Properties of Engineering Materials

Failure

Dr. Eng. Yazan Al-Zain
Department of Industrial Engineering
University of Jordan

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 interference with the availability of products and services.
- 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.

Fracture
Fundamentals of Fracture

- Simple fracture: 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.
  - Can also occur from fatigue (when cyclic stresses are imposed) and creep (time-dependent deformation, normally at elevated temperatures).
- For metals, two fracture modes are possible: **ductile** and **brittle.**
  - Ductile Metals: exhibit substantial plastic deformation with high energy absorption before fracture.
  - Brittle Metals: little or no plastic deformation with low energy absorption accompanying a brittle fracture.

Fracture
Ductile Fracture vs. Brittle Fracture

- Fracture process involves two steps: (1) crack formation and (2) propagation in response to an imposed stress.
- Ductile fracture is characterized by:
  - (1) Extensive plastic deformation in the vicinity of an advancing crack.
  - (2) The process proceeds relatively slowly as the crack length is extended. Such a crack is often said to be *stable* and resists any further extension unless there is an increase in the applied stress
- 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.

Fracture

Ductile Fracture

Extremely ductile (Au, Pb)

Moderately ductile (most metals and metal alloys)

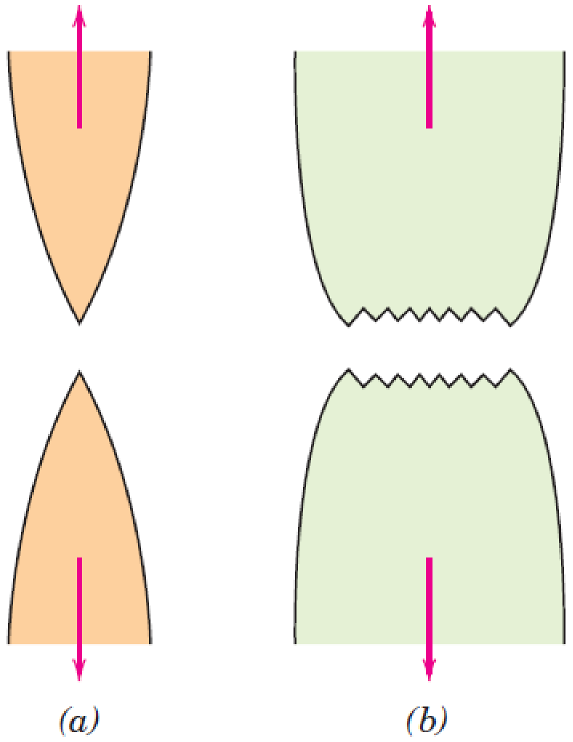
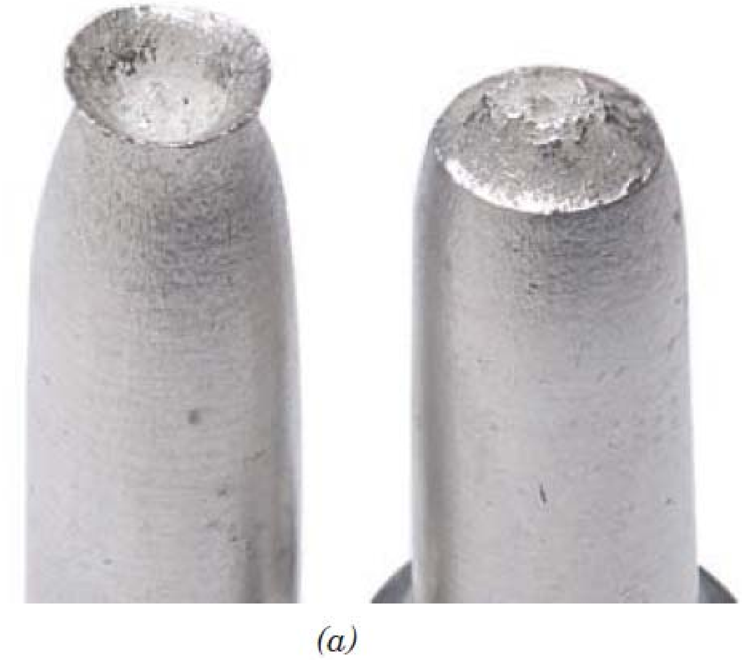


Figure 8.1 (*a*) Highly ductile fracture in which the specimen necks down to a point. (*b*) Moderately ductile fracture after some necking.

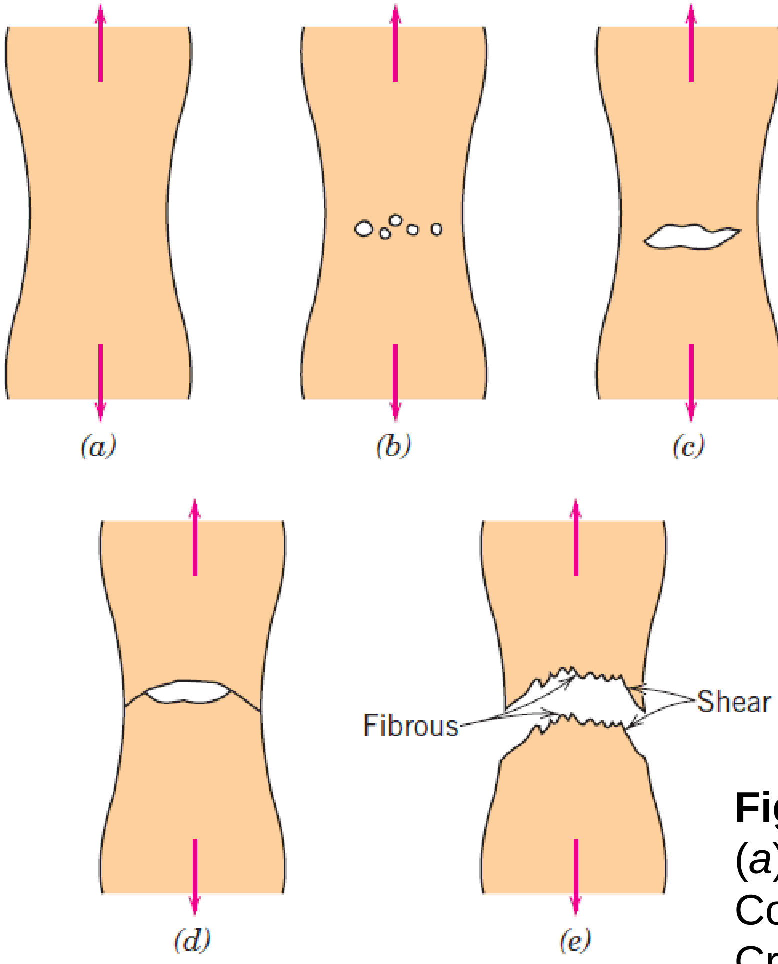
Fracture

Ductile Fracture



Irregular fibrous appearance

Figure 8.3 (*a*) Cup- and- cone fracture in aluminum.



Stages of Fracture Process

Figure 8.2 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.

Fracture

Ductile Fracture / Fractographic Studies

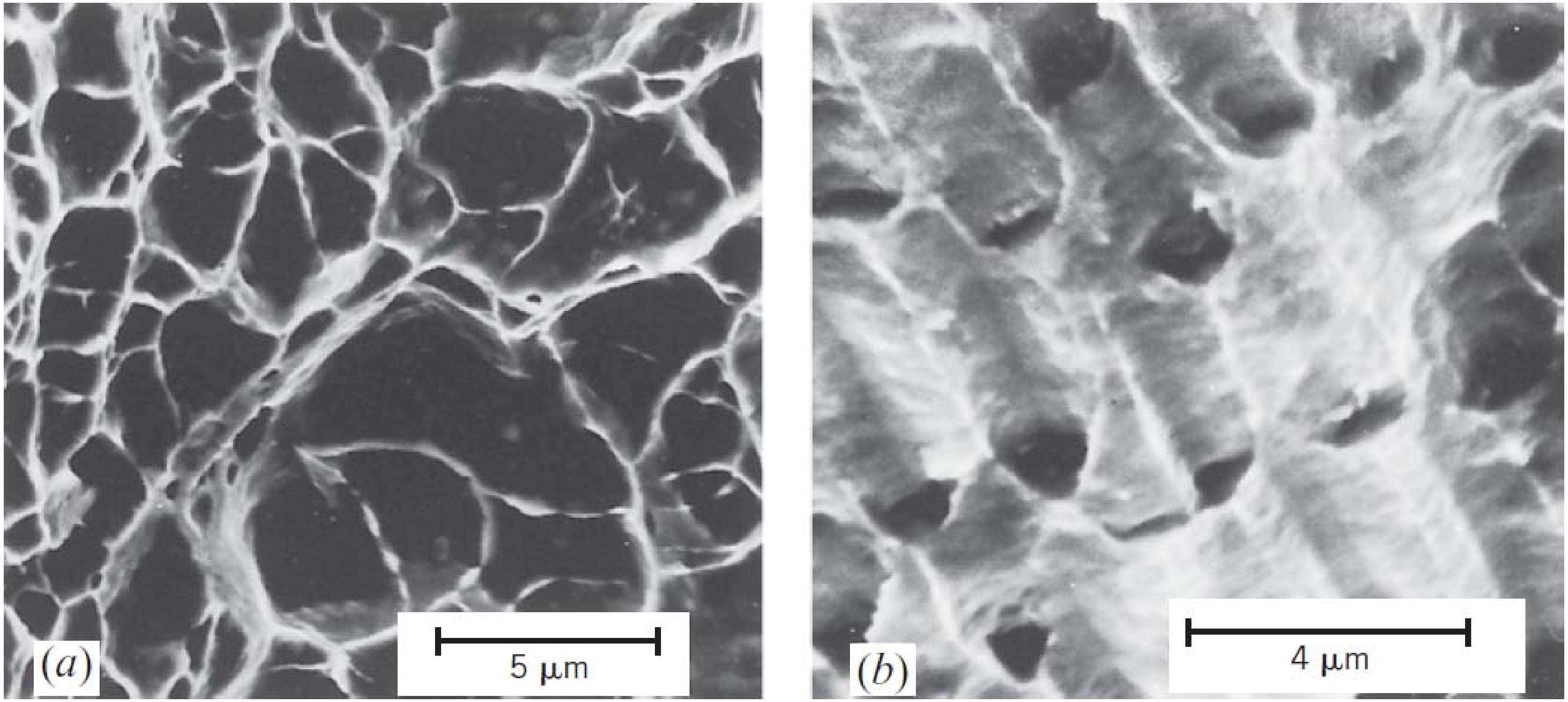


Figure 8.4 (*a*) Scanning electron fractograph showing spherical dimples characteristic of ductile fracture resulting from uniaxial tensile loads. 3300X. (*b*) Scanning electron fractograph showing parabolic-shaped dimples characteristic of ductile fracture resulting from shear loading. 5000X.

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.

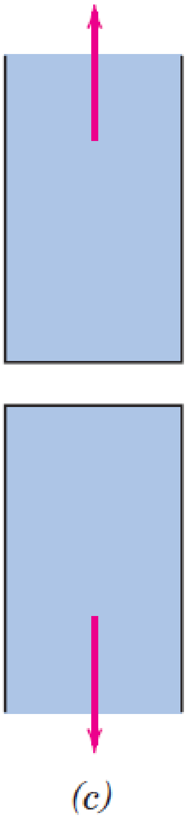


Figure 8.1 (*c*) Brittle fracture without any plastic deformation.

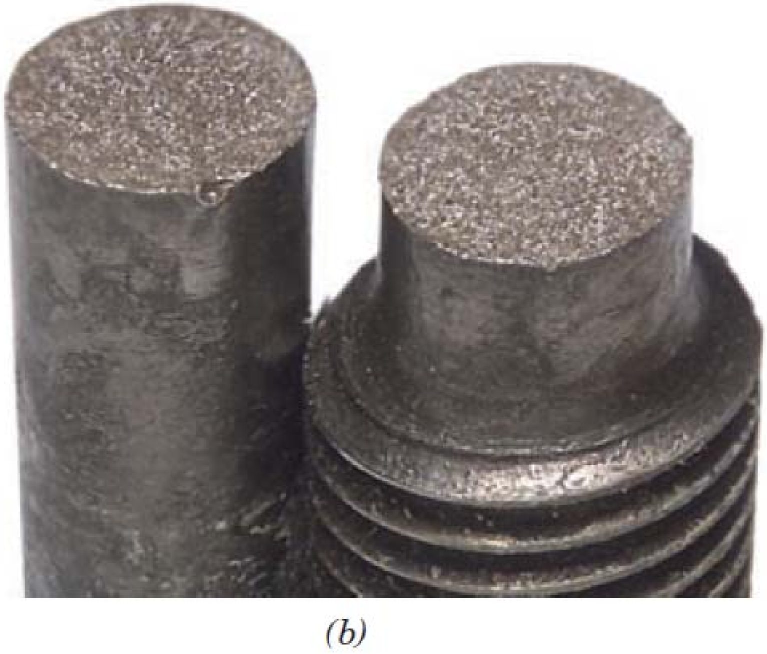


Figure 8.3 (*b*) Brittle fracture in a mild steel.

Fracture

Brittle Fracture

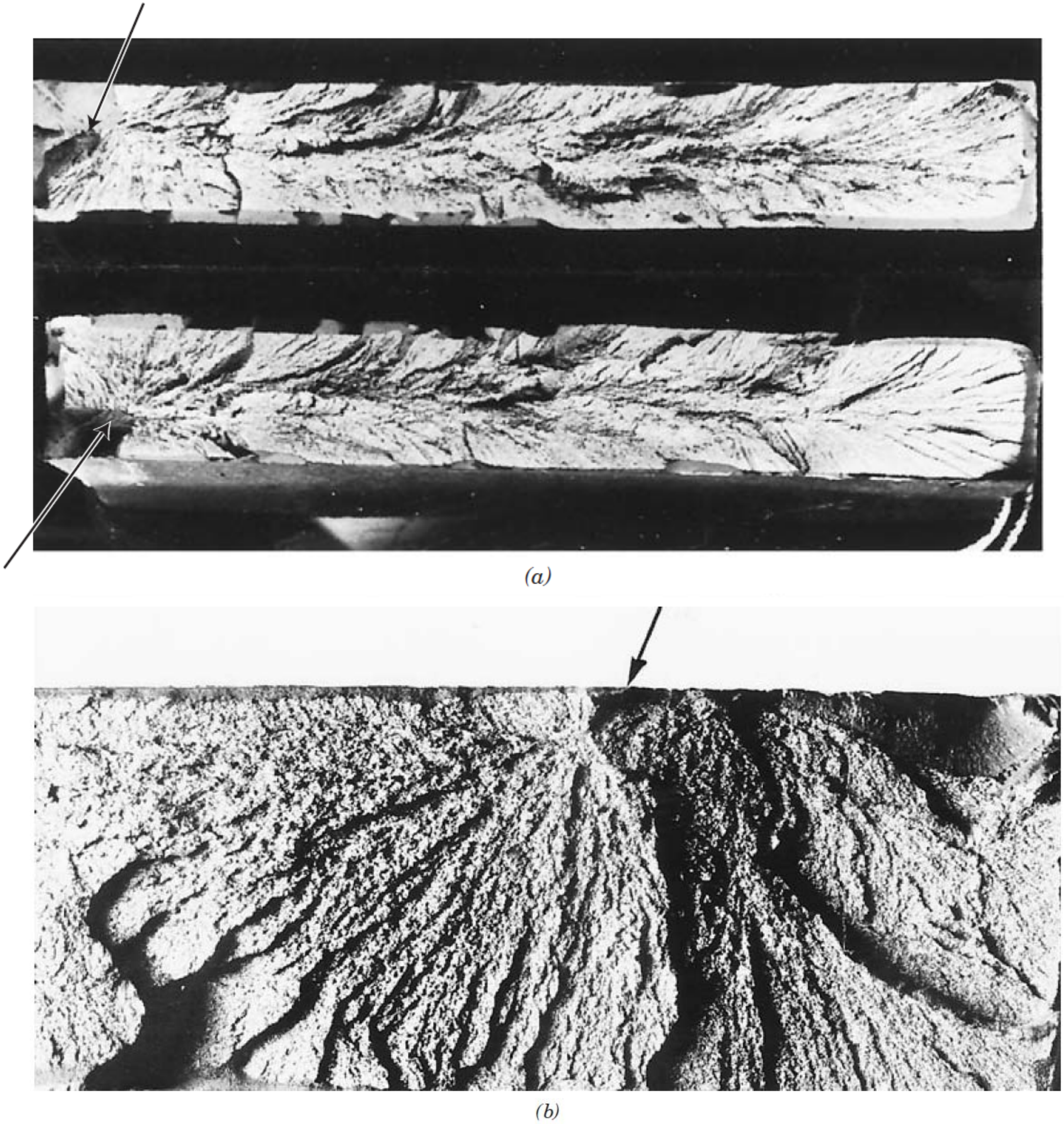


Figure 8.5 (*a*) Photograph showing V-shaped “chevron” markings characteristic of brittle fracture. Arrows indicate origin of crack. Approximately actual size. (*b*) Photograph of a brittle fracture surface showing radial fan-shaped ridges. Arrow indicates origin of crack. Approximately 2X.

Fracture
Brittle Fracture

- ***Cleavage***: (for most brittle crystalline materials) the process in which crack propagation occurs by successive and repeated breaking of atomic bonds along specific crystallographic planes.

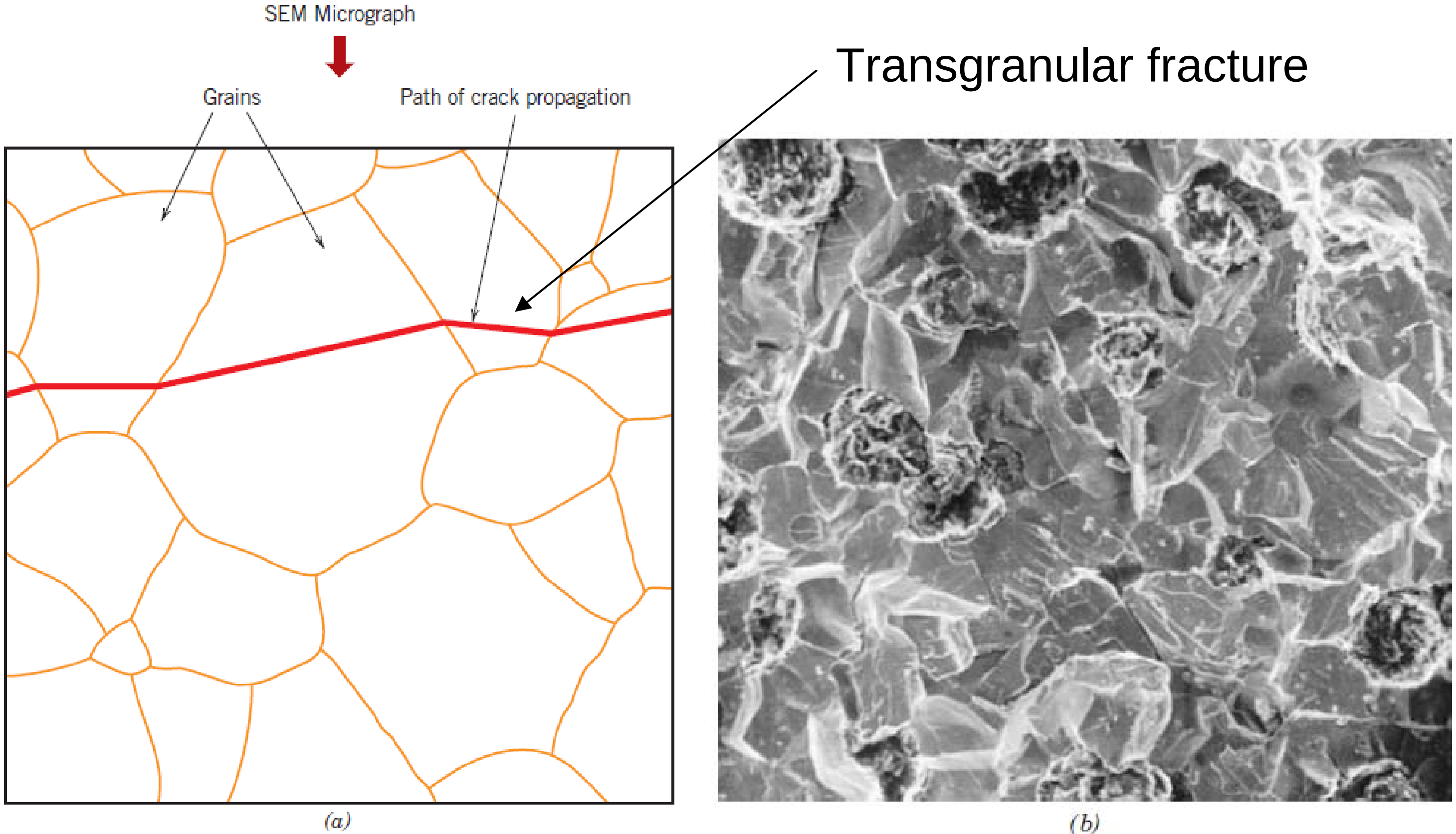
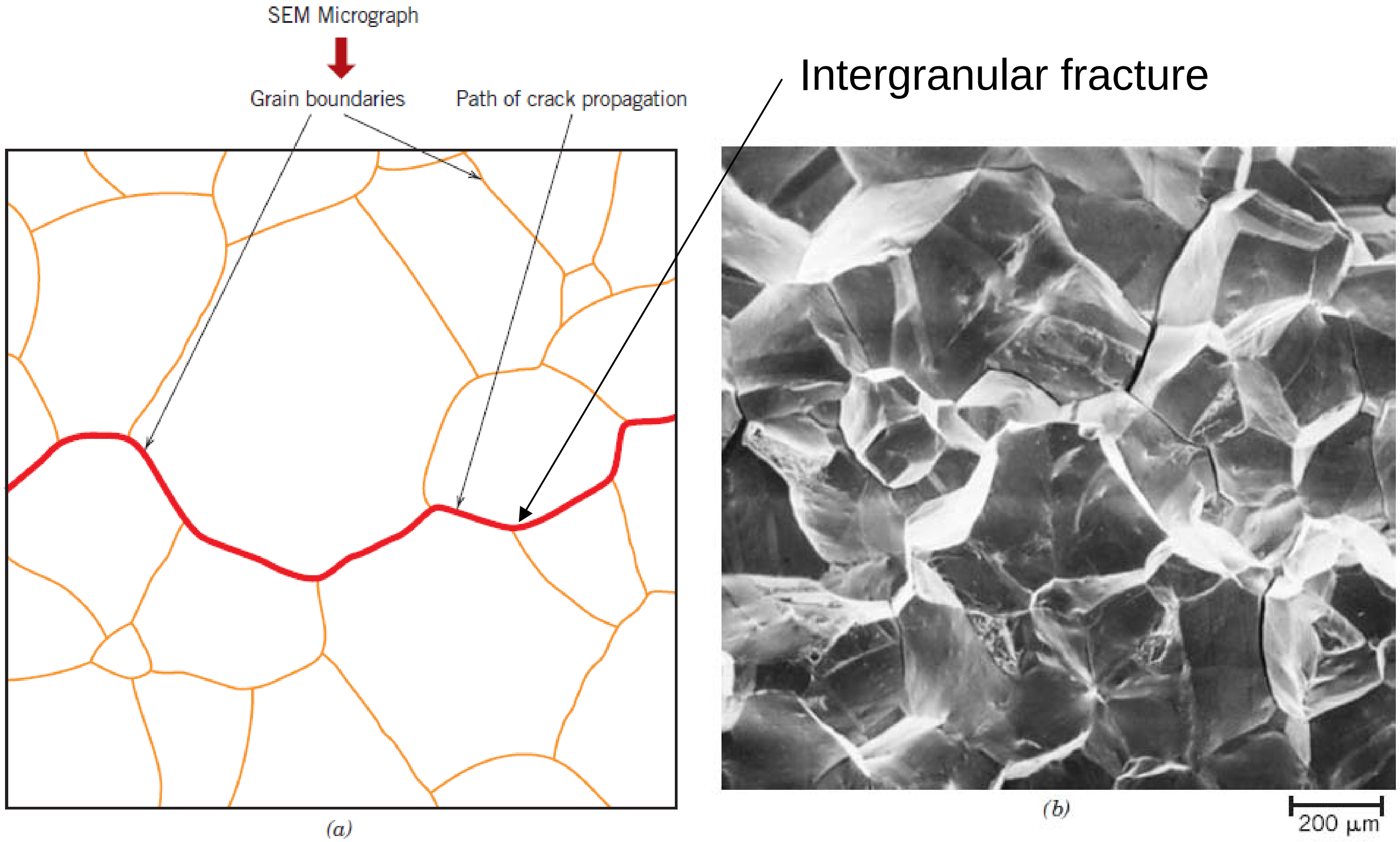


Figure 8.6 (*a*) Schematic cross-section profile showing crack propagation through the interior of grains for transgranular fracture. (*b*) Scanning electron fractograph of ductile cast iron showing a transgranular fracture surface.

Fracture
Brittle Fracture

In some alloys, crack propagation is along grain boundaries



Intergranular fracture

Figure 8.7 (*a*) Schematic cross-section profile showing crack propagation along grain boundaries for intergranular fracture. (*b*) Scanning electron fractograph showing an intergranular fracture surface.

Fracture

Principles of Fracture Mechanics / Stress Concentration

- The measured fracture strengths for most materials are significantly lower than those predicted by theoretical calculations based on atomic bonding energies.
  - This discrepancy is explained by the presence of 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.

Fracture

Principles of Fracture Mechanics / Stress Concentration

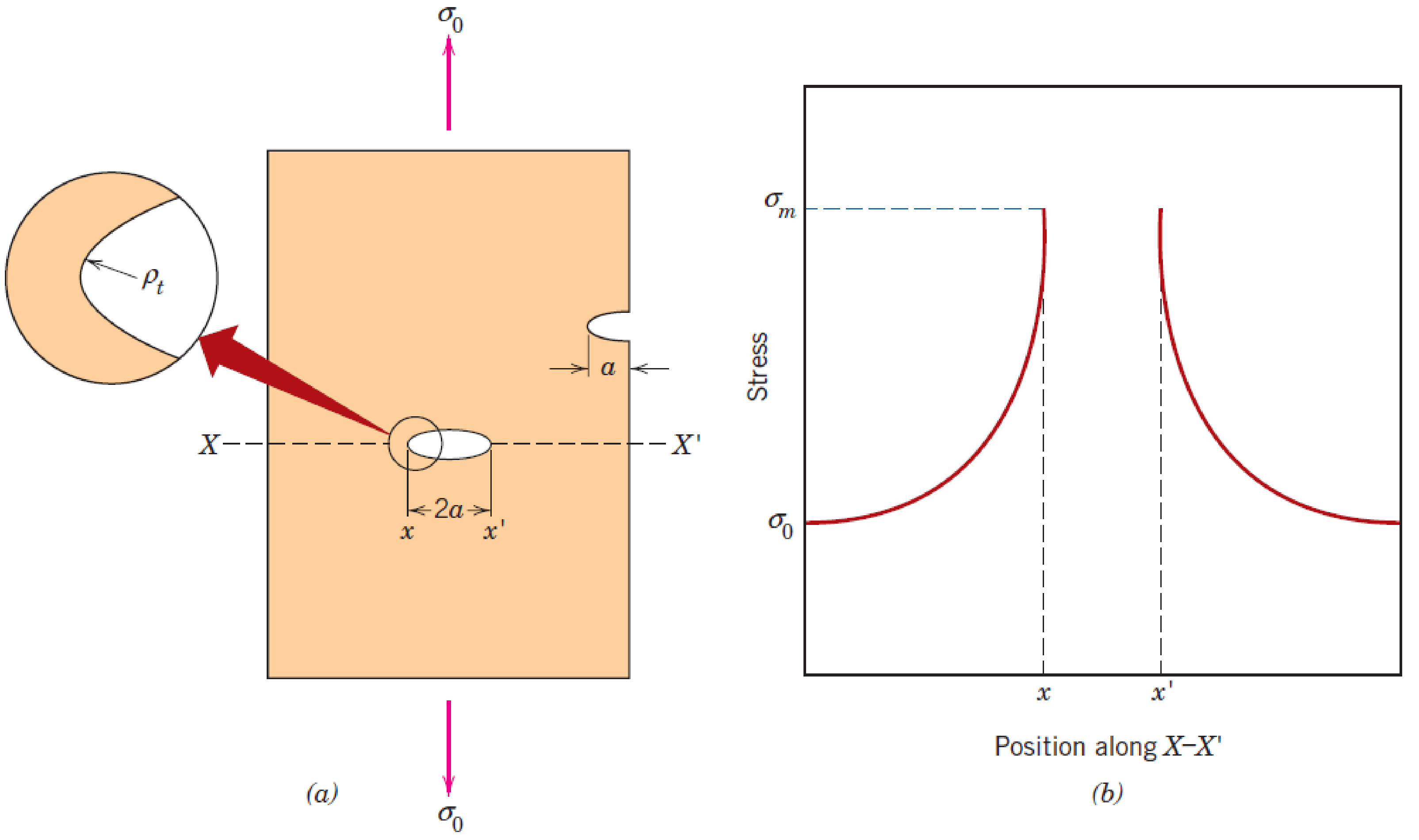


Figure 8.8 (*a*) The geometry of surface and internal cracks. (*b*) Schematic stress profile along the line *X*–*X’* in (*a*), demonstrating stress amplification at crack tip positions.

Fracture

Principles of Fracture Mechanics / Stress Concentration

maximum stress

the length of a surface crack, or half of the length of an internal crack

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

nominal applied tensile stress

radius of curvature of the crack tip

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

Stress concentration factor: a measure of the degree to which an external stress is amplified at the tip of a crack

Fracture

Principles of Fracture Mechanics / Stress Concentration

Critical stress required for crack propagation in a brittle material

modulus of elasticity

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

specific surface energy

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.
  - Very small and virtually defect-free metallic and ceramic whiskers have been grown with fracture strengths that approach their theoretical values.

Fracture

Principles of Fracture Mechanics / Stress Concentration

- Example 8.1: 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.

Fracture

Principles of Fracture Mechanics / Fracture Toughness

- An expression has been developed that relates this critical stress for crack propagation and crack length as:

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

Fracture toughness, a property that is a measure of a material's resistance to brittle fracture when a crack is present (MPa.m$^{1/2}$).

Y: a dimensionless parameter or function that depends on both crack and specimen sizes and geometries as well as the manner of load application.

Y = ~1 for planar specimens containing cracks that are much shorter than the specimen width

Fracture

Principles of Fracture Mechanics / Fracture Toughness

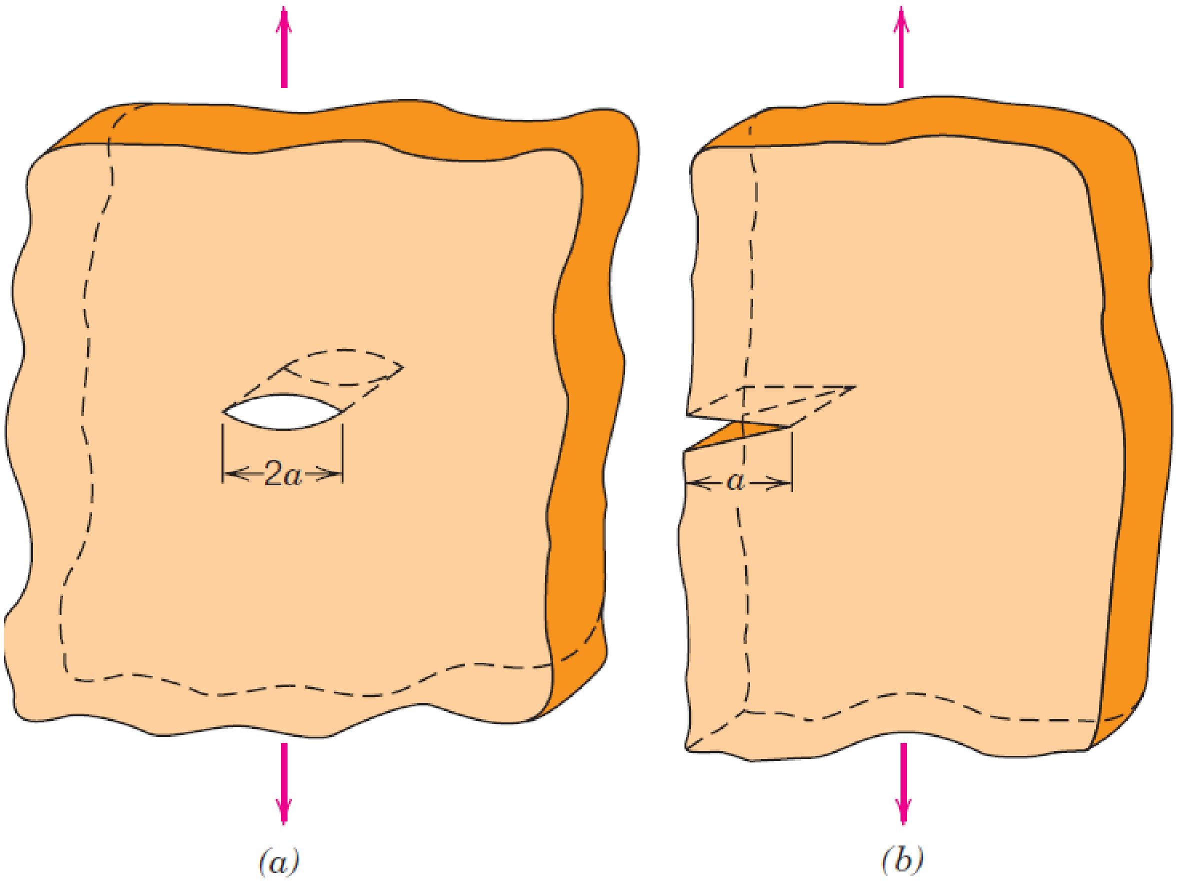


Figure 8.9 Schematic representations of (*a*) an interior crack in a plate of infinite width and (*b*) an edge crack in a plate of semi-infinite width.

$Y = 1$

$Y = \sim 1.1$

Fracture

Principles of Fracture Mechanics / Fracture Toughness

- For relatively thin specimens, the value of *Kc* will depend on specimen thickness.
    - However, when specimen thickness is much greater than the crack dimensions, K_c becomes independent of thickness; under these conditions a condition of **plane strain** exists.
    - Plane strain: when a load operates on a crack in the manner represented in Figure 8.9*a*, there is no strain component perpendicular to the front and back faces.
    - The K_c value for this thick-specimen situation is known as the **plane strain fracture toughness** K_{Ic}; furthermore, it is also defined by:

$$K_{Ic} = Y\sigma\sqrt{\pi a}$$

The *I* (i.e., Roman numeral “one”) subscript for K_{Ic} denotes that the plane strain fracture toughness is for mode I crack displacement.

Fracture

Principles of Fracture Mechanics / Fracture Toughness

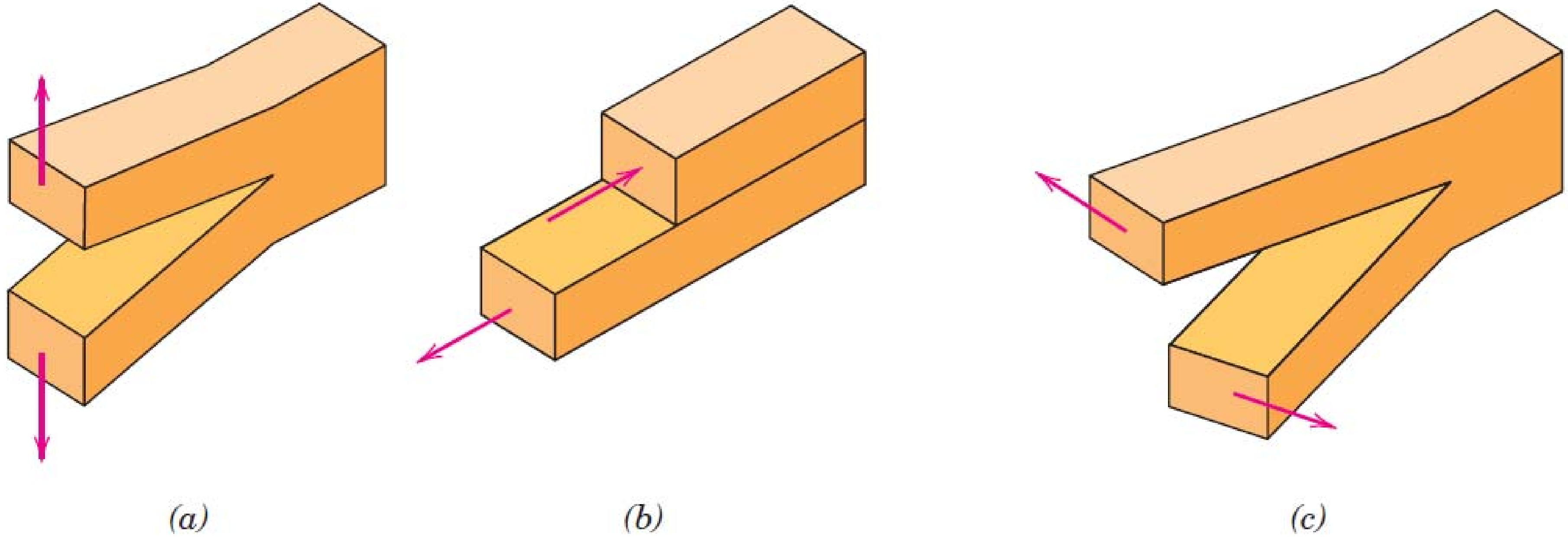


Figure 8.10 The three modes of crack surface displacement. (*a*) Mode I, opening or tensile mode; (*b*) mode II, sliding mode; and (*c*) mode III, tearing mode.

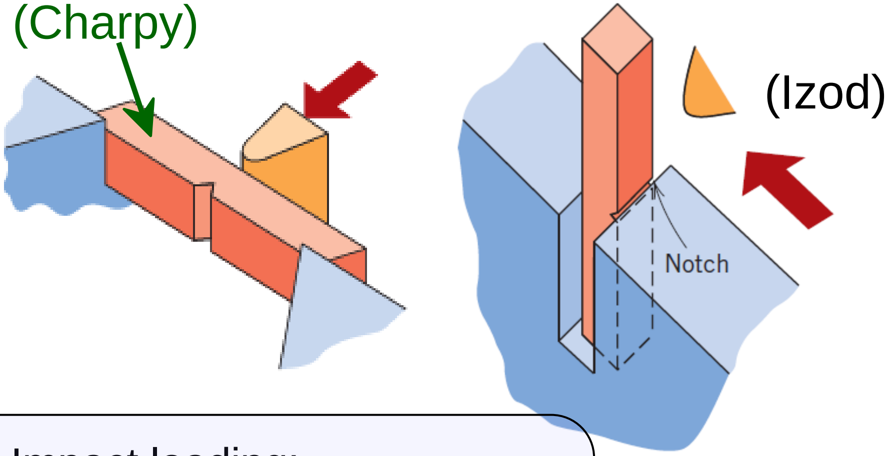
Fracture

Fracture Toughness Testing / Impact Testing Techniques

- Impact test conditions were chosen to represent those most severe relative to the potential for fracture; namely:
    - (1) deformation at a relatively low temperature,
    - (2) a high strain rate (i.e., rate of deformation), and
    - (3) a triaxial stress state (which may be introduced by the presence of a notch).
- Two standardized tests, the **Charpy** and **Izod,** were designed and are still used to measure the **impact energy** (sometimes also termed *notch toughness*).

Fracture

Fracture Toughness Testing / Impact Testing Techniques



- Impact loading:
  - -- severe testing case
  - -- makes material more brittle
  - -- decreases toughness

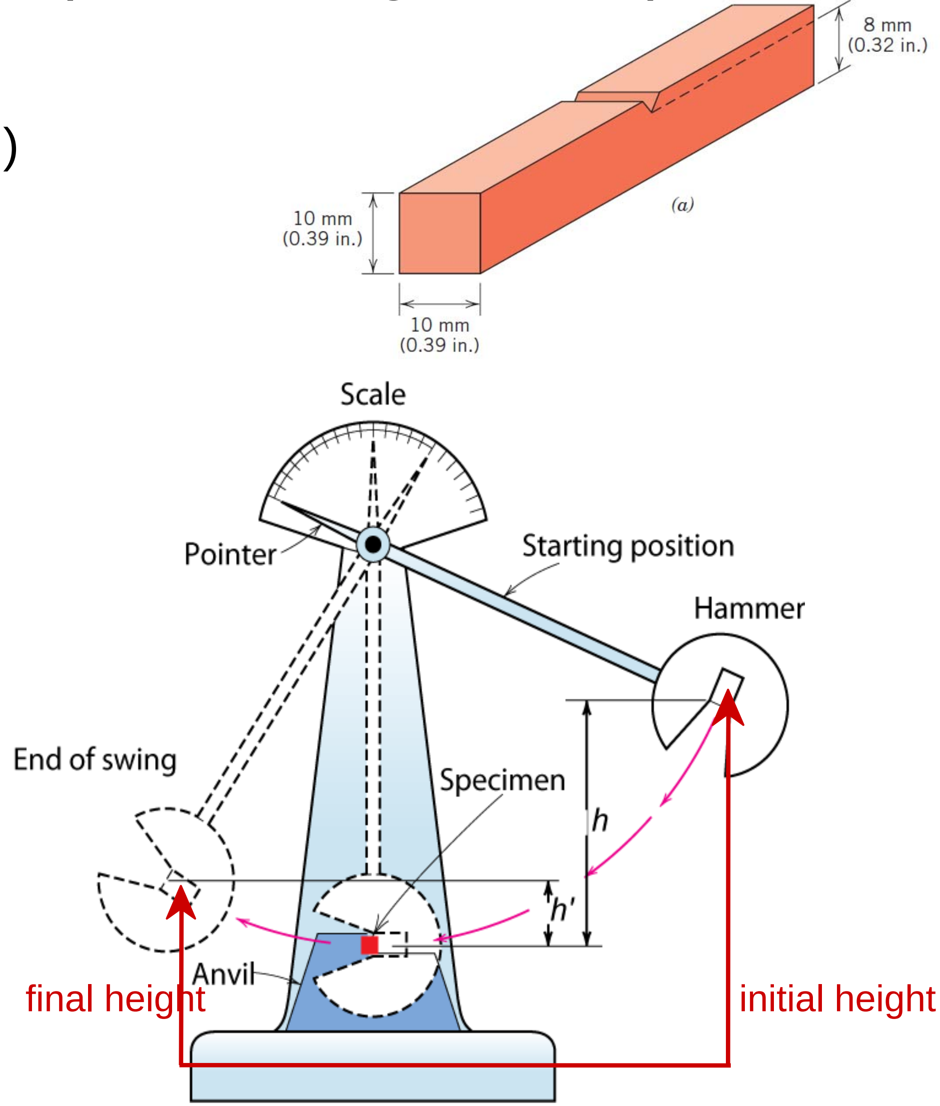


Figure 8.12 (*a*) Specimen used for Charpy and Izod impact tests. (*b*) A schematic drawing of an impact testing apparatus. The hammer is released from fixed height *h* and strikes the specimen; the energy expended in fracture is reflected in the difference between *h* and the swing height *h'*.

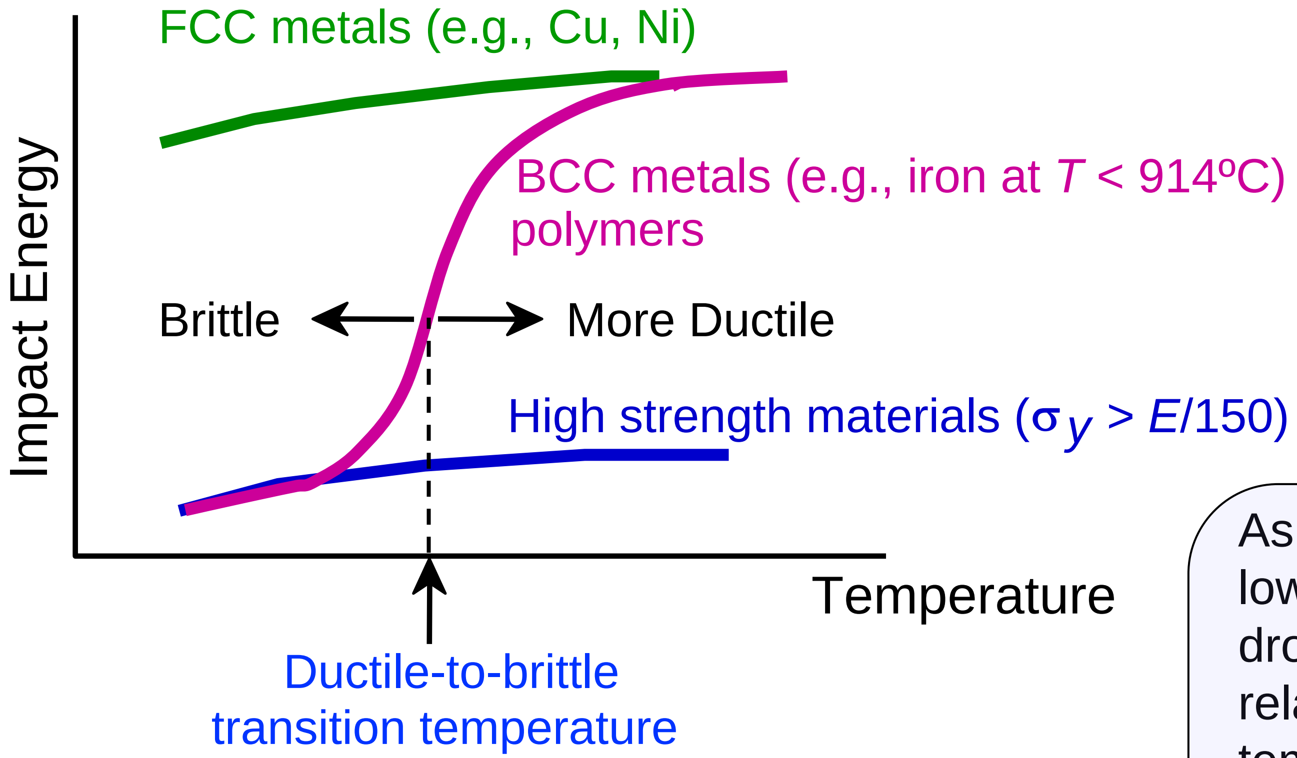
Fracture

Fracture Toughness Testing / Ductile-to-Brittle-Transition

- One of the primary functions of Charpy and Izod tests is to:
  - determine whether a material experiences a **ductile-to-brittle transition** with decreasing temperature
  - and, if so, the range of temperatures over which it occurs.

Fracture

Fracture Toughness Testing / Ductile-to-Brittle-Transition



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.

Fracture

Fracture Toughness Testing / Ductile-to-Brittle-Transition

- Alternatively, appearance of the failure surface is indicative of the nature of fracture and may be used in transition temperature determinations.

Granular (shiny) texture
(brittle fracture)

Fibrous or dull
(ductile fracture)

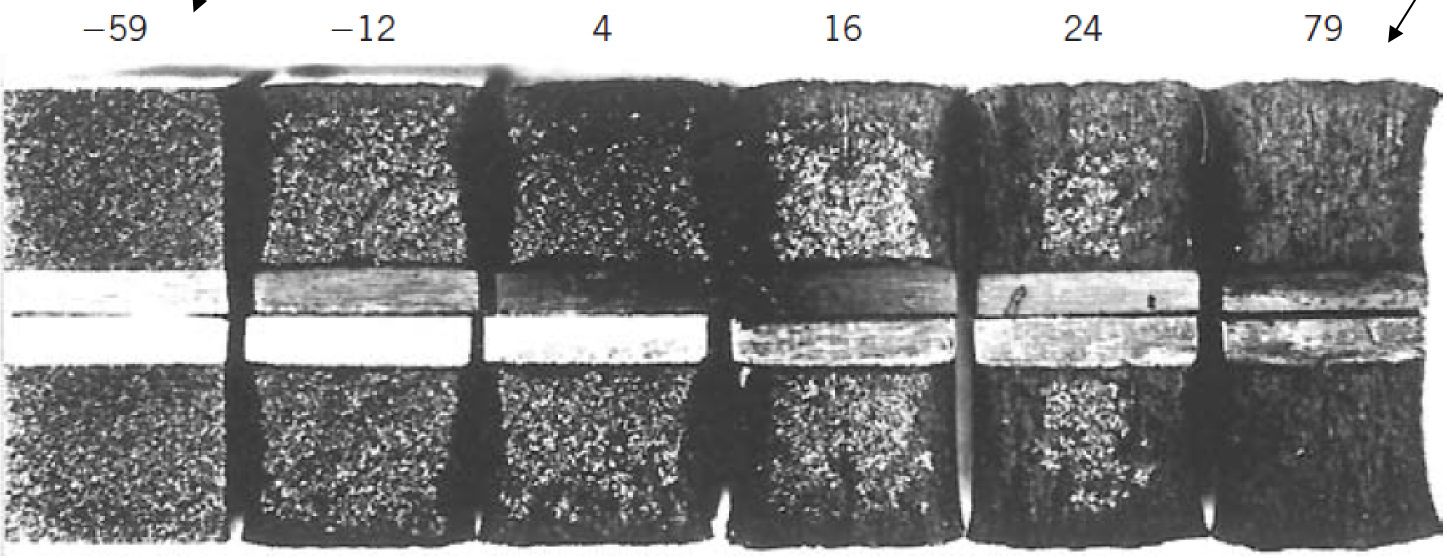


Figure 8.14 Photograph of fracture surfaces of A36 steel Charpy V-notch specimens tested at indicated temperatures (in ° C).

Fracture

Fracture Toughness Testing / Ductile-to-Brittle-Transition

- For low-strength steels (BCC), 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.

Fracture

Fracture Toughness Testing / Ductile-to-Brittle-Transition

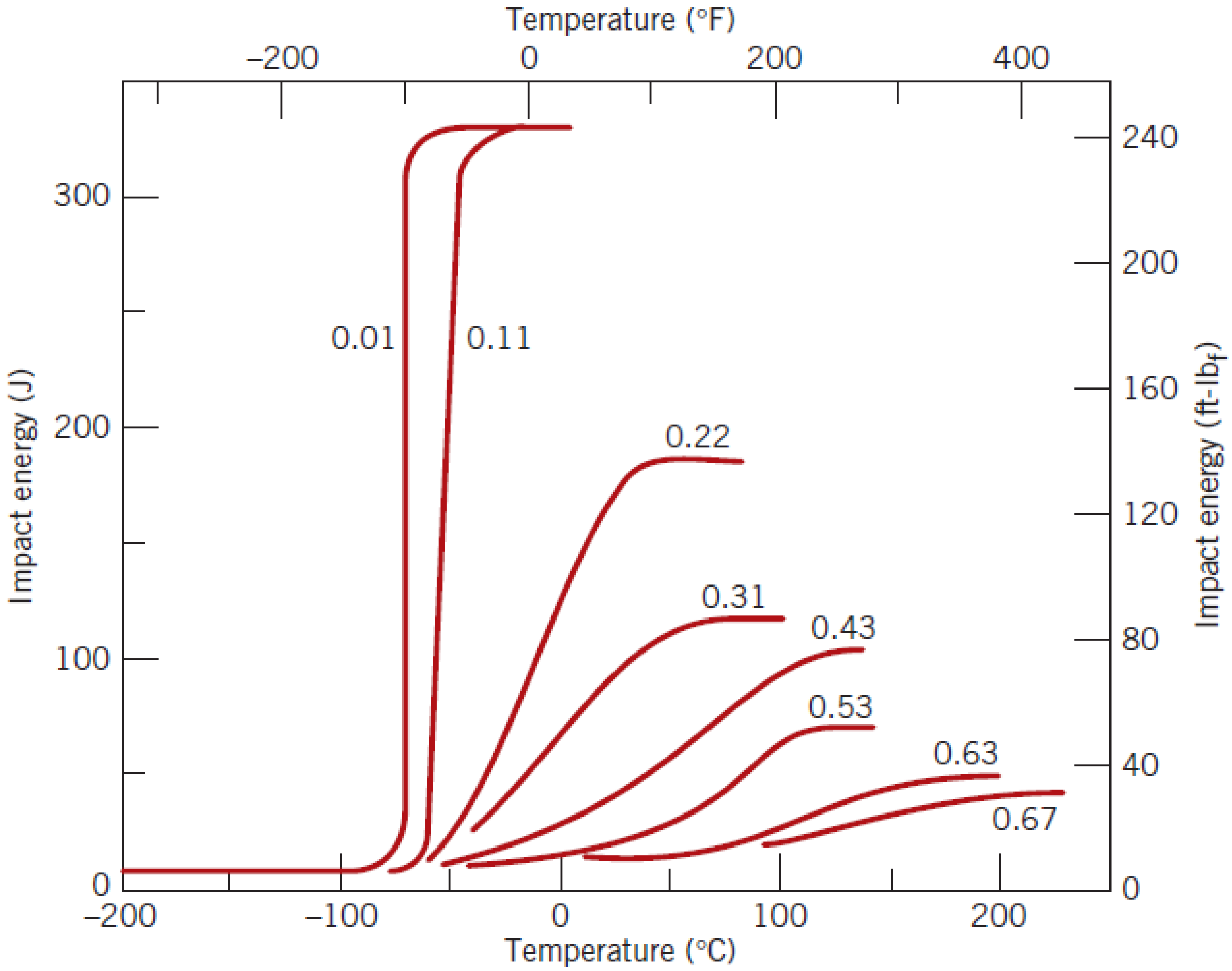


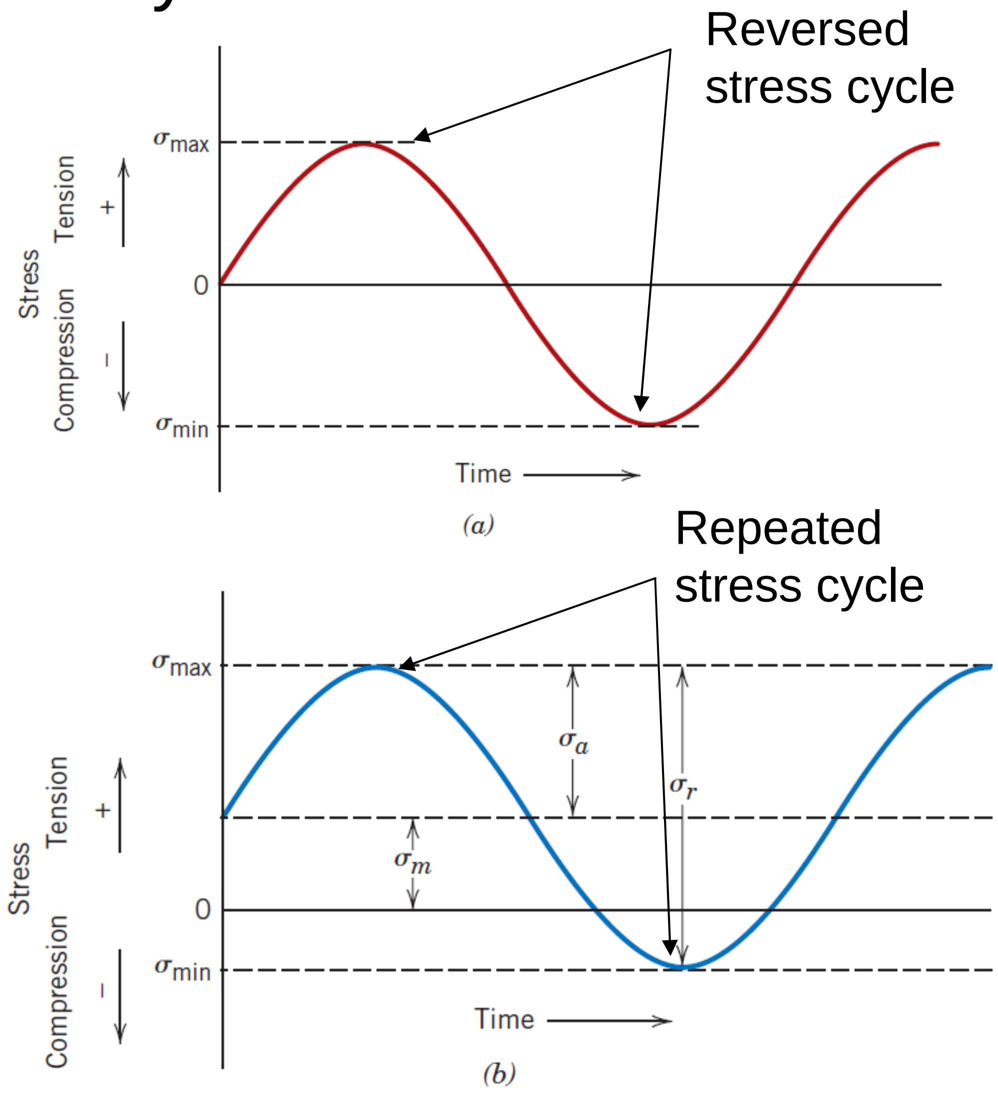
Figure 8.16 Influence of carbon content on the Charpy V-notch energy–versus–temperature behavior for steel.

Fatigue

- ***Fatigue***: a form of failure, brittle-like in nature, 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.
  - Occurs after a lengthy period of repeated stress or strain cycling.
  - It is the single largest cause of failure in metals, estimated to comprise approximately 90% of all metallic failures.
  - Fatigue is catastrophic and insidious, occurring very suddenly and without warning.

Fatigue

Cyclic Stresses



Reversed stress cycle

Repeated stress cycle

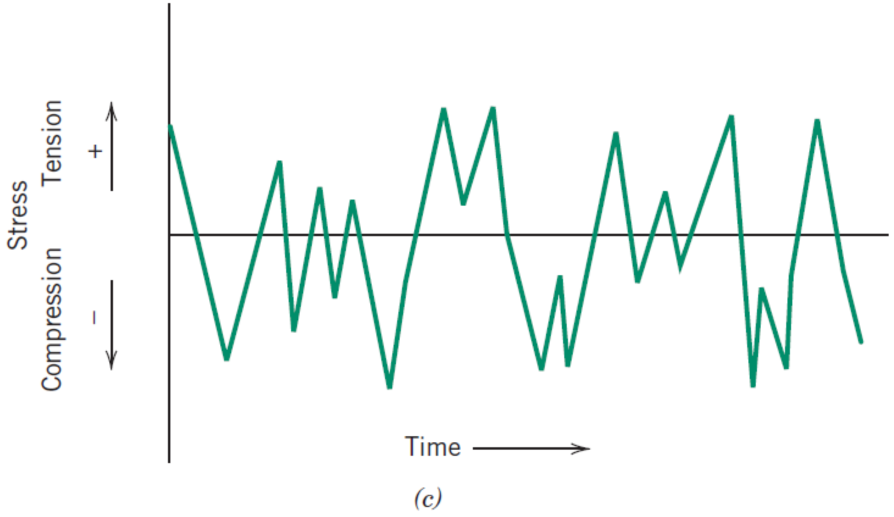


Figure 8.17 Variation of stress with time that accounts for fatigue failures. (*a*) Reversed stress cycle, in which the stress alternates from a maximum tensile stress (+) to a maximum compressive stress (-) of equal magnitude. (*b*) Repeated stress cycle, in which maximum and minimum stresses are asymmetrical 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.

Fatigue
Cyclic Stresses

The applied stress may be axial (tension–compression), flexural (bending), or torsional (twisting) in nature.

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

Mean stress

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

Average stress

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

Stress amplitude

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

Stress ratio

Fatigue
The S – N Curve

- 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.)

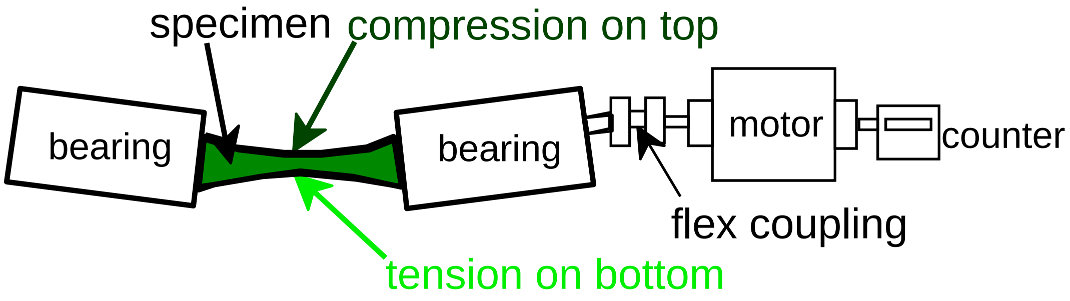
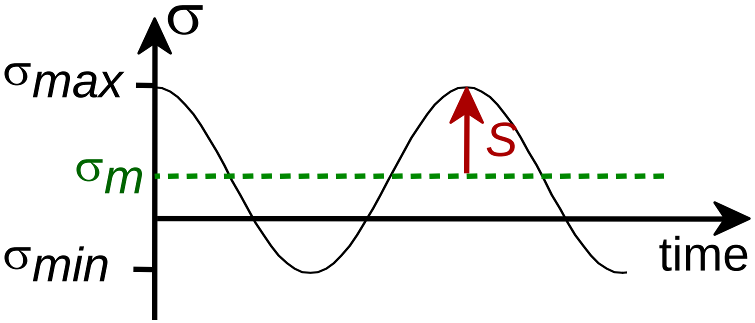


Figure 8.18 Schematic diagram of fatigue-testing apparatus for making rotating-bending tests.



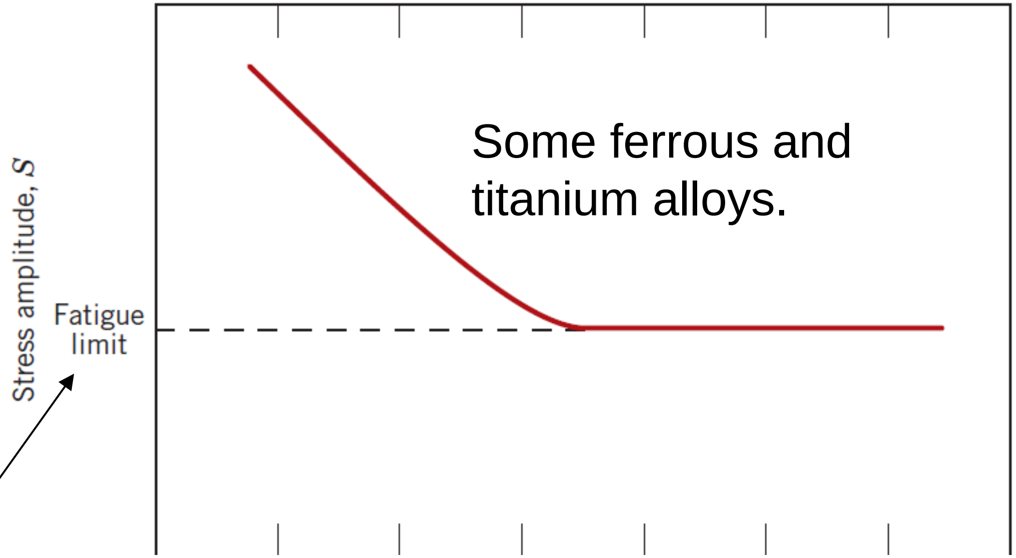
Fatigue
The S – N Curve

The higher the magnitude of the stress, the smaller the number of cycles the material is capable of sustaining before failure.

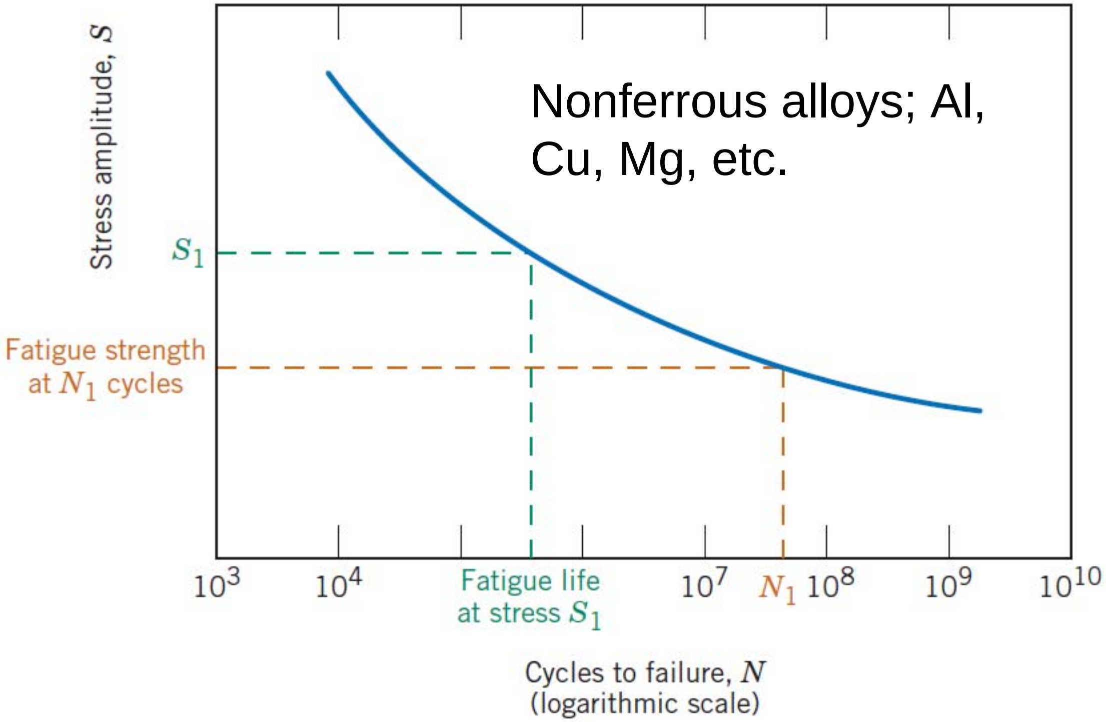
Fatigue limit: limiting stress level below which fatigue failure will not occur (35 to 60% of TS).

Fatigue strength: the stress level at which failure will occur for some specified number of cycles.

Fatigue life N_f: number of cycles to cause failure at a specified stress level.



Some ferrous and titanium alloys.



Nonferrous alloys; Al, Cu, Mg, etc.

Fatigue
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.

Fatigue
Crack Initiation and Propagation

- 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, etc.
- The region of a fracture surface that formed during the crack propagation step may be characterized by two types of markings termed *beachmarks* (macroscopic) and *striations* (microscopic).

Fatigue

Crack Initiation and Propagation

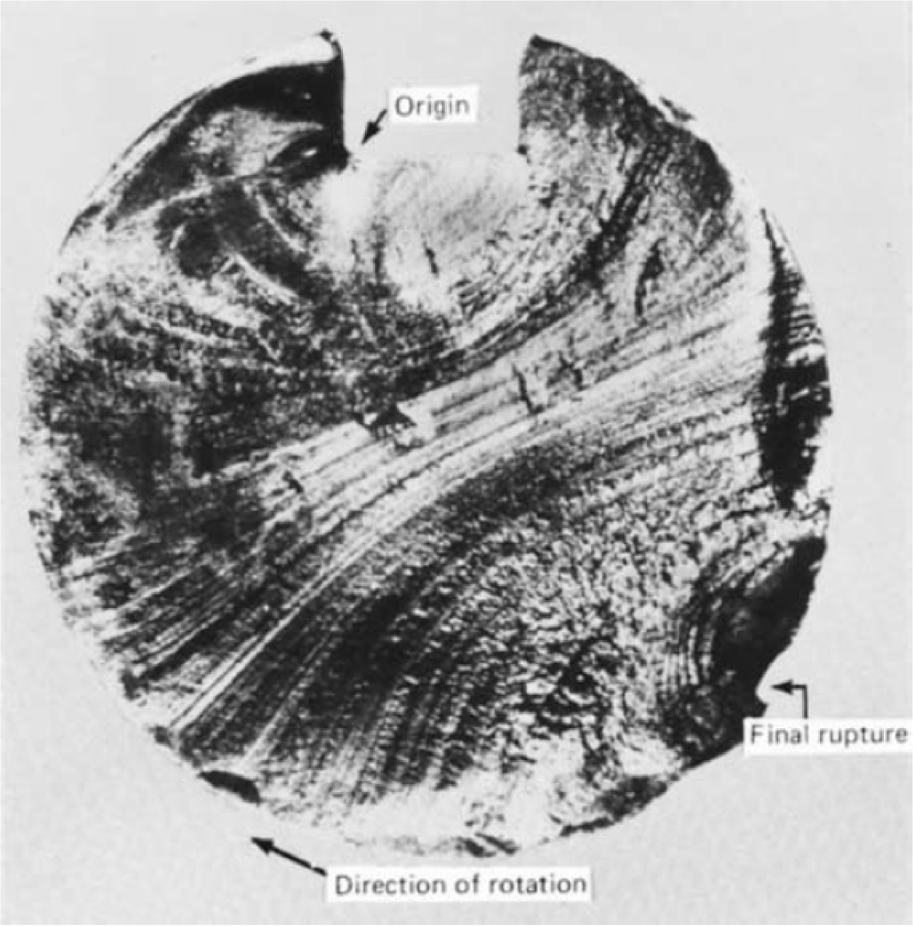


Figure 8.21 Fracture surface of a rotating steel shaft that experienced fatigue failure. Beachmark ridges (clamshell marks) are visible in the photograph.

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.

Fatigue

Crack Initiation and Propagation

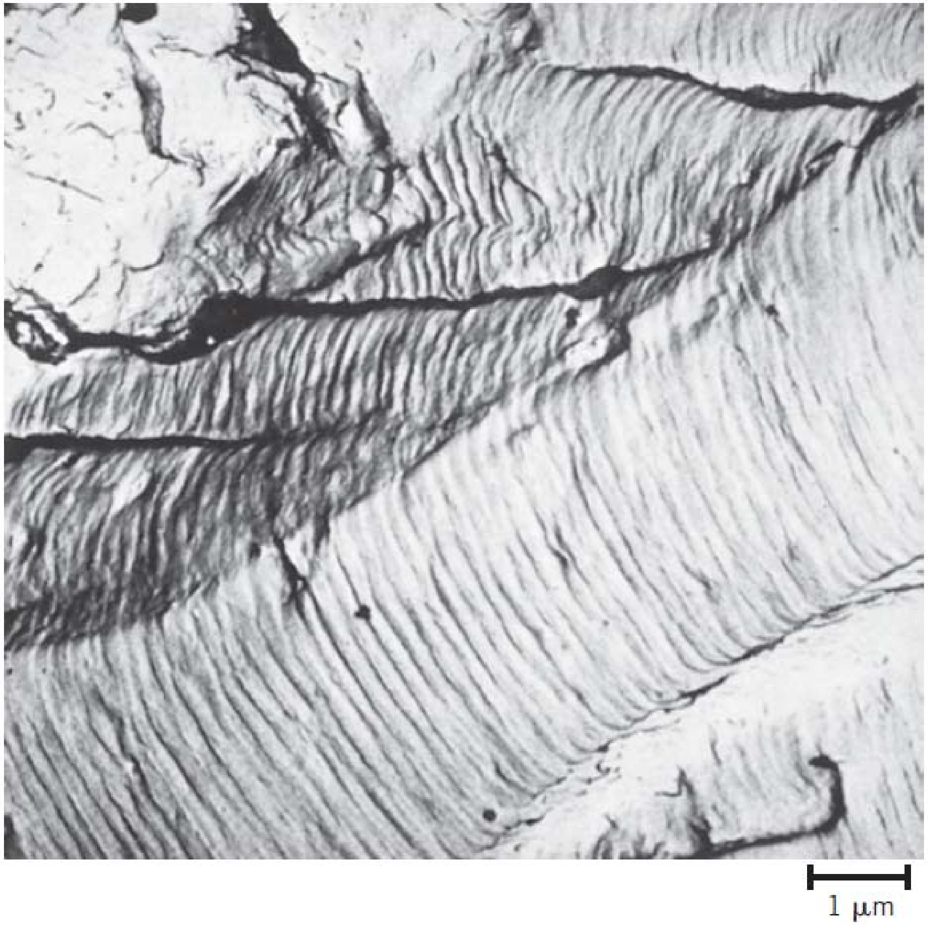


Figure 8.22 Transmission electron fractograph showing fatigue striations in aluminum. 9000X.

There may be thousands of striations within a single beachmark.

Fatigue
Factors That Affect Fatigue Life / Mean Stress

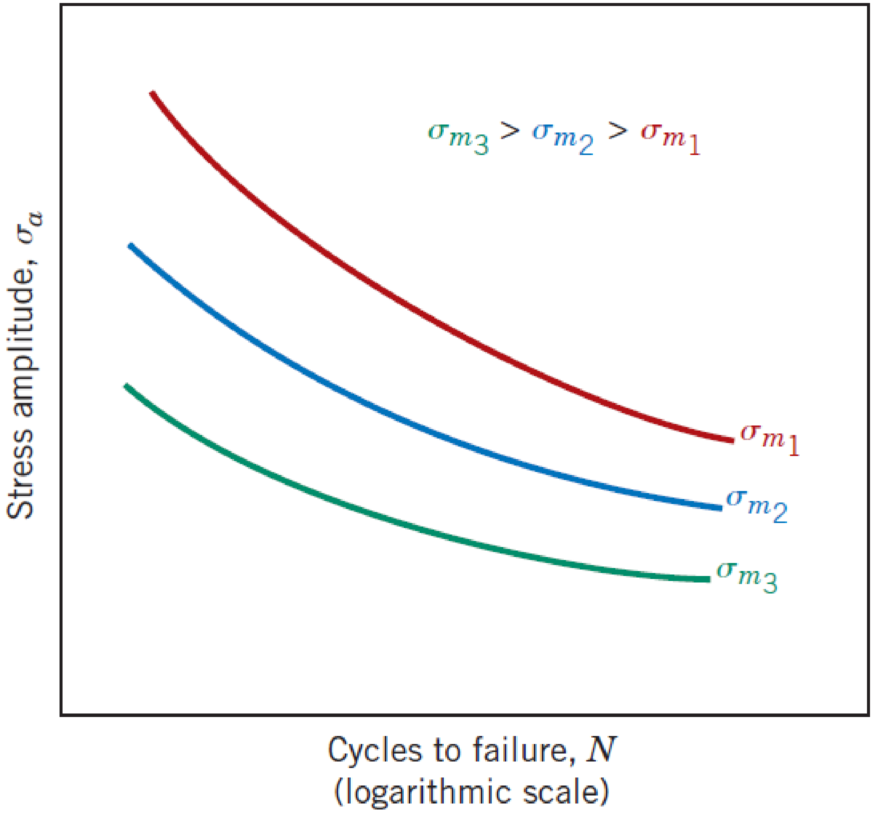


Figure 8.24 Demonstration of the influence of mean stress σ_m on *S–N* fatigue behavior.

Increasing the mean stress level leads to a decrease in fatigue life.

Fatigue
Factors That Affect Fatigue Life / 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.
- Hence, fatigue life is especially sensitive to the condition and configuration of the component surface.
  - We need good design of part and appropriate surface treatment.

Fatigue

Factors That Affect Fatigue Life / Design Factors

- Good design, good fatigue characteristics.
- Any notch or geometrical discontinuity can act as a stress raiser and fatigue crack initiation site;
  - these design features include grooves, holes, threads, etc.
- 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 sharp corners.
  - 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

Fatigue

Factors That Affect Fatigue Life / Design Factors

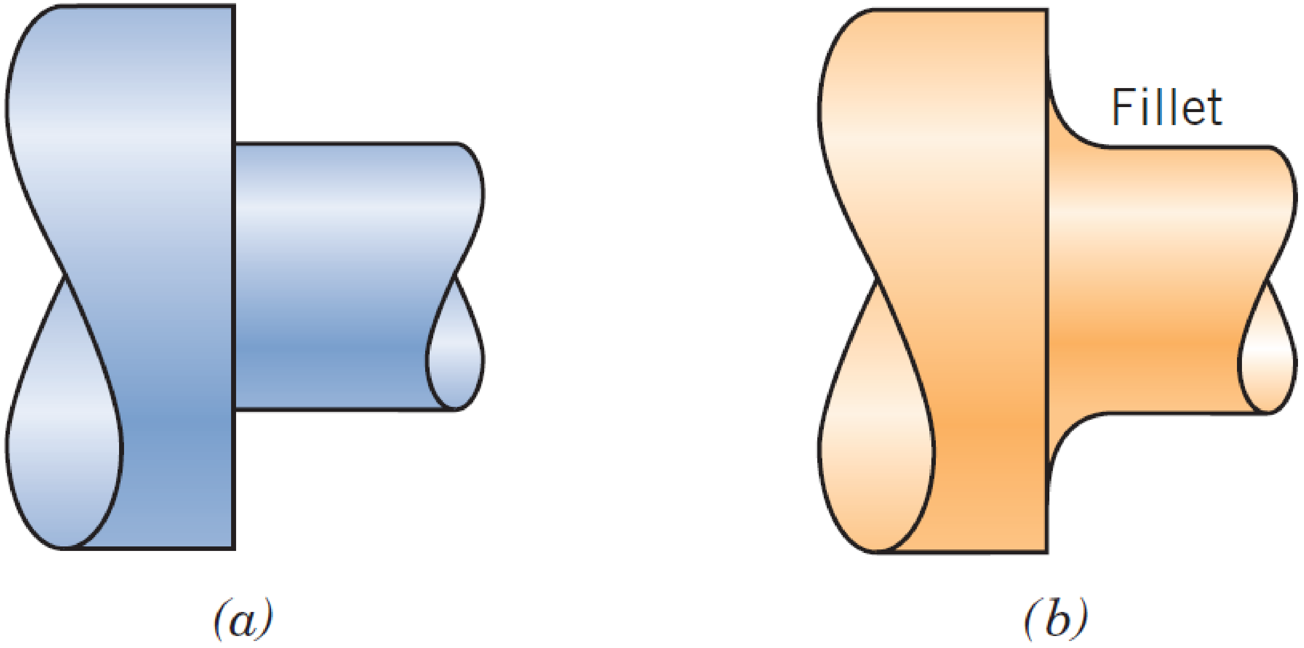


Figure 8.25 Demonstration of how design can reduce stress amplification. (*a*) Poor design: sharp corner. (*b*) Good design: fatigue lifetime improved by incorporating rounded fillet into a rotating shaft at the point where there is a change in diameter.

Fatigue

Factors That Affect Fatigue Life / Surface Treatments

- Surface markings created during machining operations can limit fatigue life.
- Solutions:
  - (1) polish the surface.
  - (2) Introduce surface residual compressive stresses (will partially nullify surface tensile stresses of external origin).
    - 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.

Fatigue

Factors That Affect Fatigue Life / Surface Treatments

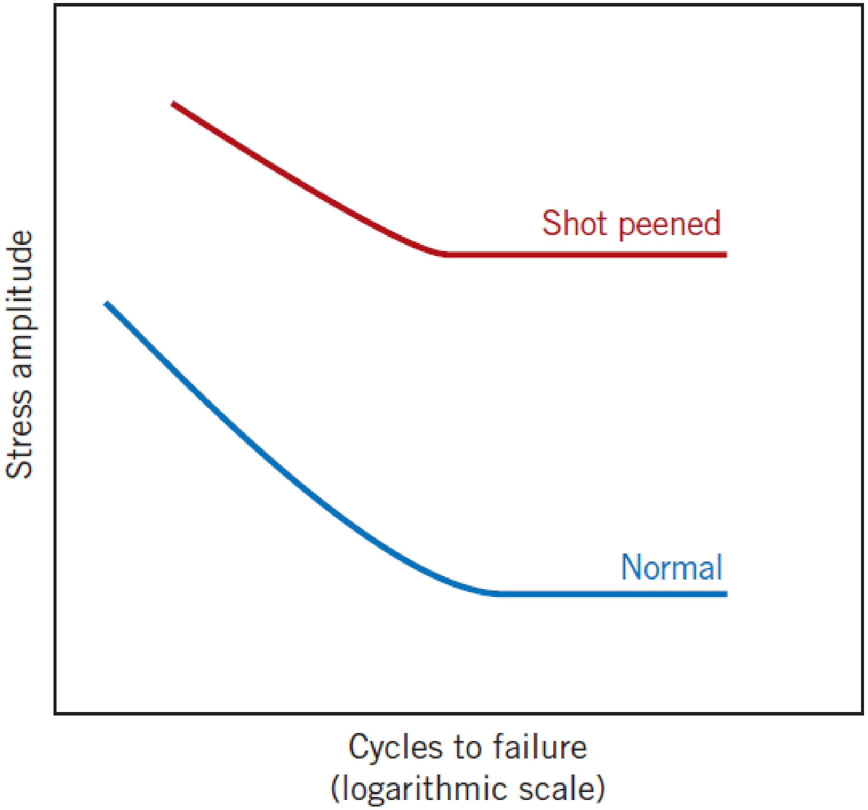


Figure 8.26 Schematic *S–N* fatigue curves for normal and shot-peened steel.

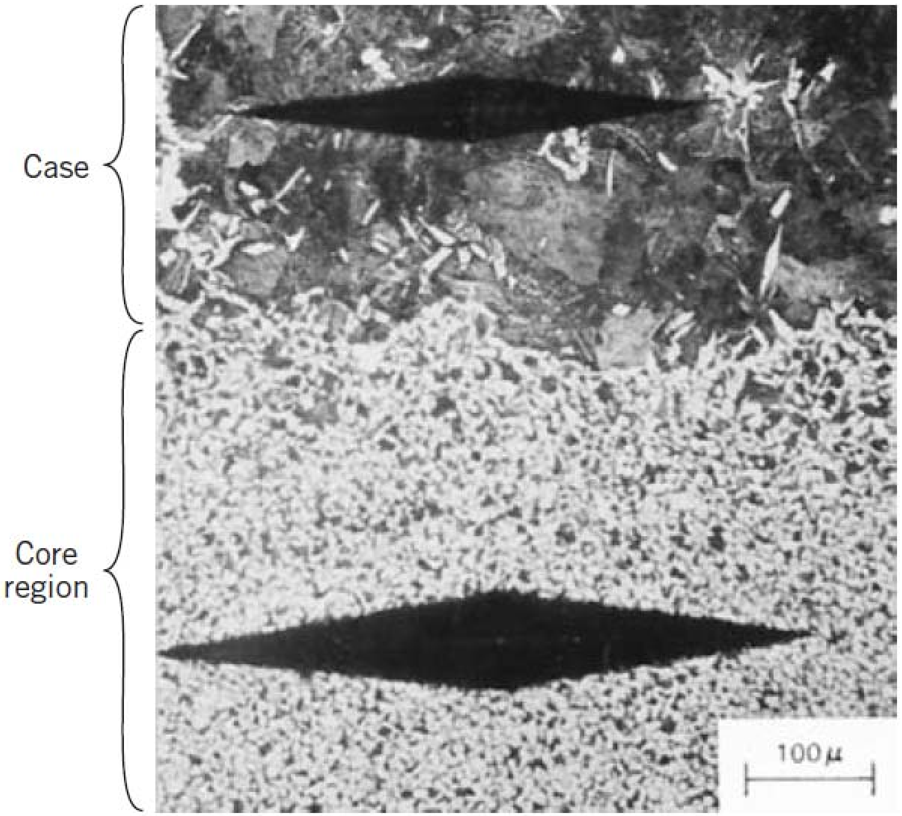
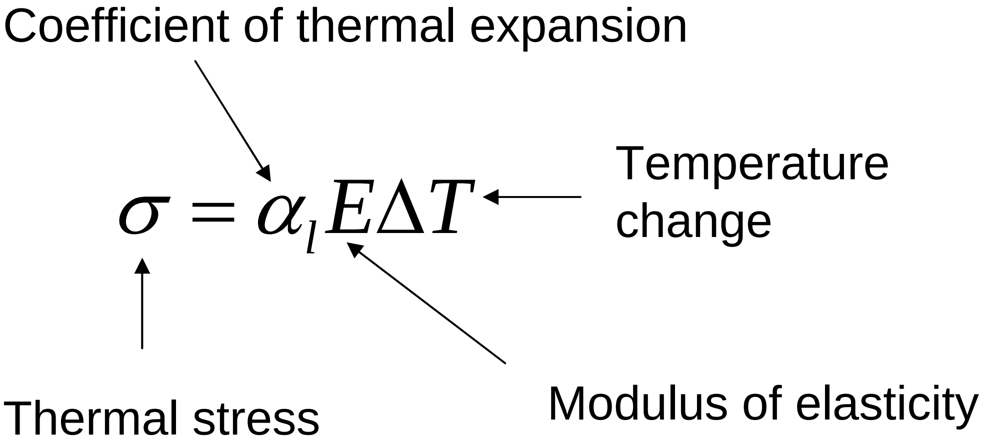


Figure 8.27 Photomicrograph showing both core (bottom) and carburized outer case (top) regions of a case-hardened steel. The case is harder, as attested by the smaller microhardness indentation.

Fatigue

Environmental Effects

- ***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.



Coefficient of thermal expansion

$$\sigma = \alpha_l E \Delta T$$

Temperature change

Thermal stress

Modulus of elasticity

Prevent this type of fatigue:

(1) Eliminate, or at least reduce, the restraint source, thus allowing unhindered dimensional changes with temperature variations, or

(2) Choose materials with appropriate physical properties.

Fatigue
Environmental Effects

- ***Corrosion fatigue***: Failure that occurs by the simultaneous action of a cyclic stress and chemical attack.
  - Corrosive environments have a deleterious influence and produce shorter fatigue lives.
- 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.

Prevention:
(1) Apply protective surface coatings.
(2) select a more corrosion-resistant material.
(3) reduce the corrosiveness of the environment.
(4) Reduce the applied tensile stress level and impose residual compressive stresses on the surface of the member.

Creep

- ***Creep***: the time-dependent and permanent deformation of materials when subjected to a constant load or stress.
  - Materials that are in service at elevated temperatures and exposed to static mechanical stresses (e.g., turbine rotors in jet engines) are subjected to creep.
- It is observed in all materials types;
  - for metals it becomes important only for temperatures greater than about $0.4T_m$.

Creep

Generalized Creep Behavior

- Creep test: consists of subjecting a specimen to a constant load or stress while maintaining the temperature constant; deformation or strain is measured and plotted as a function of elapsed time.

$$\dot{\varepsilon}_s = \frac{\Delta\varepsilon}{\Delta t}$$

Steady state creep rate

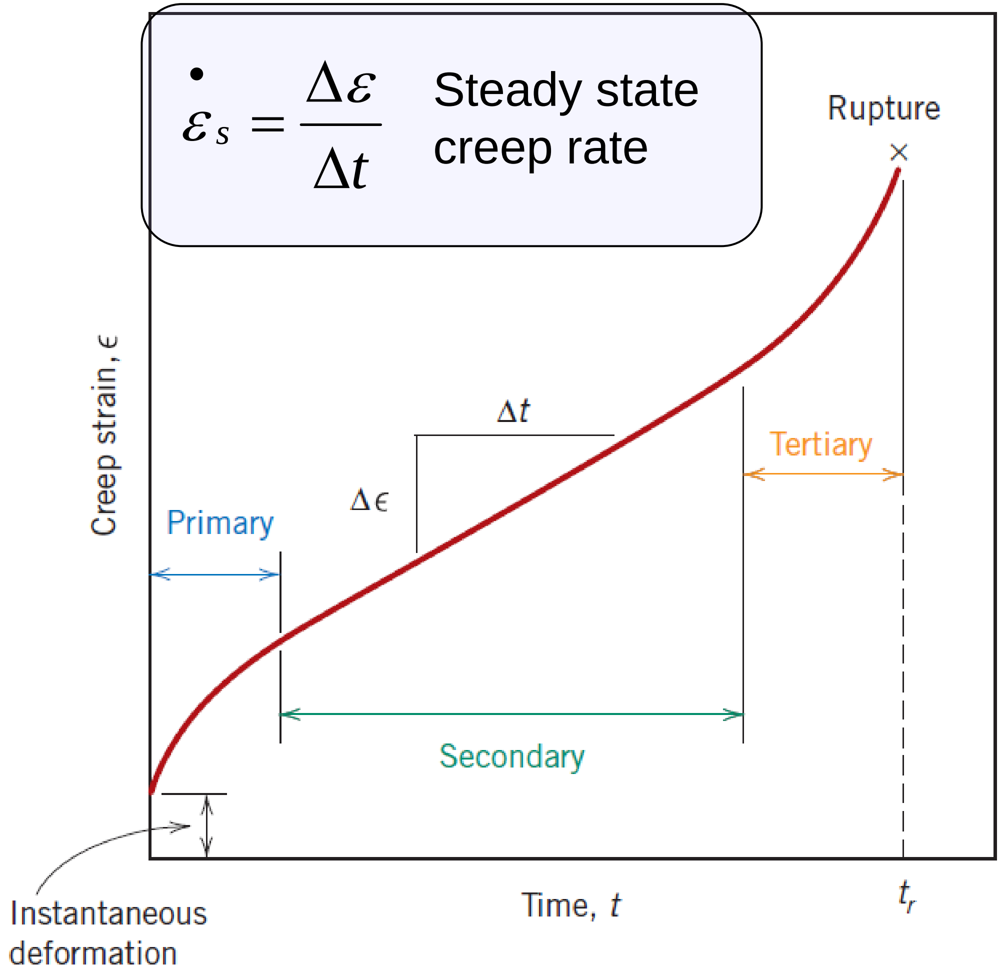


Figure 8.28 Typical creep curve of strain versus time at constant load and constant elevated temperature. The minimum creep rate $\Delta\varepsilon/\Delta t$ is the slope of the linear segment in the secondary region. Rupture lifetime t_r is the total time to rupture.

Creep

Generalized Creep Behavior

- From figure:
  - (1) *Instantaneous elastic region*.
  - (2) *Primary* or *transient creep*: continuously decreasing creep rate, as a result of strain hardening (more difficult creep).
  - (3) *Secondary creep* (*steady-state creep*): rate in constant. explained on the basis of a balance between the competing processes of strain hardening and recovery.
  - (4) *Tertiary creep,* there is an acceleration of the rate and ultimate failure. Failure is termed rupture.

Creep
Stress and Temperature Effects

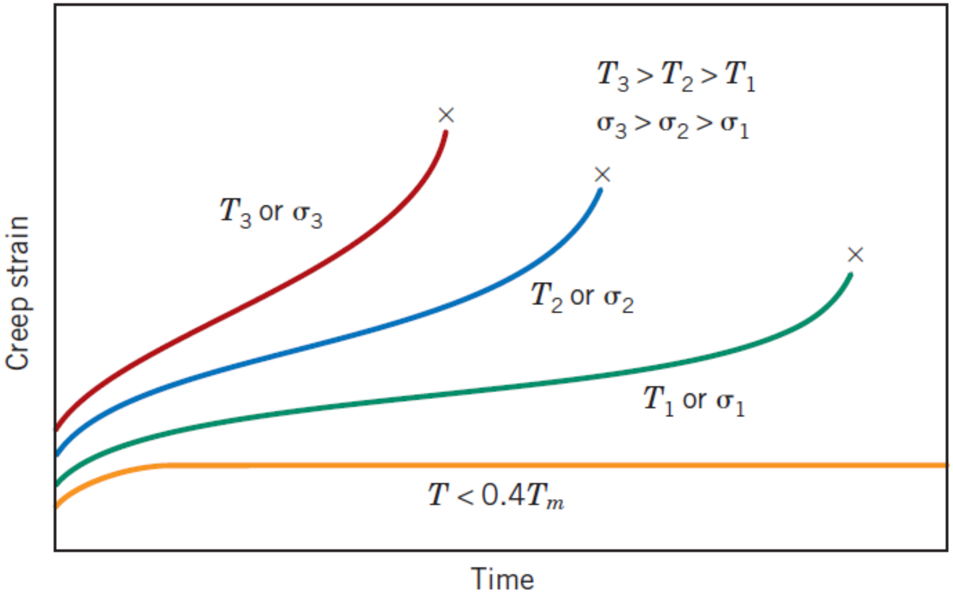


Figure 8.29 Influence of stress σ and temperature *T* on creep behavior.

-At a temperature substantially below 0.4*Tm*, 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.

$$\dot{\varepsilon}_s = K_1\sigma^n$$

K_1 & n are constants.

When temperature is considered →

$$\dot{\varepsilon}_s = K_2\sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

K_2 and Q_c are constants; Q_c is termed the activation energy for creep.

Creep
Alloys for High Temperature Use

- Factors affecting the creep characteristics of metals:
  - Melting temperature, elastic modulus, and grain size.
- The higher the melting point, the greater the elastic modulus, and the larger the grain size, the better a material’s resistance to creep.
  - Relative to grain size, smaller grains permit more grain boundary sliding, which results in higher creep rates.

Creep

Alloys for High Temperature Use

- Stainless steels and the superalloys are especially resilient to creep and are commonly employed in high-temperature service applications.

- The creep resistance of the superalloys is enhanced by solid-solution alloying and also by the formation of precipitate phases.

- In addition, advanced processing techniques have been utilized;

  - one such technique is directional solidification, which produces either highly elongated grains or single-crystal components