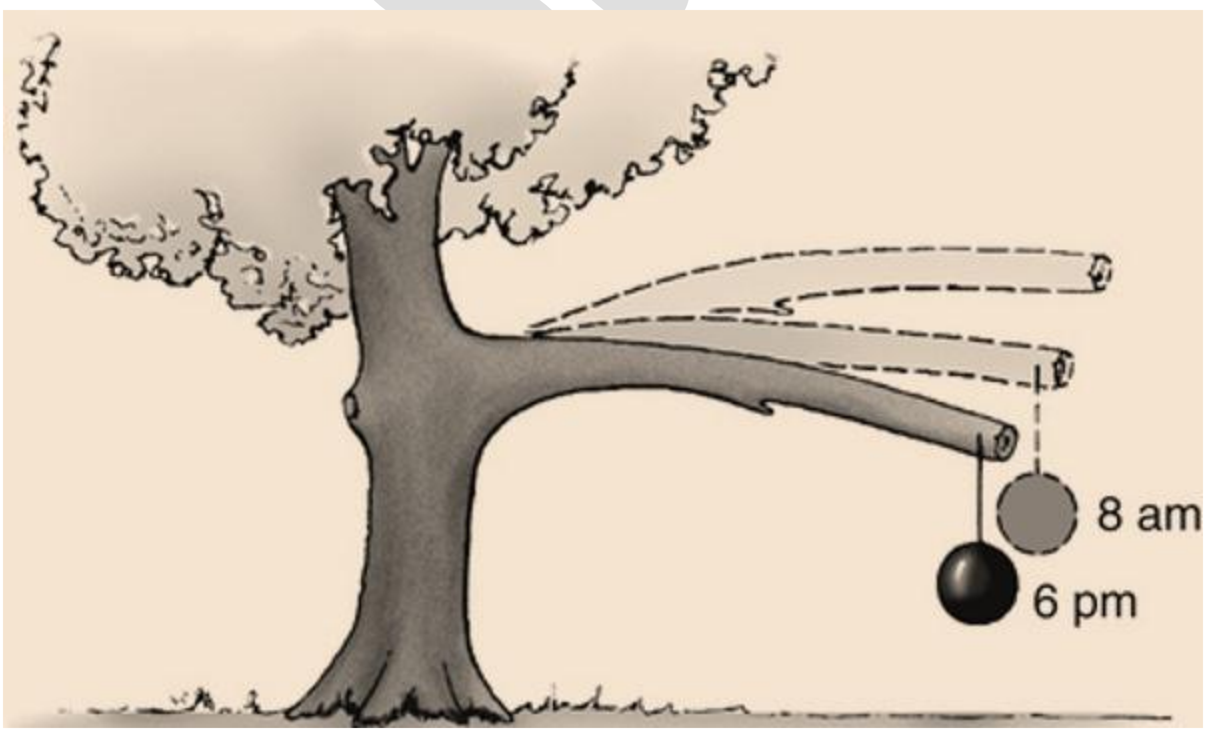
3. Creep Failure:

The term " Creep Fracture" may be defined as the fracture , which take place due to excessive creeping of materials under steady loading .

It is always exhibited in metals like iron, nickel , copper ,and their alloys at higher temperatures, but some metals like zinc , tin , lead and their alloys also creep at room temperature.

Materials are often placed in service at elevated temperatures and exposed to static mechanical stresses (e.g., turbine rotors in jet engines and steam generators that experience centrifugal stresses, and high-pressure steam lines). Deformation under such circumstances is termed **creep. Defined as the time-dependent and permanent deformation of materials when subjected to a constant load or stress, creep is normally an undesirable phenomenon and is often the limiting factor in the lifetime of a part.**

It is observed in all materials types; for metals it becomes important only for temperatures greater than about $0.4T_m$ (T_m= absolute melting temperature).



- ❖ It has been observed that the tendency of creep fracture increases with the increase in temperature , and higher rate of the straining .
- ❖ It has been observed that the creep resistance may be increased by addition of certain elements such as cobalt , nickel , manganese , tungsten etc.
- ❖ Creep takes place at a high temperature (> 0.4 T_m) .

Creep Testing :

A typical creep test consists of subjecting a specimen to a constant load or stress while maintaining the temperature constant by furnace; as shown in figure (3.20) , deformation or strain is measured and plotted as a function of elapsed time. Most tests are the constant load type, which yield information of an engineering nature; constant stress tests are employed to provide a better understanding of the mechanisms of creep.

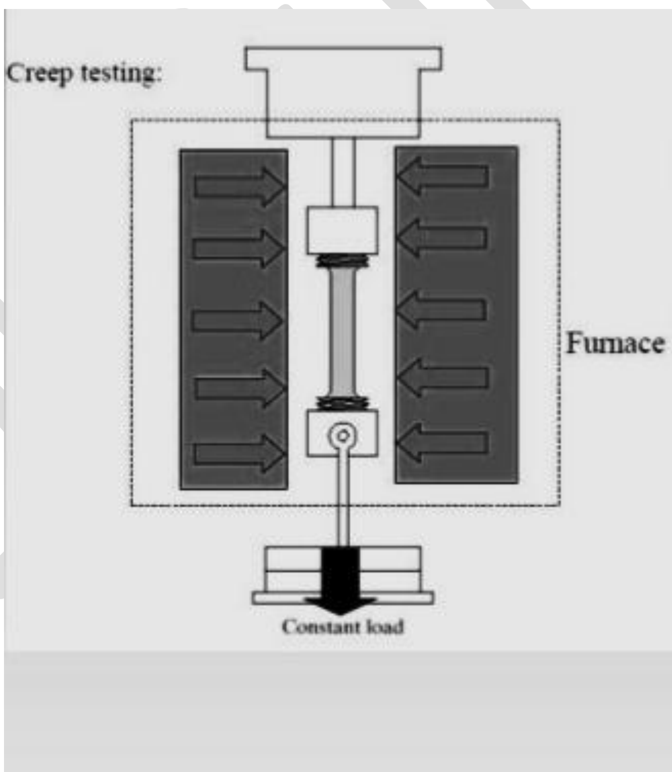


Figure (3.20): Creep Test .

GENERALIZED CREEP BEHAVIOR:

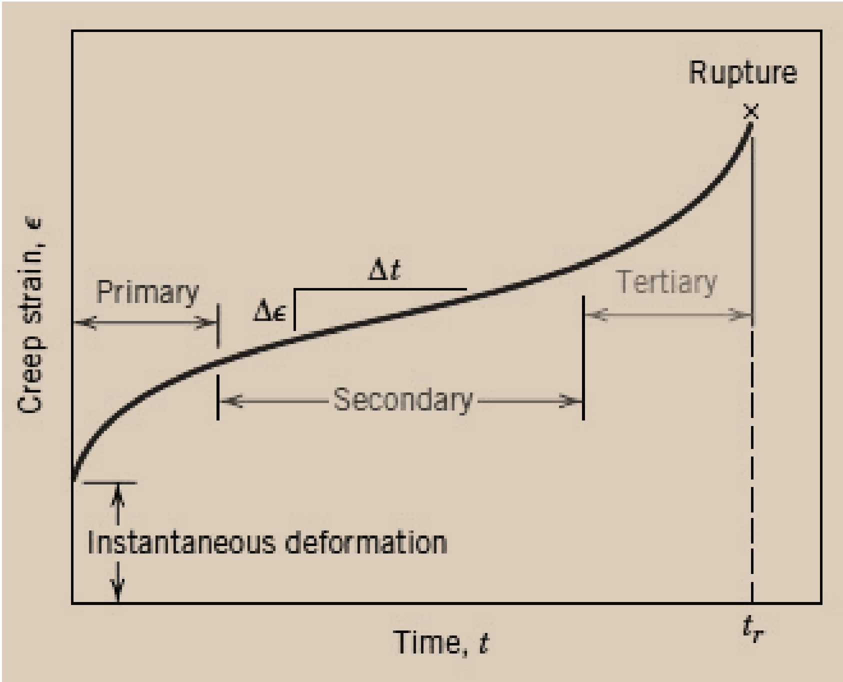


Figure (3.21) : Typical creep curve of strain versus time at constant stress and constant elevated temperature.

Figure (3.21) is a schematic representation of the typical constant load creep behavior of metals. Upon application of the load there is an instantaneous deformation, as indicated in the figure, which is mostly elastic. The resulting creep curve consists of three regions, each of which has its own distinctive strain–time feature.

1. ***Primary stage : Primary* or *transient creep* occurs first**, typified by a continuously decreasing creep rate; that is, the slope of the curve diminishes with time. This suggests that the material is experiencing an increase in creep resistance or strain hardening ,deformation becomes more difficult as the material is strained.

2. ***secondary stage :*** Sometimes termed ***steady-state creep***, the rate is constant; that is, the plot becomes linear. This is often the stage of creep that is of the longest duration. The constancy of creep rate is explained on the basis of a balance between the competing processes of strain hardening and recovery, recovery being the process

whereby a material becomes softer and retains its ability to experience deformation. This stage is the most important stage , which indicates that the creep occurs at more or less constant rate .

3. ***Finally stage* , for *tertiary creep***, there is an acceleration of the rate and ultimate failure. This failure is frequently termed ***rupture*** and results from microstructural and/or metallurgical changes; for example, grain boundary separation, and the formation of internal cracks, cavities, and voids. Also, for tensile loads, a neck may form at some point within the deformation region. These all lead to a decrease in the effective cross-sectional area and an increase in strain rate.

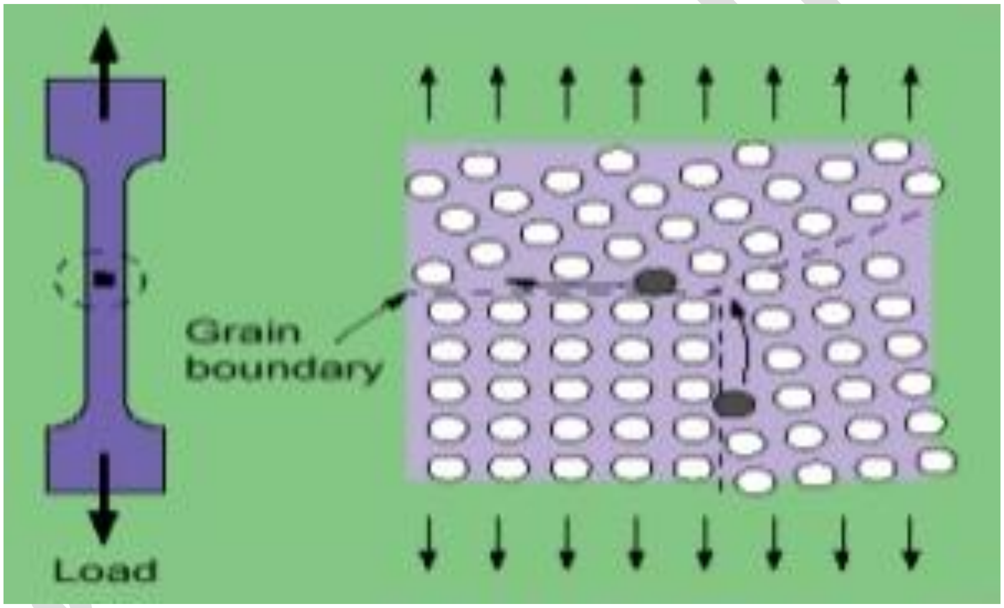
For metallic materials most creep tests are conducted in uniaxial tension using a specimen having the same geometry as for tensile tests . On the other hand, uniaxial compression tests are more appropriate for brittle materials; these provide a better measure of the intrinsic creep properties inasmuch as there is no stress amplification and crack propagation, as with tensile loads.

- Possibly the most important parameter from a creep test is the slope of the secondary portion of the creep curve($\mathcal{E}/\ t$ in Figure 3.21); this is often called the minimum or *steady-state creep rate ( )*It is the engineering design parameter that is considered for long-life applications, such as a nuclear power plant component that is scheduled to operate for several decades, and when failure or too much strain are not options. On the other hand, for many relatively short-life creep situations (e.g., turbine blades in military aircraft and rocket motor nozzles), *time to rupture*, or the *rupture lifetime* , is the dominant design consideration; it is also indicated in Figure 8.28. Of course, for its determination, creep tests must be conducted to the point of failure; these are termed *creep rupture* tests. Thus, a knowledge of these creep characteristics of a material allows the design engineer to ascertain its suitability for a specific application.

Mechanisms of Creep :

Different mechanisms are responsible for creep in different materials and under different loading and temperature conditions . The mechanism include :

1. Stress assisted vacancy diffusion .
2. Grain boundary diffusion .
3. Grain boundary sliding .
4. Dislocation motion .
   See figure (3.22).



Figure(3.22): Grain boundary sliding

STRESS AND TEMPERATURE EFFECTS:

Both temperature and the level of the applied stress influence the creep characteristics (Figure 3.23).

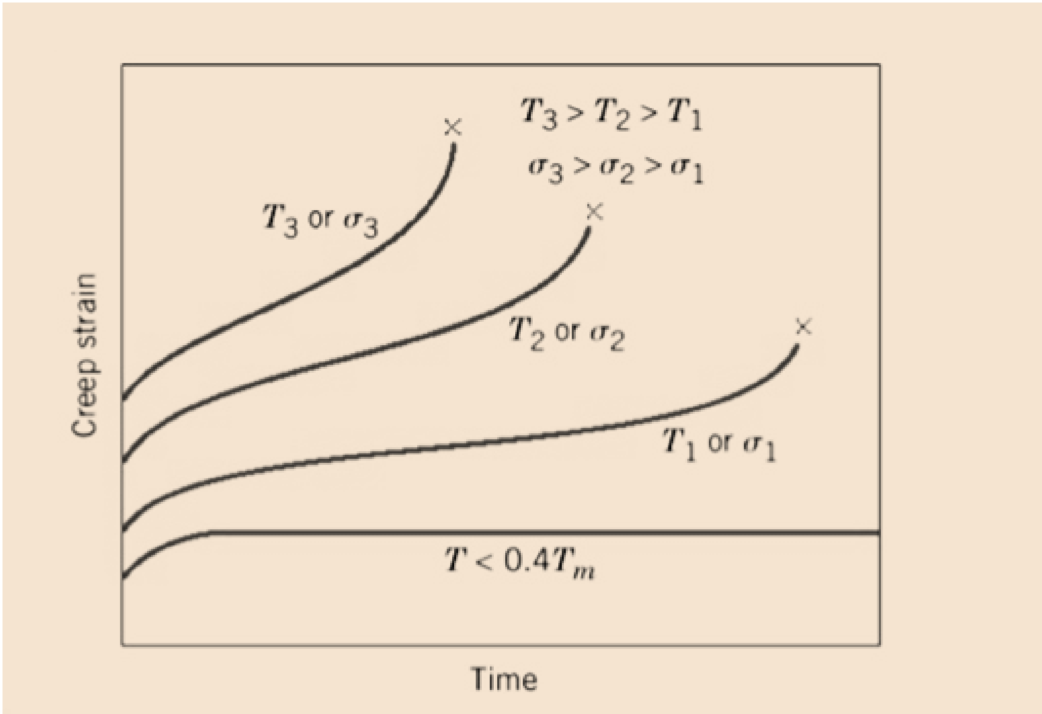


Figure (3.23) : Influence of stress and temperature on creep behavior.

At a temperature substantially below and after the initial deformation, the strain is virtually independent of time.
With either increasing stress or temperature, the following will be noted:

(1) the instantaneous strain at the time of stress application increases,
(2) the steady-state creep rate is increased,
and (3) the rupture lifetime is diminished.

It may be noted that as the applied stress or temperature increase , the creep curve shifts upwards and the time duration of the various stages reduces as shown in figure(3.23).

This indicates that the value of creep increases with increase in temperature as well as stress , therefore the material to be used at high temperature must have high melting point .

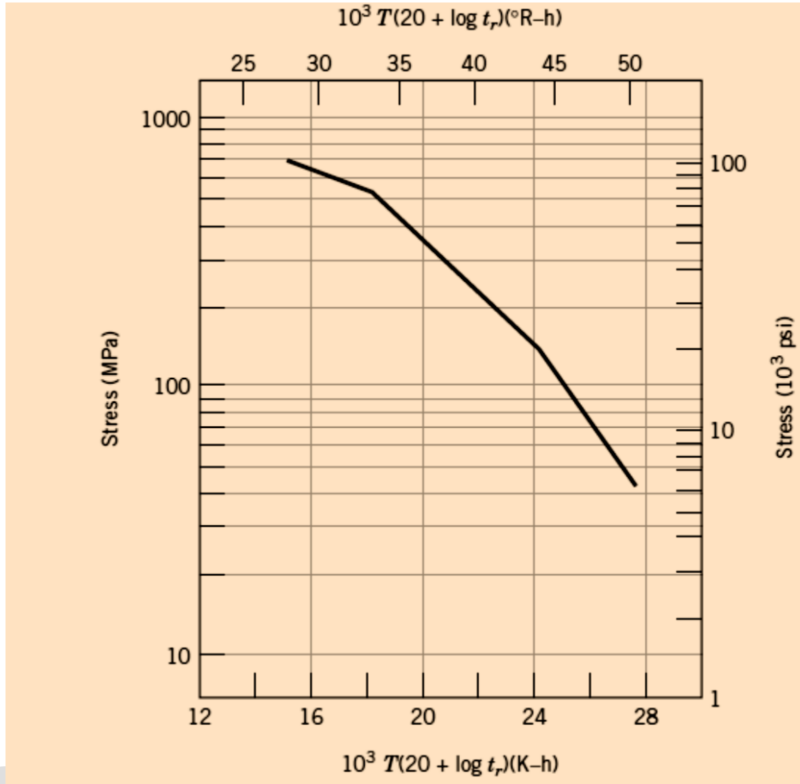
DATA EXTRAPOLATION METHODS:

The need often arises for engineering creep data that are impractical to collect from normal laboratory tests. This is especially true for prolonged exposures (on the order of years). One solution to this problem involves performing creep and/or creep rupture tests at temperatures in excess of those required, for shorter time periods, and at a comparable stress level, and then making a suitable extrapolation to the in-service condition. A commonly used extrapolation procedure employs the Larson–Miller parameter, defined as

$$T(C + \log t_r)$$

where C is a constant (usually on the order of 20), for T in Kelvin and the rupture lifetime in hours. The rupture lifetime of a given material measured at some specific stress level will vary with temperature such that this parameter remains constant.
Or, the data may be plotted as the logarithm of stress versus the Larson–Miller parameter, as shown in Figure (3.24). Utilization of this technique is demonstrated in the following design example.

Figure 3.24 Logarithm stress versus the Larson–Miller parameter for an S-590 iron.



Rupture Lifetime Prediction

Using the Larson–Miller data for S-590 iron shown in Figure 8.32, predict the time to rupture for a component that is subjected to a stress of 140 MPa (20,000 psi) at 800°C (1073 K).

Solution

From Figure 8.32, at 140 MPa (20,000 psi) the value of the Larson–Miller parameter is 24.0×10^3, for T in K and t_r in h; therefore,

$$24.0 \times 10^3 = T(20 + \log t_r)$$
$$= 1073(20 + \log t_r)$$

and, solving for the time,

$$22.37 = 20 + \log t_r$$
$$t_r = 233 \text{ h (9.7 days)}$$

Factors Affecting Creep Resistance :

There are several factors that affect the creep characteristics of metals. These Include:

1. **Melting Point :** the higher the melting temperature, the better is a material's resistance to creep.
2. **Grain Size :** smaller grains permit more grain-boundary sliding, which results in higher creep rates. This effect may be contrasted to the influence of grain size on the mechanical behavior at low temperatures [i.e., increase in both strength and toughness] So a coarse grained structure has better creep resistance .
3. **Elastic modulus :** the higher the elastic modulus , the better is a material's resistance to creep.
4. **Heat Treatment :** The creep resistance of metal is greatly affected by heat treatment .
5. **Alloying Element :** At low temperature , the creep resistance is increased by the addition of cobalt , nickel , manganese, etc. But at high temperature , the creep resistance is increased by the addition of chromium ,tungsten , vanadium , etc .

So , creep is generally minimized in materials with :

- High melting temperature.
- High elastic modulus .
- Large grain size .

The following materials are especially used :

- Stainless steel
- Refractory metals (containing elements of high melting point like Nb, Mo, W , Ta .
- Super alloys (Co, Ni based)
- In addition, advanced processing techniques have been utilized; one such technique is directional solidification, which produces either highly elongated grains or single-crystal components (Figure 2.25).

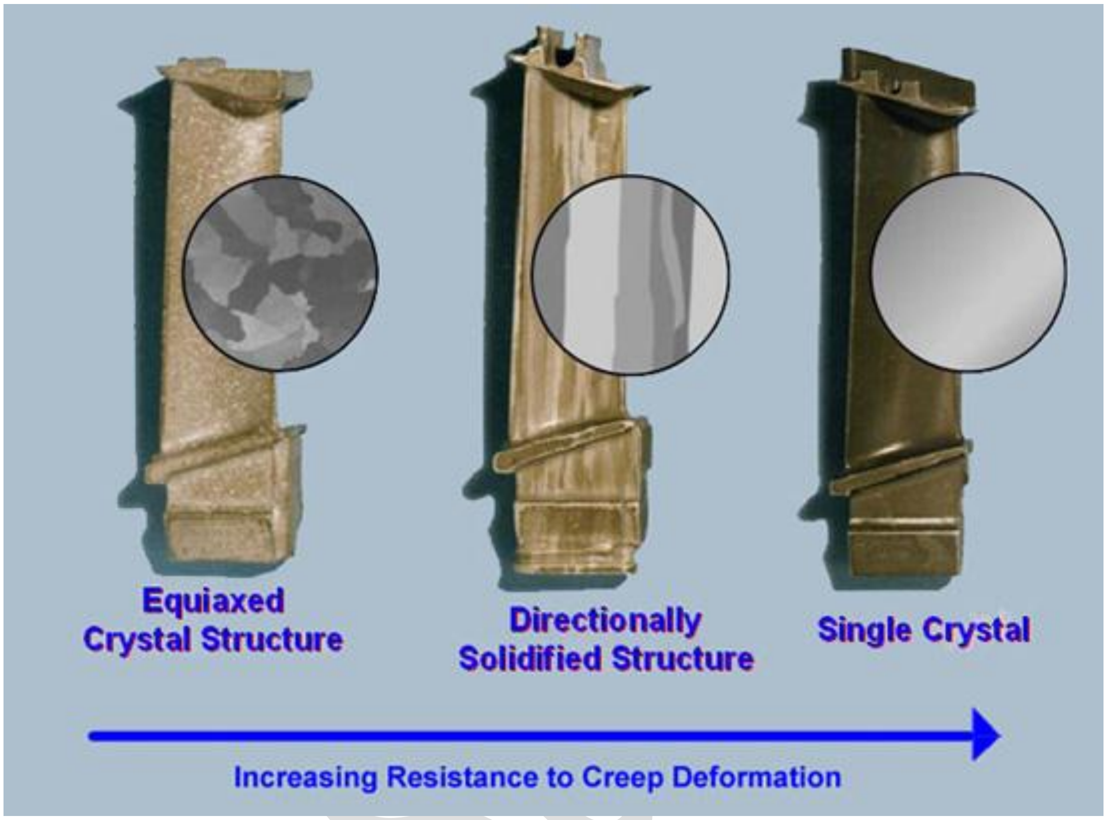


Figure (3.25): Increasing resistance to creep