Failure Analysis and Prevention

What happened ?

Preventing Failure

In service, under loading (mechanical, thermal)

- How to assure performance, safety and durability?
  - Avoid excess deformation that may deteriorate the functionality
  - Avoid cracking that may propagate to complete fracture
- The study of deformation and fracture in materials the response of materials to mechanical loads or deformation.

Deformation and Failure

- Deformation
  - Time independent
    - Elastic
    - Plastic
  - Time dependent
    - Creep
- Fracture
  - Static loading
    - Brittle: rapid run of cracks through a stressed material
    - Ductile
    - Environmental (combination of stress and chemical effects)
      - High-strength steel may crack in the presence of hydrogen gas
      - Creep rupture (creep deformation proceeding to the point of separation)

  - Fatigue/cycling loading
    - High cycle/low cycle
    - Fatigue crack growth
    - Corrosion fatigue

Types of Failure

- Fracture
  - Cracking to the extent that component to be separated into pieces
  - Steps in fracture:

    - crack formation
    - crack propagation

- Depending on the ability of material to undergo plastic deformation before the fracture two fracture modes can be defined - **ductile or brittle**

  - **Ductile fracture** - most metals (not too cold):
    - Extensive plastic deformation ahead of crack
    - Crack is "stable": resists further extension unless applied stress is increased

  - **Brittle fracture** - ceramics, ice, cold metals:
    - Relatively little plastic deformation
    - Crack is "unstable": propagates rapidly without increase in applied stress

Fracture of Materials

Crack formation mechanisms

Metals typically form cracks by the accumulation of dislocations at a crack nucleation site (grain boundaries, precipitate interface, free surface, etc.)

Ceramics, semiconductors, some plastics (hard and brittle, eg., thermosetting plastics) and intermetallic compounds form cracks by planar defects (grain boundaries, two-phase interfaces, etc.)

Soft plastics crack by the sliding of the long polymer chairs across each other by breaking the Van der Wall bonds.
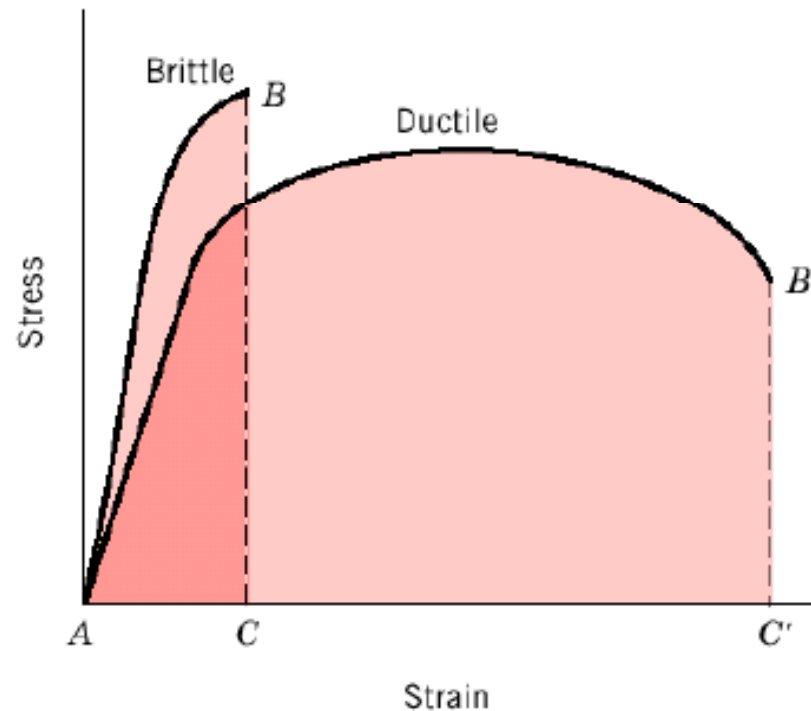
Fracture of Materials

Fracture can be classified according to the path of crack propagation:

• Transgranular – the crack travels directly through the grains of the material (sometimes called cleavage because it occurs along certain crystallographic planes). It can be ductile or brittle.

• Intergranular – the crack propagates along grain boundaries. This is primarily brittle fracture.

A variety of Loading Conditions can lead to fracture:

• Static Overloading ($\sigma > \sigma_{yield}$) and ($\sigma >$ Tensile Strength)

• Dynamic Overloading (impacting)

• Cyclic loading (fatigue)

• Loaded at elevated temperatures (creep)

• Loading at cryogenic temperatures (ductile to brittle transition)

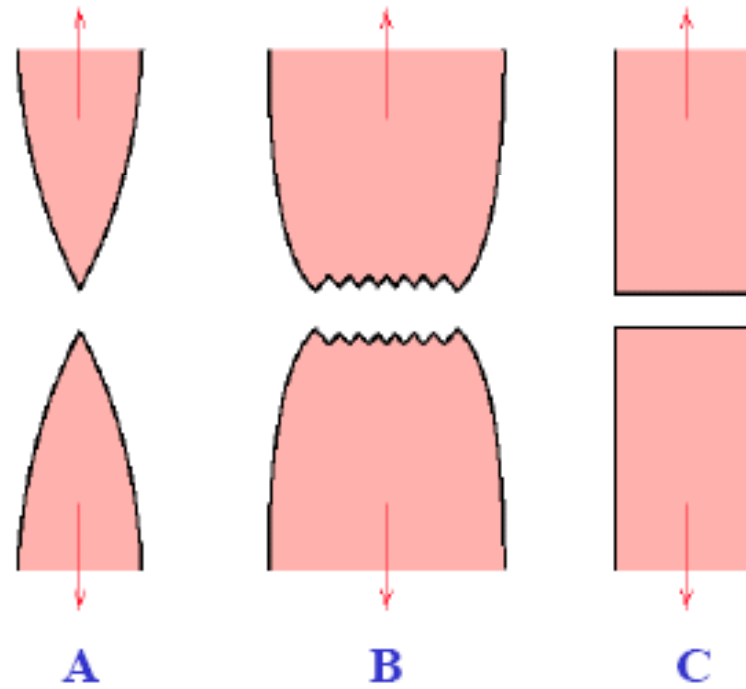• Loading in a corrosive environment (stress corrosion)

Brittle vs. Ductile Fracture

- **Ductile materials** - extensive plastic deformation and energy absorption ("toughness") before fracture
- **Brittle materials** - little plastic deformation and low energy absorption before fracture

Brittle vs. Ductile Fracture

A. **Very ductile**, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.

B. **Moderately ductile fracture**, typical for ductile metals

C. **Brittle fracture,** cold metals, ceramics.

Ductile Fracture

Crack grows 90° to applied stress

45° - maximum shear stress

Fibrous — Shear
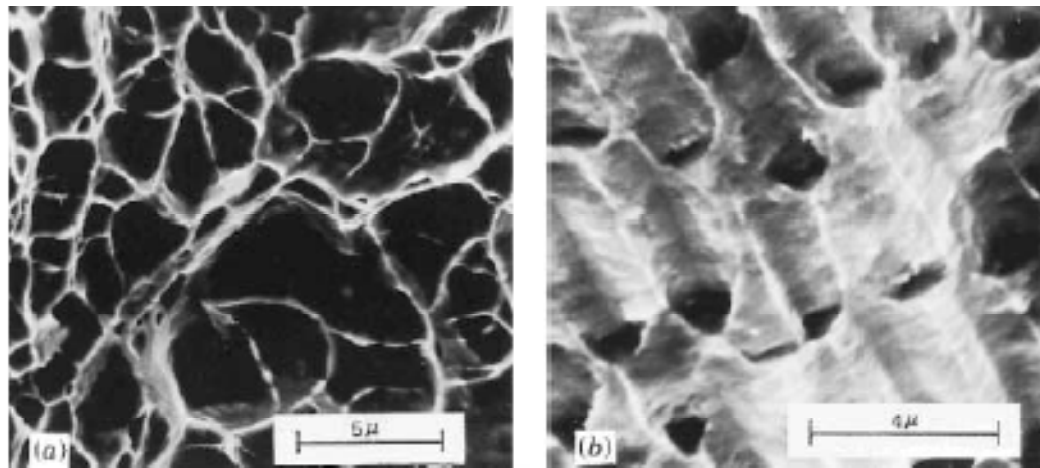
(a) (b) (c) (d) (e)
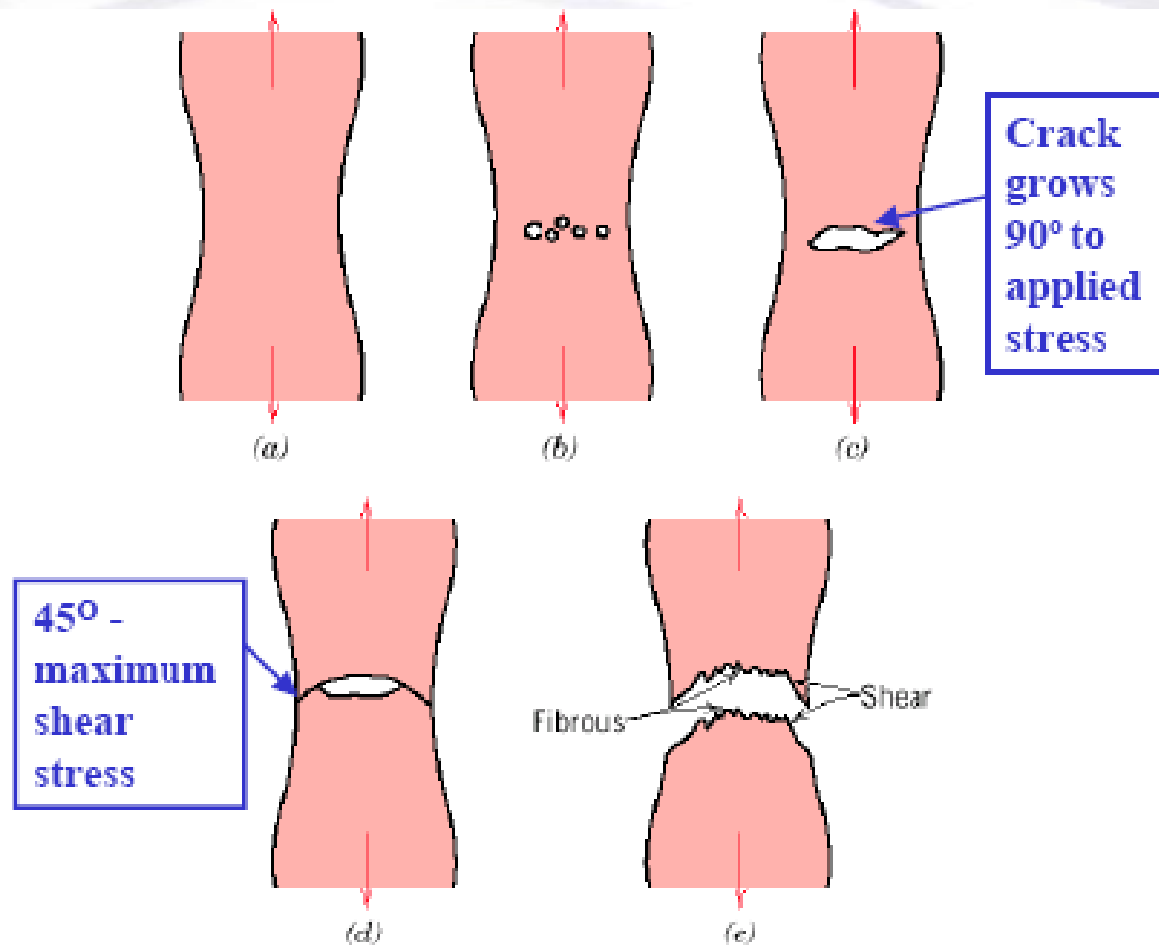
(a) Necking,   (b) Cavity Formation,

(c) Cavity coalescence to form a crack,

(d) Crack propagation,   (e) Fracture

Ductile Fracture
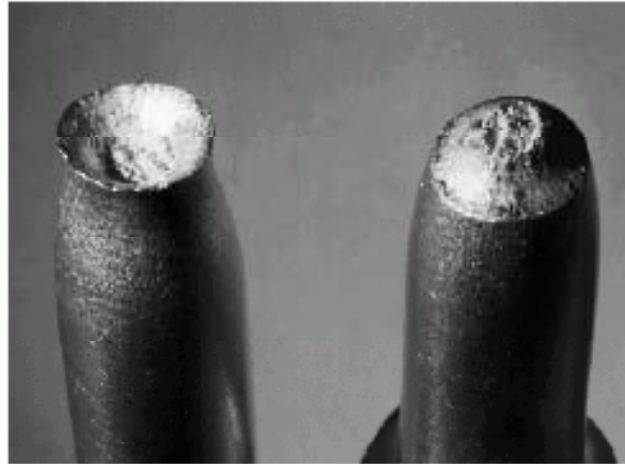
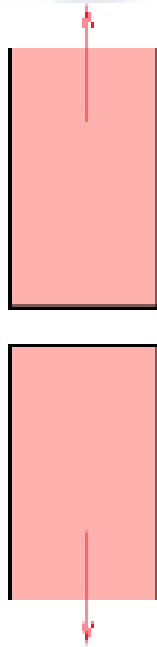

(Cap-and-cone fracture in Al

Scanning Electron Microscopy: *Fractographic* studies at high resolution. Spherical "dimples" correspond to micro-cavities that initiate crack formation.

Brittle Fracture

Brittle fracture in a mild steel

➢ No appreciable plastic deformation

➢ Crack propagation is very fast

➢ Crack propagates nearly perpendicular to the direction of the applied stress

➢ Crack often propagates by cleavage - breaking of atomic bonds along specific crystallographic planes (cleavage planes).

Impact Fracture Testing

Fracture behavior depends on many external factors:

- **Strain rate**
- **Temperature**
- **Stress rate**

Impact testing is used to ascertain the fracture characteristics of materials at a high strain rate and a triaxial stress state.

In an impact test, a notched specimen is fractured by an impact blow, and the energy absorbed during the fracture is measured.

There are two types of tests – Charpy impact test and Izod impact test.

Impact Test: The Charpy Test
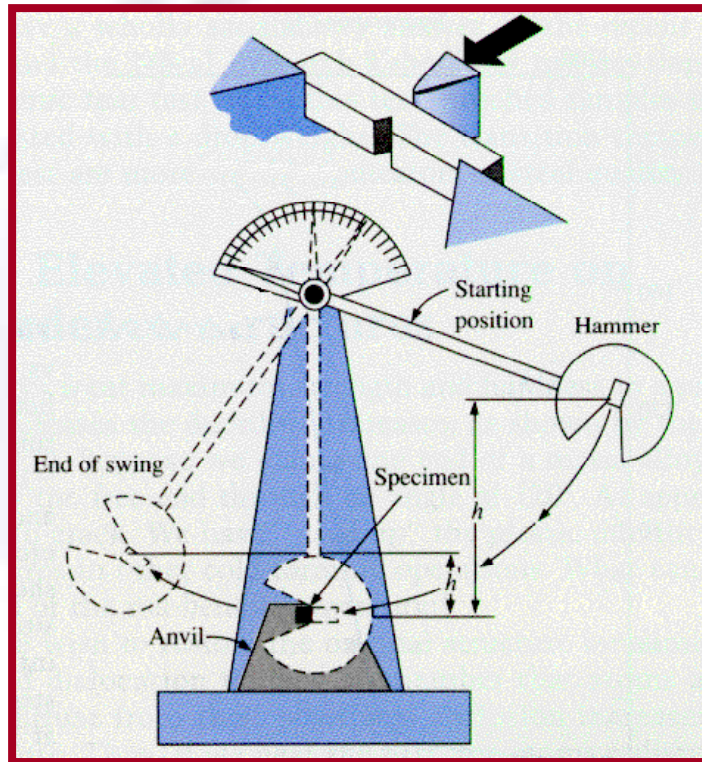
The ability of a material to withstand an impact blow is referred to as notch toughness.

The energy absorbed is the difference in height between initial and final position of the hammer. The material fractures at the notch and the structure of the cracked surface will help indicate whether it was a brittle or ductile fracture.
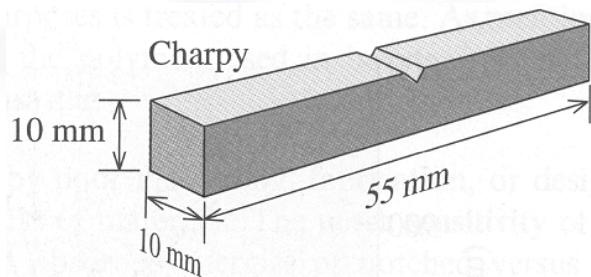
Impact Test (Charpy) Data for some of the Alloys

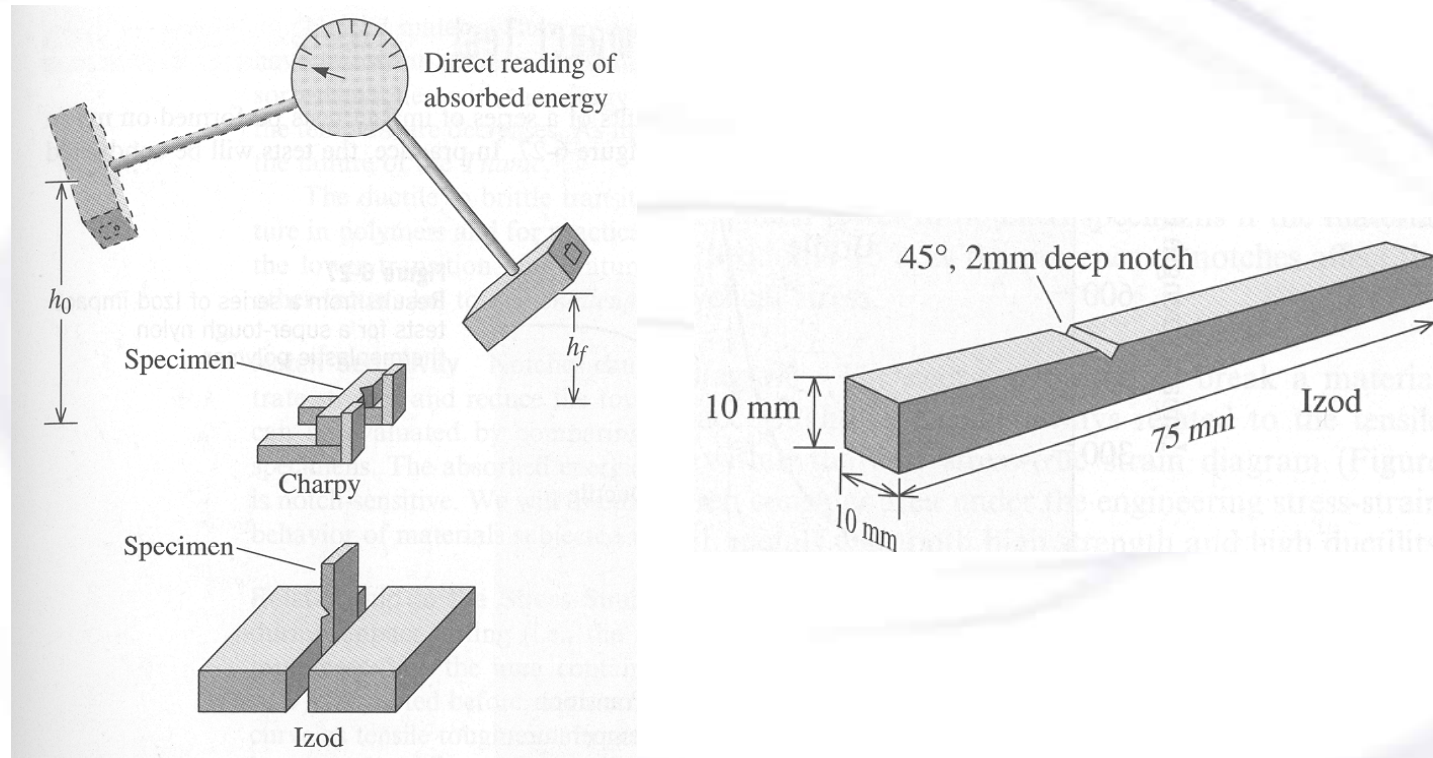|	Alloy	Impact energy [J (ft·lb)]
1.	1040 carbon steel	180 (133)
2.	8630 low-alloy steel	55 (41)
3.	c. 410 stainless steel	34 (25)
4.	L2 tool steel	26 (19)
5.	Ferrous superalloy (410)	34 (25)
6.	a. Ductile iron, quench	9 (7)
7.	b. 2048, plate aluminum	10.3 (7.6)
8.	a. AZ31B magnesium	4.3 (3.2)
	b. AM100A casting magnesium	0.8 (0.6)
9.	a. Ti–5Al–2.5Sn	23 (17)
10.	Aluminum bronze, 9% (copper alloy)	48 (35)
11.	Monel 400 (nickel alloy)	298 (220)
13.	50:50 solder (lead alloy)	21.6 (15.9)
14.	Nb–1 Zr (refractory metal)	174 (128)

Table 8.1

Impact Test (Charpy) Data for Some of the Alloys of Table 6.1.

In effect, the Charpy test takes the tensile test to completion very rapidly. The impact energy from the Charpy test correlates with the area under the total stress-strain curve (toughness)

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Impact Test: The Izod Test

Direct reading of absorbed energy

h_0

Specimen

Charpy

Specimen

Izod

h_f

45°, 2mm deep notch

10 mm

75 mm

10 mm

Izod

Generally used for polymers. Izod test is different from the Charpy test in terms of the configuration of the notched test specimen

Impact Test (Izod) Data for various polymers

Polymer	Impact energy [J (ft·lb)]
General-use polymers	
Polyethylene	
High-density	1.4–16 (1–12)
Low-density	22 (16)
Polyvinylchloride	1.4 (1)
Polypropylene	1.4–15 (1–11)
Polystyrene	0.4 (0.3)
Polyesters	1.4 (1)
Acrylics (Lucite)	0.7 (0.5)
Polyamides (nylon 66)	1.4 (1)
Cellulosics	3–11 (2–8)
Engineering polymers	
ABS	1.4–14 (1–10)
Polycarbonates	19 (14)
Acetals	3 (2)
Polytetrafluoroethylene (Teflon)	5 (4)
Thermosets	
Phenolics (phenolformaldehyde)	0.4 (0.3)
Urea-melamine	0.4 (0.3)
Polyesters	0.5 (0.4)
Epoxies	1.1 (0.8)

Source: From data collections in R. A. Flinn and P. K. Trojan, *Engineering Materials and Their Applications*, 2nd ed., Houghton Mifflin Company, Boston, MA, 1981; M. F. Ashby and D. R. H. Jones, *Engineering Materials*, Pergamon Press, Inc., Elmsford, NY, 1980; and *Design Handbook for Du Pont Engineering Plastics.*

Table 8.2

*Impact Test (Izod) Data for Various Polymers.*

Impact Tests: Test conditions

- The impact data are sensitive to test conditions. Increasingly sharp notches can give lower impact-energy values due to the stress concentration effect at the notch tip

- The FCC alloys→ generally ductile fracture mode

- The HCP alloys→ generally brittle fracture mode

- Temperature is important

- The BCC alloys→ brittle modes at relatively low temperatures and ductile mode at relatively high temperature

Transition Temperatures

- As temperature decreases a ductile material can become brittle - ductile-to-brittle transition

  - The transition temperature is the temp at which a material changes from ductile-to-brittle behavior

- Alloying usually increases the ductile-to-brittle transition temperature. FCC metals remain ductile down to very low temperatures. For ceramics, this type of transition occurs at much higher temperatures than for metals.

Ductile to Brittle Transition

The results of impact tests are absorbed energy, usually as a function of temperature. The ABSORBED ENERGY vs. TEMPERATURE curves for many materials will show a sharp decrease when the temperature is lowered to some point. This point is called the ductile to brittle transition temperature (*relatively narrow temperature range*) .
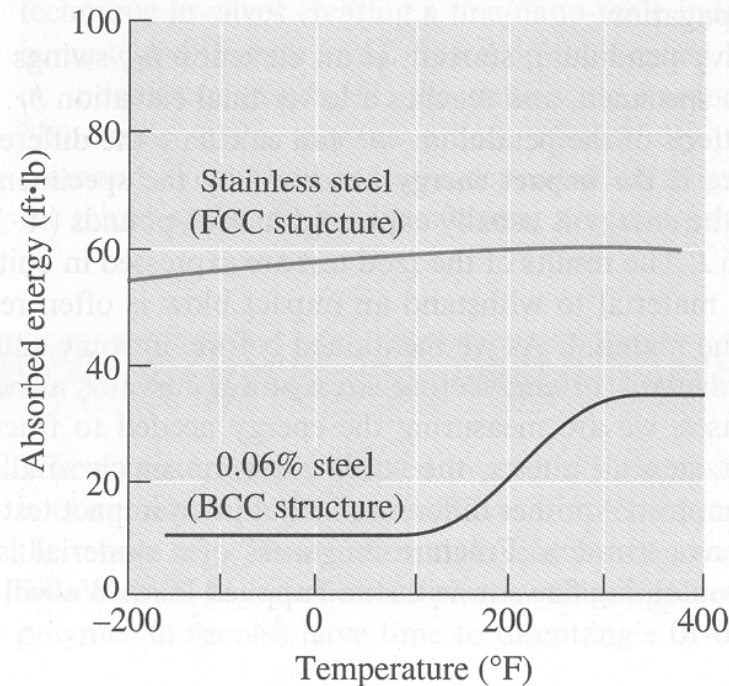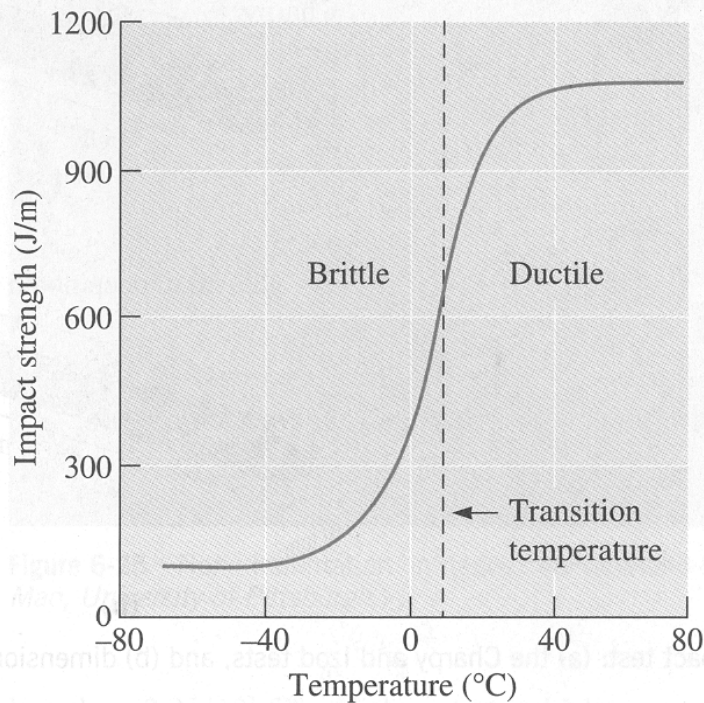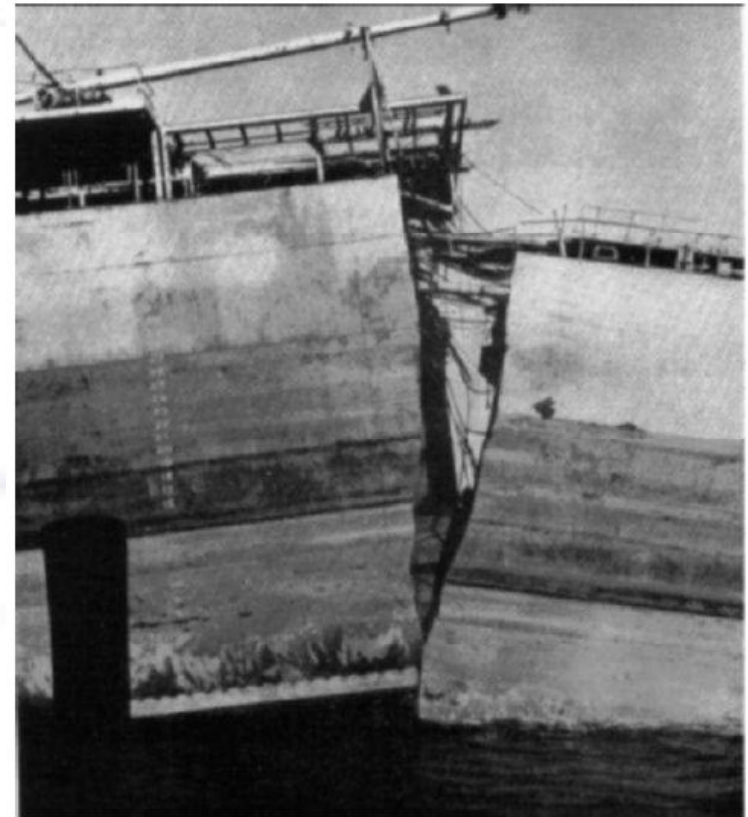

A typical ductile to brittle transition as a function of temperature. The properties of BCC carbon steel and FCC stainless steel, where the FCC crystal structure typically leads to higher absorbed energies and no transition temperature.

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Transition Temperatures

- BCC metals have transition temperatures
- FCC metals do not
- Can use FCC metals at low temperatures (eg Austenitic Stainless Steel)

Brittle Fracture

Failure of Liberty ships in WW II - Low-carbon steels were ductile at RT tensile tests, they became brittle when exposed to lower-temperature ocean environmets.The ships were built and used in the Pacific Ocean but when they were employed in the Atlantic Ocean, which is colder, the ship's material underwent a ductile to brittle transition.

# Alloying usually shifts the ductile-to-brittle transition temperature
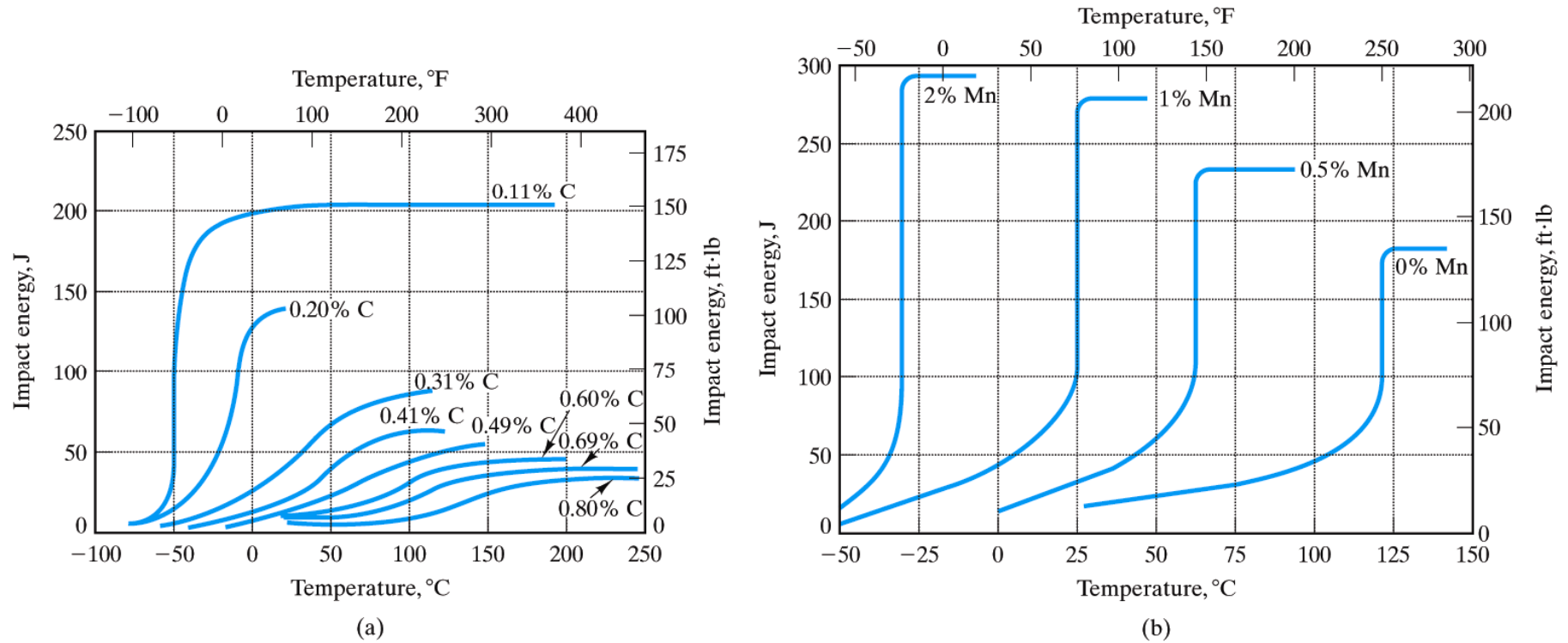
Carbon content increases the brittleness

Figure 8.3

*Variation in ductile-to-brittle transition temperature with alloy composition. (a) Charpy V-notch impact energy with temperature for plain-carbon steels with various carbon levels (in weight percent). (b) Charpy V-notch impact energy with temperature for Fe–Mn–0.05C alloys with various manganese levels (in weight percent). (From* Metals Handbook, *9th ed., Vol. 1, American Society for Metals, Metals Park, OH, 1978.)*

The fracture surface

Ductile → a dimpled texture
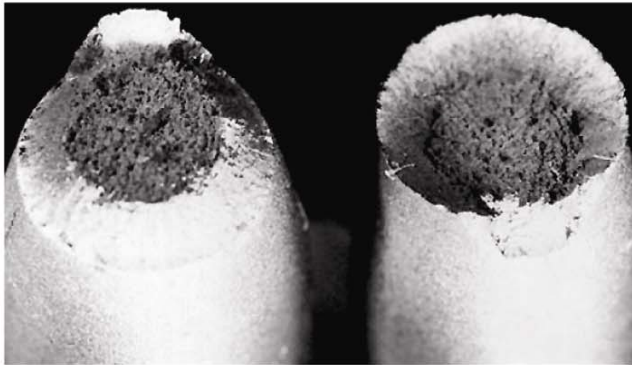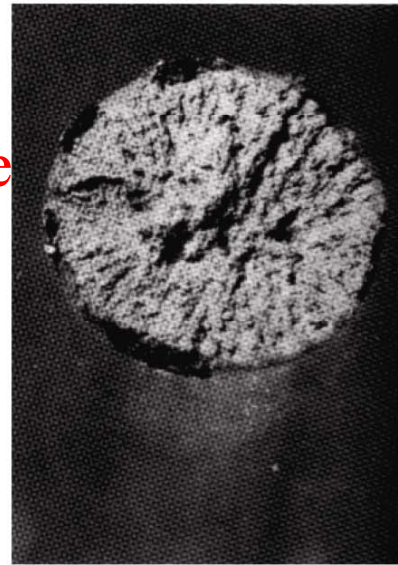
(a)   (b)

Brittle → cleavage surface

Figure 8.4

(a) Typical "cup and cone" ductile fracture surface. Fracture originates near the center and spreads outward with a dimpled texture. Near the surface, the stress state changes from tension to shear, with fracture continuing at approximately 45°. (From Metals Handbook*, 9th ed., Vol. 12, ASM International,* Metals *Park, Ohio, 1987.)*
(b) Typical cleavage texture of a brittle fracture surface. (From Metals Handbook*, 8th ed., Vol. 9, American Society for Metals, Metals Park, OH, 1974.)*

cleavage : The tendency of certain minerals to break along distinct planes in their crystal structures where the bonds are weakest

Near the ductile-to-brittle transition temperature, the fracture surface exhibits a mixed texture

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Fracture Mechanics:

The general analysis of the failure of structural materials with preexisting flaws→ The main outcome of the analysis is fracture toughness

Fracture Mechanics

- Fracture strength of a brittle solid is related to the cohesive forces between atoms.

-

- One can estimate that the theoretical cohesive strength of a brittle material should be ~ E/10. But experimental fracture strength is normally E/100 - E/10,000.

- This much lower fracture strength is explained by the effect of **stress concentration** at microscopic flaws.

- The applied stress is amplified at the tips of micro-cracks, voids, notches, surface scratches, corners, etc. that are called **stress raisers.** The magnitude of this amplification depends on micro-crack orientations, geometry and dimensions.

Fracture Mechanics

- Cracks or crack-like flaws (surface scratches, voids in welds, delaminations, foreign substances in cast materials…) exist frequently

  - Commercial aircraft
  - Ship structures
  - Bridges
  - Pressure vessels and piping

- Fracture mechanics: a methodology to aid in selecting materials and designing components to minimize the possibility of fracture where cracks are difficult to avoid

Fracture Mechanics

One important reason for the big difference in theoretical and experimental values in **fracture strength** is **cracks**.

•There **always** exists cracks or flaws in solid materials. **Why?**

•Stress is enlarged at the crack tip (**stress raisers**).

(a)   (b)   (c)
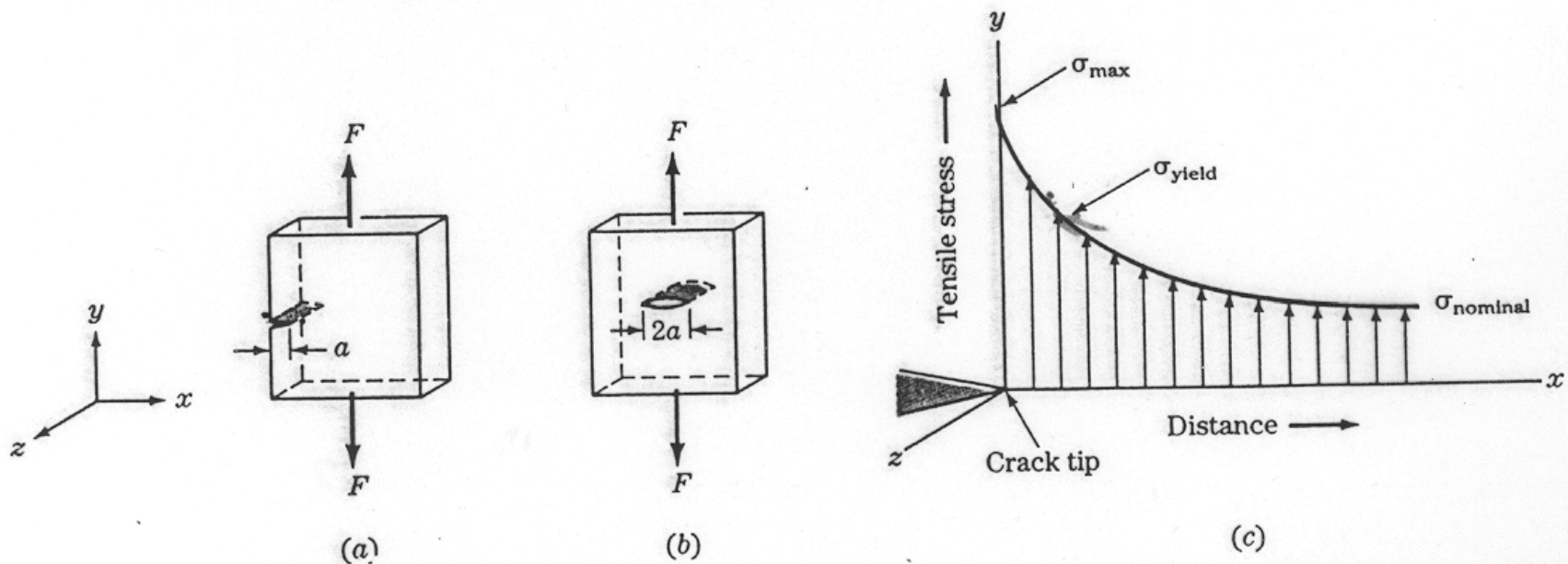
- The uniform stress field is altered in the vicinity of the hole
- Stress concentration factor depends of geometry
- Theoretically, a sharp crack (zero tip radius) causes a severe concentration of stress (**infinite stress)**

Cracks as stress raisers

- In practice, the theoretically infinite stress relieved by modifying the sharp crack tip
  - ductile material can accommodate the presence of an initially sharp crack as large plastic deformation in the vicinity of the tip results in blunted crack tip and finite stress values - the plastic zone

  - Some polymers, a region containing elongated voids develops that contains a fibrous structure bridging the crack faces- craze zone

  - Brittle materials, a region containing high density of tiny crack

- Crack tip experiences intense deformation and finite separation near its tip
- High stress is spread over a larger region - redistributed
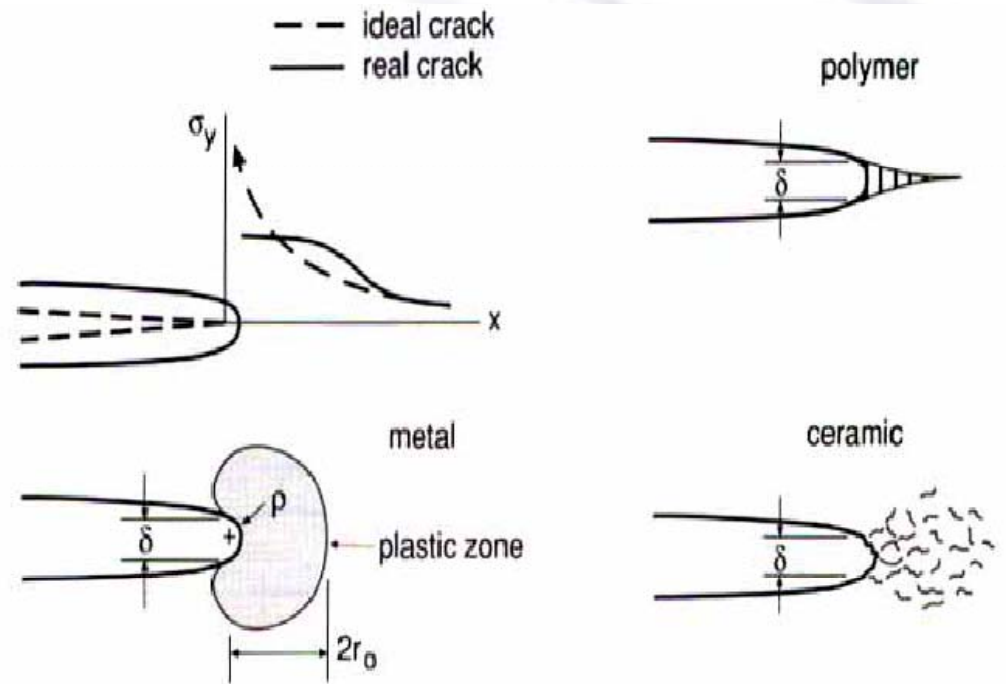
Figure 8.4 Finite stresses and nonzero radii at tips of cracks in real materials. A region of intense deformation forms due to plasticity, crazing, or microcracking.

Mechanical Behaviour of Materials, N. E. Dowling

Fracture Toughness

What is **fracture toughness**? Critical value of the **stress-intensity factor** at a crack tip necessary to produce catastrophic failure under simple uniaxial load.

The **stress intensity** at the crack tip is dependent on both the **applied stress** and the **length of the crack**. A new mechanical variable, **Stress Intensity Factor**, K_I, is used to describe the relationship:

$$K_I = f\sigma\sqrt{\pi a}$$

Where,

I$\rightarrow$ stands for mode: uniaxial loading

C $\rightarrow$ stands for mode: critical

f is a dimensionless constant (related to geometry of specimen and flaw)

σ is the applied stress

a is the crack length or half the length of an internal crack

K_I is a variable but NOT a materials property

K_I has unusual unit of Mpa(m)^{½} or psi(in)^{½} .

Fracture Toughness

Fracture Toughness

When the stress intensity, K_I is increased to a critical value, K_{IC} , crack propagation will occur, which will lead to fracture.

Analogy: A balloon with a small pinhole will catastrophically fails starting from the pinhole location when the pressure has reached a critical value.

$$K_{IC} = f\sigma\sqrt{\pi a}$$

Where,

$\underline{K_{IC}}$ is a measure of a materials resistance to crack propagation.

It is a material property.

K_{IC} is dependent on temperature, microstructure, and strain rate.

K_{IC} usually increases with a reduction in grain size.

Fracture Toughness

How to use K_{IC} ?

- Fracture toughness is **most useful in mechanical designs** involving materials with **limited toughness or ductility**.

- Usually $\sigma \leq \sigma_{yield}/n$ is good enough for ductile materials, which are statically loaded.

- Design criterion using K_{IC} :

$$\boxed{K_I \leq K_{IC}}$$

taking into account K_{IC} , which is a material property, **the allowable stress (σ) and/or the allowable flaw size (a) can be determined.**

Material Selection:

•If the maximum applied stress, σ_{max} , and **maximum crack length** are **specified** for a certain application, **then only the materials with K_{IC} greater than K_I can be used:**

$$\boxed{K_{IC} = f\sigma_{max}\sqrt{\pi a_{max}}}$$

Fracture Toughness

Highly brittle materials with little or no ability to deform plastically in the vicinity of a crack tip **have low K$_{IC}$** values and are susceptible to catastrophic failure.

High ductility alloys can undergo significant plastic deformation on both macroscopic and microscopic scale before fracture.

Material	K_{IC} (MPa $\sqrt{m}$)
Metal or alloy	
Mild steel	140
Medium-carbon steel	51
Rotor steels (A533; Discalloy)	204–214
Pressure-vessel steels (HY130)	170
High-strength steels (HSS)	50–154
Cast iron	6–20
Pure ductile metals (e.g., Cu, Ni, Ag, Al)	100–350
Be (brittle, hcp metal)	4
Aluminum alloys (high strength–low strength)	23–45
Titanium alloys (Ti–6Al–4V)	55–115
Ceramic or glass	
Partially stabilized zirconia	9
Electrical porcelain	1
Alumina (Al_2O_3)	3–5
Magnesia (MgO)	3
Cement/concrete, unreinforced	0.2
Silicon carbide (SiC)	3
Silicon nitride (Si_3N_4)	4–5
Soda glass ($Na_2O–SiO_2$)	0.7–0.8
Polymer	
Polyethylene	
High-density	2
Low-density	1
Polypropylene	3
Polystyrene	2
Polyesters	0.5
Polyamides (nylon 66)	3
ABS	4
Polycarbonates	1.0–2.6
Epoxy	0.3–0.5

Source: Data from M. F. Ashby and D. R. H. Jones, *Engineering Materials—An Introduction to Their Properties and Applications*, Pergamon Press, Inc., Elmsford, NY, 1980; GTE Laboratories, Waltham, MA; and *Design Handbook for Dupont Engineering Plastics*.

Table 8.3

Typical Values of Fracture Toughness (K$_{IC}$) for Various Materials.

Fracture Toughness

Allowable stress design (if "a" and K_{IC} are specified by application constraints)

$$\sigma_{max} \leq \frac{K_{IC}}{f\sqrt{\pi a_{max}}}$$

Effects of Cracks on Strength

- The value of K_{IC} decreases with increasing strain rate and decreasing temperature

- Refining the grain increases K_{IC}

- If load is too high the crack may suddenly grow, fracture in brittle manner with little plastic deformation

- Stress intensity factor, K: characterizes the severity of the crack situation as affected by crack size, stress, and geometry
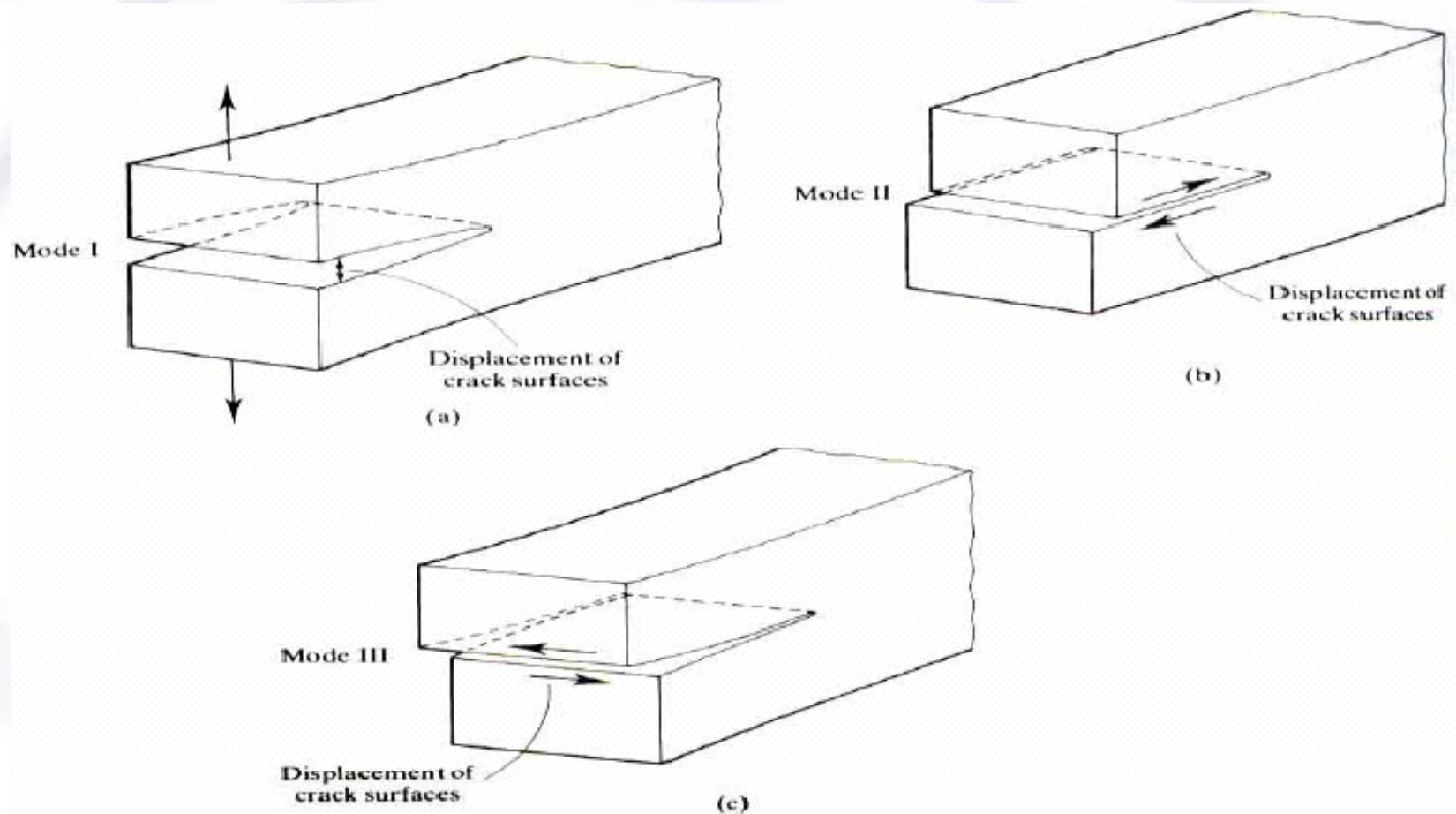
Displacement modes on cracked body

Figure 9.8
The three primary macroscopic fracture modes. (a) Mode I fracture (the tensile opening mode) is the most common tensile fracture. It is caused by a force tending to open up the crack and its tip. The crack propagates in a direction normal to the applied stress. (b) In Mode II fracture (a shear fracture), separation of the bar is achieved by propagation of the crack in a direction parallel to the sense of the applied shear stress. (c) In Mode III fracture (antiplane strain fracture), a shear stress causes displacement of the crack surfaces. This results in the crack propagating in the direction normal to the shear stress, and produces a tearing type of fracture.
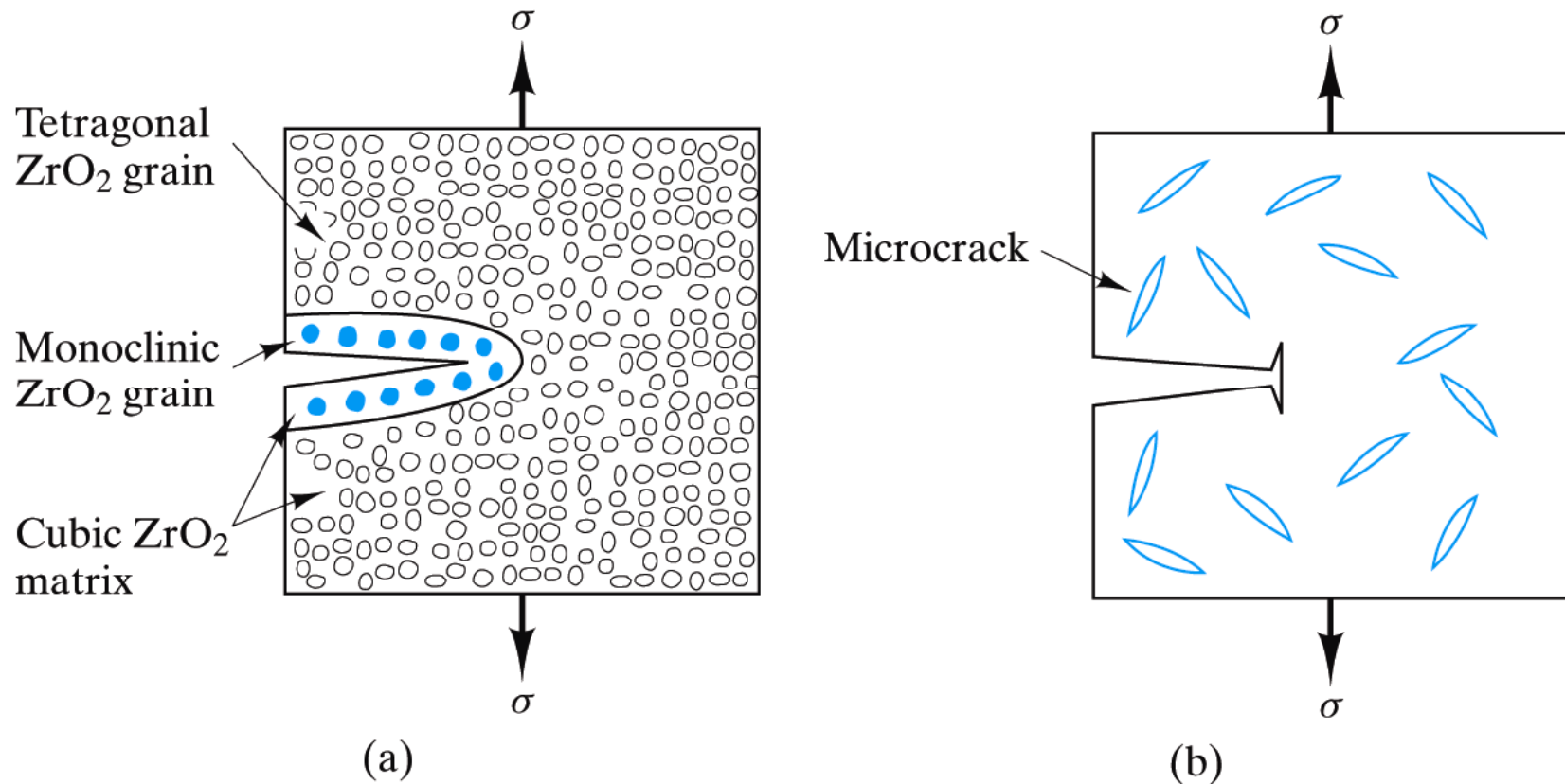
Figure 8.7

Two mechanisms for improving fracture toughness of ceramics by crack arrest. (a) Transformation toughening of partially stabilized zirconia involves the stress-induced transformation of tetragonal grains to the monoclinic structure, which has a larger specific volume. The result is a local volume expansion at the crack tip, squeezing the crack shut and producing a residual compressive stress. (b) Microcracks produced during fabrication of the ceramic can blunt the advancing crack tip.

Microstructure of Fracture in Metals

Most often ductile fracture occurs in a **transgranular** manner, which means through the grains rather than only along grain boundaries.

Brittle fracture is typically **intergranular** or along the grain boundaries, which is enhanced when impurities collect and weaken the grain boundaries.

In a simple tensile test, ductile fracture begins by the **nucleation, growth and coalescence of microvoids** at the center of a sample (in the necked region).

The **stress causes separation of the grain boundaries or the interfaces between the metal and small impurity particles** (inclusions or precipitates).

As the local stresses increase, the micro-voids grow and coalesce into larger cavities.

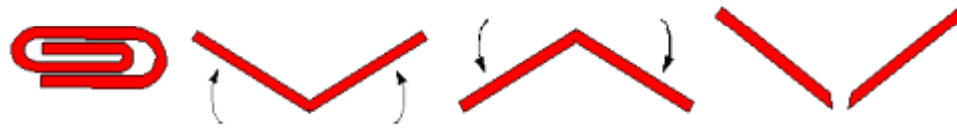Eventually the metal-to-metal contact is too small to support the load and fracture occurs.

Microstructure of Fracture in Metals
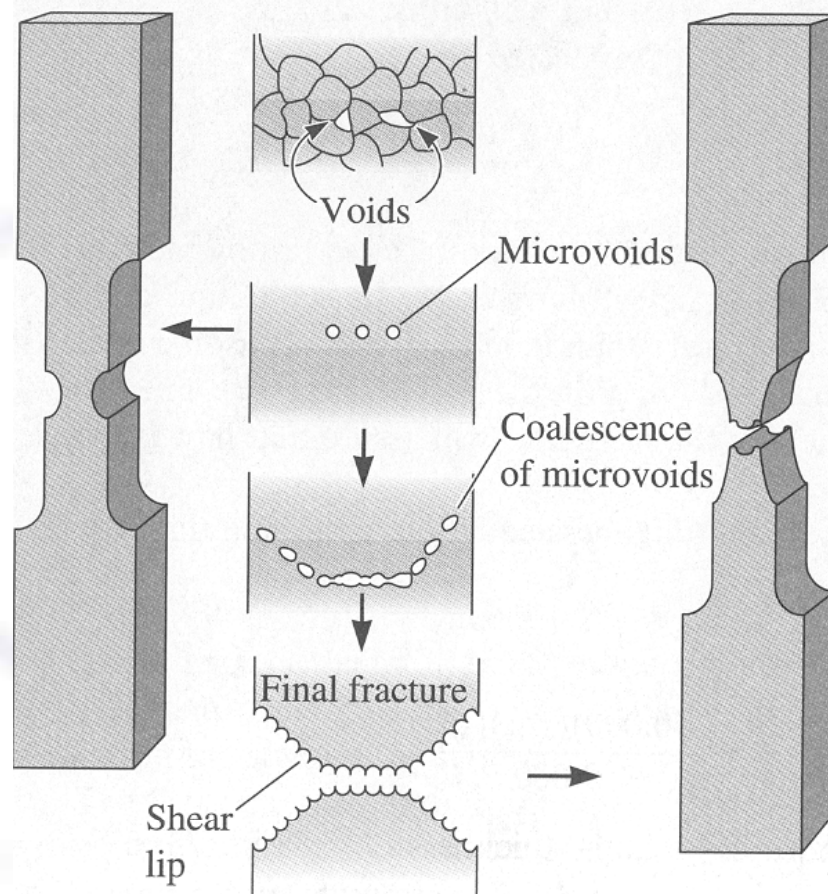
Formation of voids in the necked region during tensile testing, leading to fracture.

Fatigue

Fatigue

Fatigue is the lowering of strength or failure of a material due to repetitive stress, which may be above or below the yield strength.

Many engineering materials such as those used in cars, planes, turbine engines, machinery, shoes, etc are subjected constantly to repetitive stresses in the form of tension, compression, bending, vibration, thermal expansion and contraction or other stresses.

There are typically three stages to fatigue failure.

First a small crack is initiated or nucleates at the surface and can include scratches, pits, sharp corners due to poor design or manufacture, inclusions, grain boundaries or dislocation concentrations.

Second the crack gradually propagates as the load continues to cycle.

Third a sudden fracture of the material occurs when the remaining cross-section of the material is too small to support the applied load.

At a local size scale the _stress intensity_ exceeds the yield strength.

For fatigue to occur at least part of the stress in the material has to be tensile.

Fatigue is most common in metals and plastics, whereas ceramics fail catastrophically without fatigue because of their low fracture toughness.

Fatigue

Fatigue failures are often easy to identify.

**The fracture surface near the origin is usually smooth (Beach mark-crack initiation point). The surface becomes rougher as the crack increases in size.**

Striations (concentric line patterns): the slow cyclic build up of crack growth from a surface intrusion. Striations are on a much finer scale and show the position of the crack tip after each cycle.
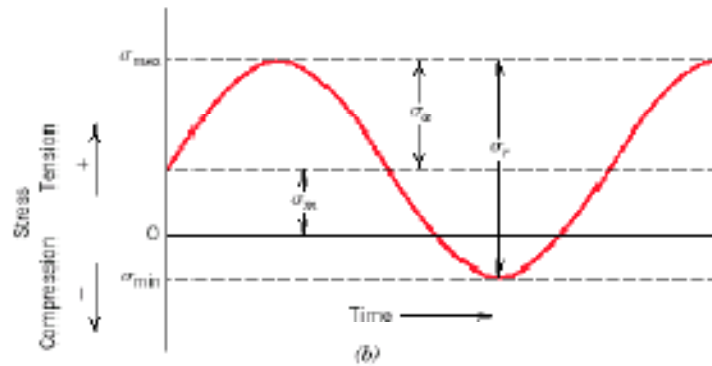
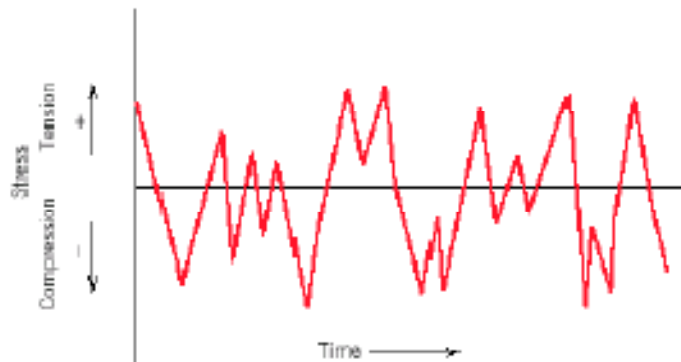**Granular portion of the fracture surface: rapid crack propagation at the time of catastrophic failure**

Initiation

Fatigue crack propagation

Catastrophic rupture

(a)
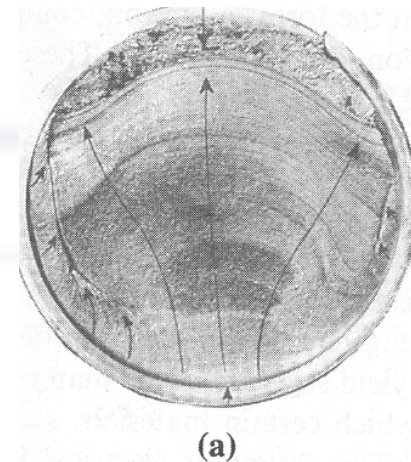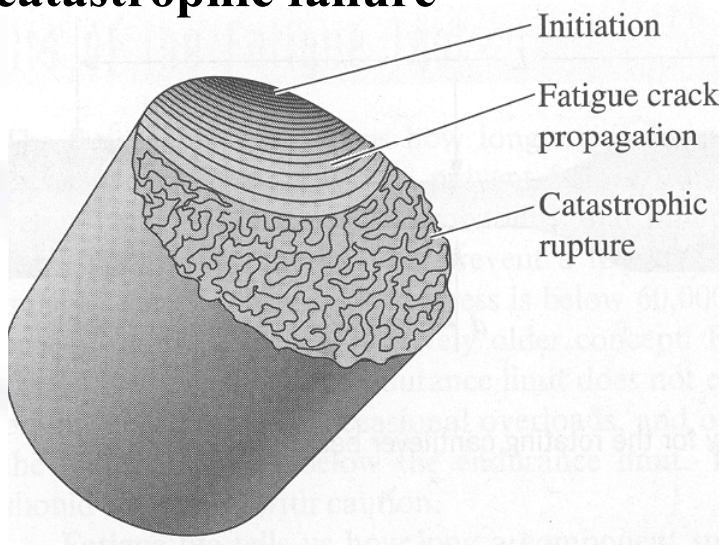
Dynamic Loading and Fatigue
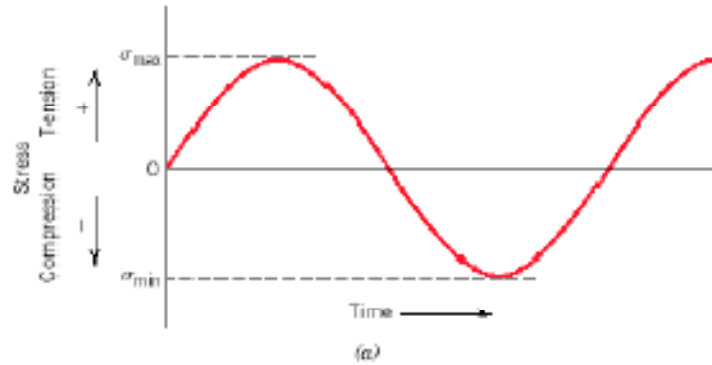
Fatigue under cyclic/repeated loading

- Cracks generally grow under repeated loading

  - Trucks passing over bridges,
  - Sailboat rudders
  - Bicycle pedals

- May result failure or fracture: fatigue fracture
  - Periodic inspections required for fatigue critical systems

- Thermal fatigue: repeated heating and cooling can cause a cyclic stress due to differential thermal expansion and contraction

Fatigue

- Repeated, also called cyclic loads resulting in cyclic stresses can lead to microscopic physical damage.

- Accumulation of this microscopic damage with continued cycling is possible until it develops into a macroscopic crack such as cracks that may lead to failure

- **Fatigue**: Damage progression to failure due to repeated or cyclic loading at amplitudes considerably *lower than tensile or yield strengths of material under a static load*

- Estimated to causes 90 % of all failures of metallic structures (bridges, aircraft, machine components, etc.)

- Fatigue failure is brittle-like (relatively little plastic deformation) - even in normally ductile materials. Thus sudden and catastrophic!

Fatigue Data

The most important fatigue data for engineering designs are the S-N curves, which is the **Stress-Number of Cycles** curves.

In a fatigue test, a specimen is subjected to a cyclic stress of a certain form and amplitude and the number of cycles to failure is determined.

The number of cycles, N, to failure is a function of the stress amplitude, S. A plot of S versus N is called the S-N curve.
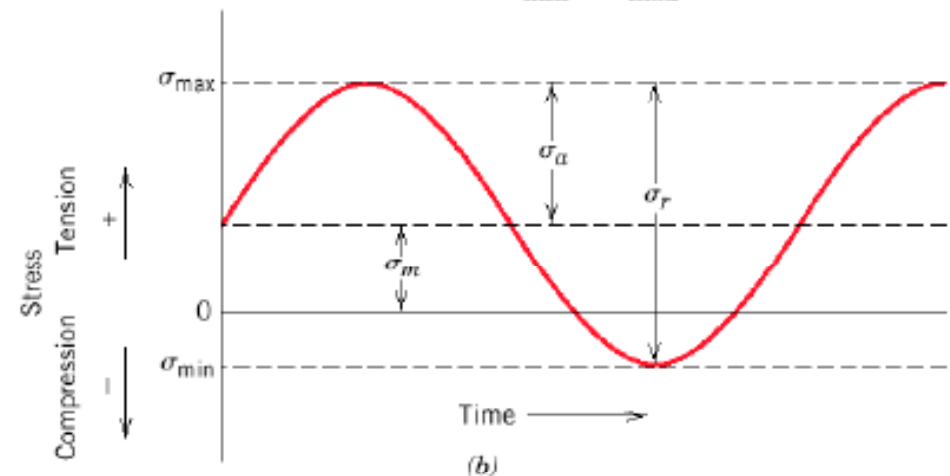
Definitions and Concepts

- Constant amplitude stressing
- Mean stress
- Stress amplitude (half of the range)→ variation about the mean
- Stress ratio R, Amplitude ratio
- Completely reversed stressing, R=-1

Mean stress: $\sigma_m = (\sigma_{max} + \sigma_{min}) / 2$

Range of stress: $\sigma_r = (\sigma_{max} - \sigma_{min})$

Stress amplitude: $\sigma_a = \sigma_r/2 = (\sigma_{max} - \sigma_{min}) / 2$

Stress ratio: $R = \sigma_{min} / \sigma_{max}$

Remember the convention that tensile stresses are positive, compressive stresses are negative

Types of stresses for fatigue tests include,

    axial (tension – compression)

    flexural (bending)

    torsional (twisting)

From these tests the following data is generated.
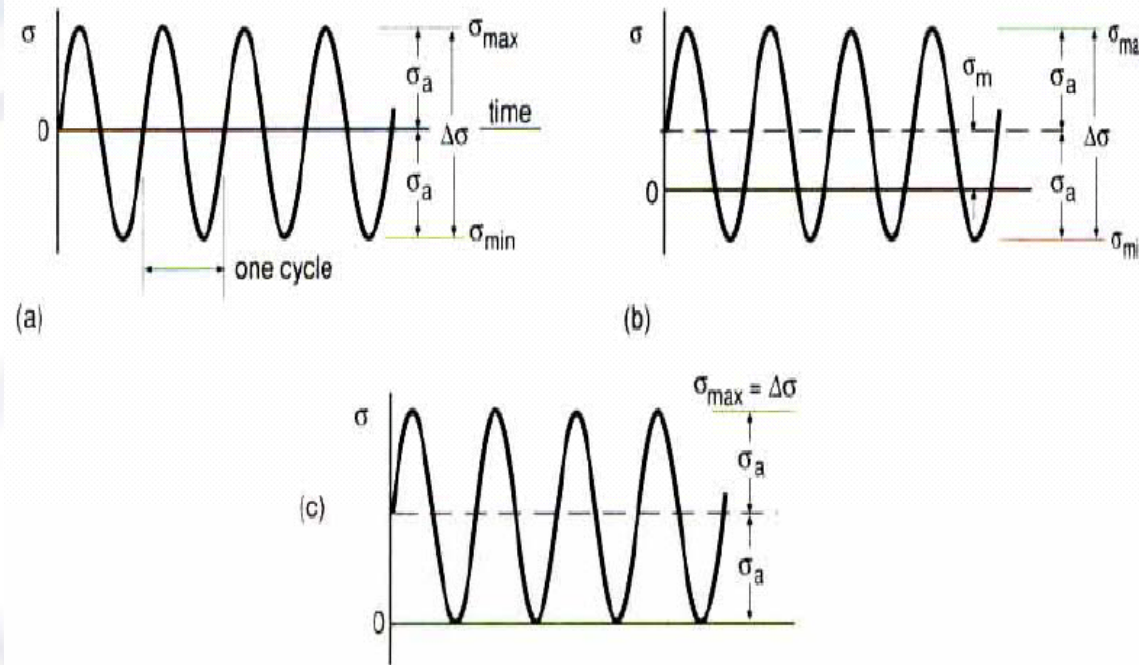
$$\text{Mean Stress,} \ \sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

$$\text{Stress Amplitude,} \ \sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$

$$\text{Stress Range,} \ \sigma_r = \sigma_{max} - \sigma_{min}$$

$$\text{Stress Ratio,} \ R = \frac{\sigma_{min}}{\sigma_{max}}$$

**By convention, tensile stresses are positive and compression stresses are negative.**

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Figure 9.2 Constant amplitude cycling and the associated nomenclature. Case (a) is completely reversed stressing, $\sigma_m = 0$, (b) has a nonzero mean stress σ_m, and (c) is zero-to-tension stressing, $\sigma_{min} = 0$.

Low cycle fatigue: high loads, plastic and elastic deformation

High cycle fatigue: low loads, elastic deformation ($N > 10^5$)

S-N curve
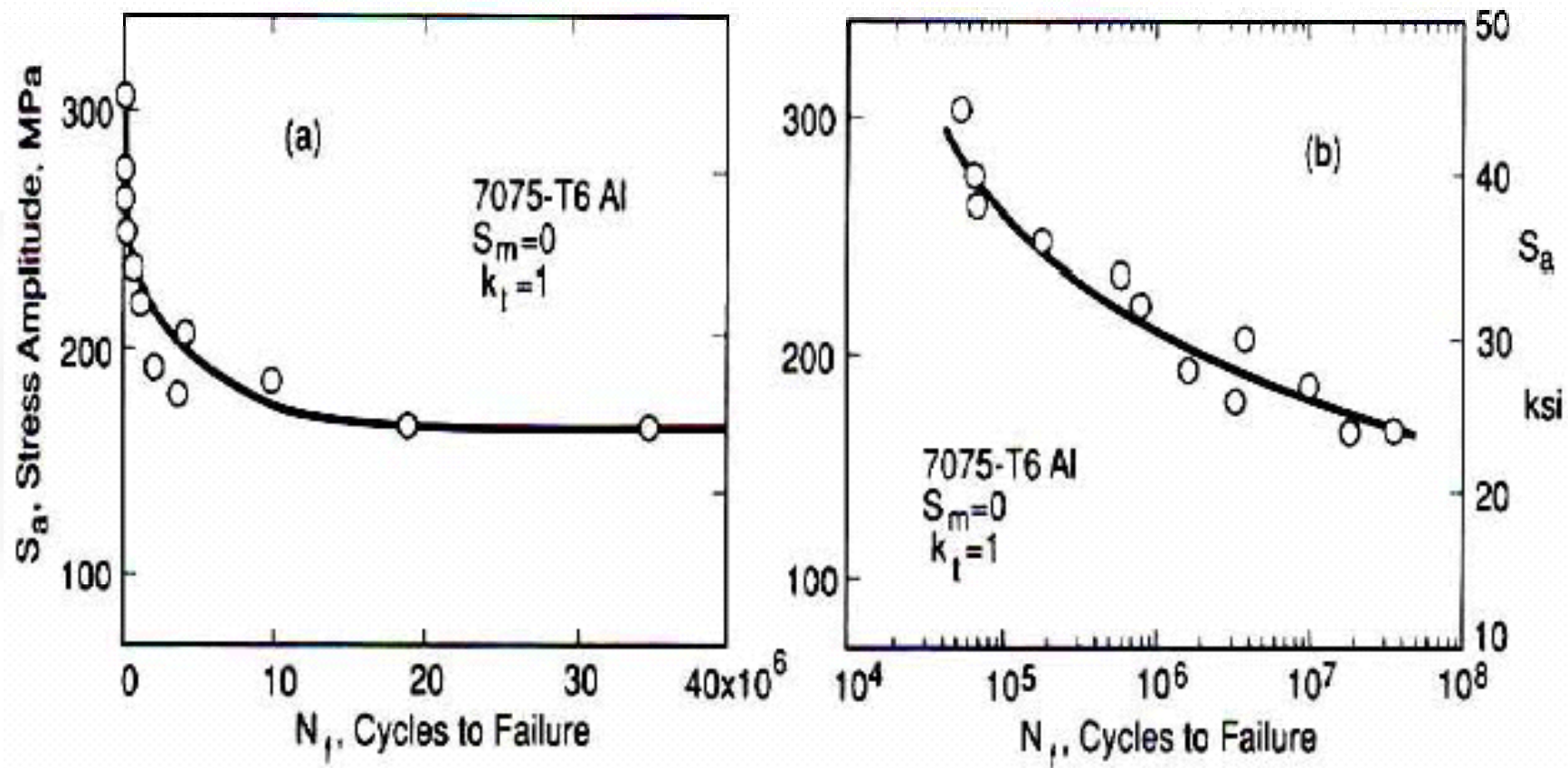
Figure 9.4 Stress versus life (S-N) curves from rotating bending tests of unnotched specimens of an aluminum alloy. Identical linear stress scales are used, but the cycle numbers are plotted on a linear scale in (a), and on a logarithmic one in (b). (Data from [MacGregor 52].)

Fatigue Limit:

•For some materials such as BCC steels and Ti alloys, the S-N curves become horizontal when the **stress amplitude is decreased to a certain level.**

•This stress level is called the Fatigue Limit, or **Endurance Limit.**

Fatigue Strength:

For materials, which do not show a fatigue limit such as **Al, Cu, and Mg (non-ferrous alloys),** and some steels with a FCC structure, **fatigue strength** is specified as the stress level **at which failure will occur for a specified number** of cycles, where **10^7 cycles** is often used.
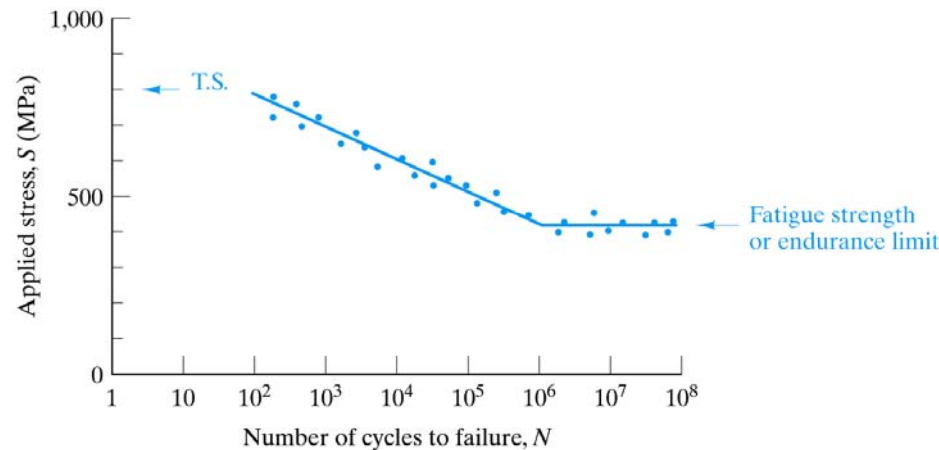

Figure 8.10

*Typical fatigue curve. (Note that a log scale is required for the horizontal axis.)*

Alloy	F.S. (MPa)	T.S. (MPa)
1. 1040 carbon steel	280	750
2. 8630 low-alloy steel	400	800
3. a. 304 stainless steel		515
3. b. 304 stainless steel	170	
7. a. 3003-H14 aluminum	62	150
8. b. AM100A casting magnesium	69	150
9. a. Ti–5Al–2.5Sn	410	862
10. Aluminum bronze, 9% (copper alloy)	200	652
11. Monel 400 (nickel alloy)	290	579
12. AC41A zinc	56	328

Table 8.4

Comparison of Fatigue Strength (F.S.) and Tensile Strength (T.S.) for Some of the Alloys of Table 6.1.

Definitions

- **Fatigue life**: indicates how long (no. of cycles) a component survives a particular stress.
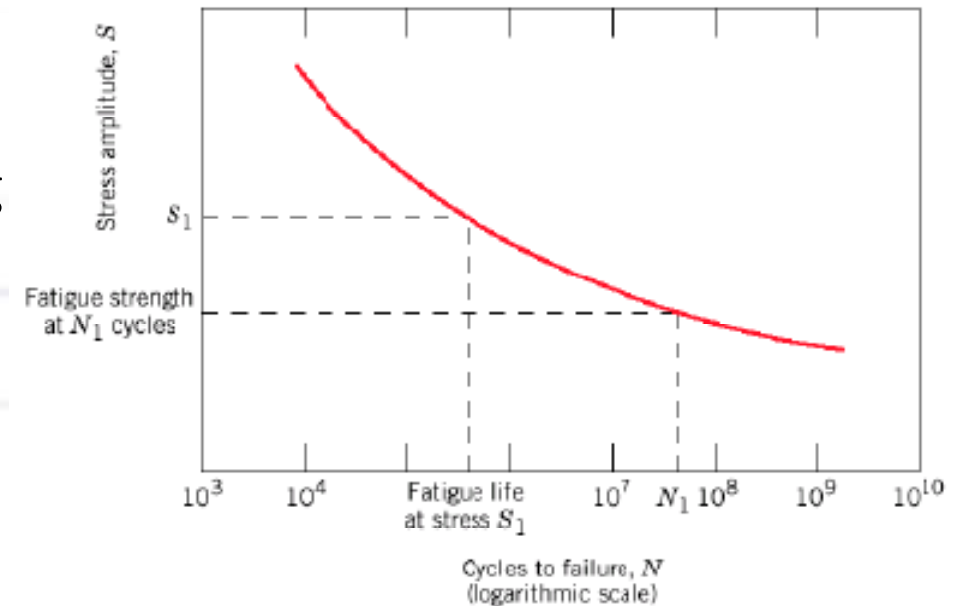
Fatigue strength: is applicable to a component with No endurance limit. It is the maximum stress for which fatigue will not occur at a particular number of cycles, in general, 10^8 cycles for metals.

Endurance ratio: the endurance limit is approximately ¼ to ½ the tensile strength.

$$\textbf{Endurance ratio} = \frac{\textbf{endurance limit (fatigue strenght)}}{\textbf{tensile strength}} \approx 0.25 - 0.5$$
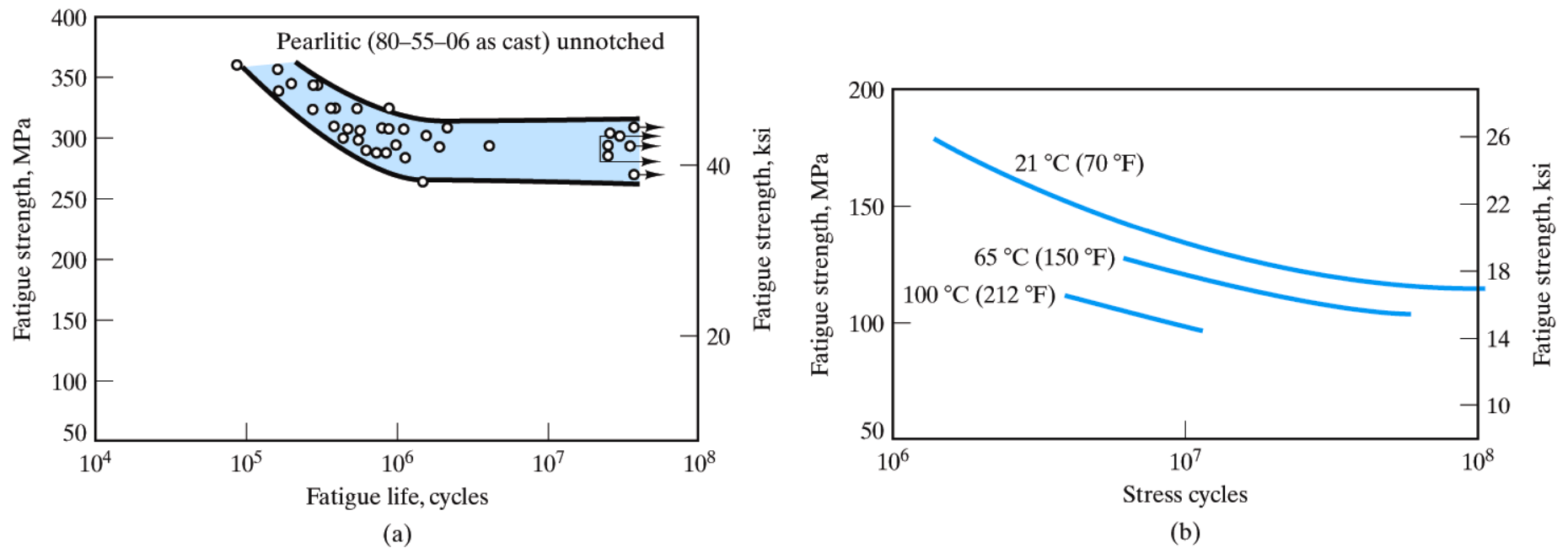
53

Figure 8.15

Comparison of fatigue curves for (a) ferrous and (b) nonferrous alloys. The ferrous alloy is a ductile iron. The nonferrous alloy is C11000 copper wire. The nonferrous data do not show a distinct endurance limit, but the failure stress at $N = 10^8$ cycles is a comparable parameter. (After Metals Handbook, *9th ed., Vols. 1 and 2, American Society for Metals, Metals Park, OH, 1978, 1979.)*

Factors Affecting Fatigue Life

- Magnitude of stress (mean, amplitude...)

- Quality of the surface (scratches, sharp transitions and edges).

- **Solutions:**
- Polishing (removes machining flaws etc.)

- Introducing compressive stresses (compensate for applied tensile stresses) into thin surface layer by "Shot Peening"- firing small shot into surface to be treated. High-tech solution - ion implantation, laser peening.

- Case Hardening - create C- or N- rich outer layer in steels by atomic diffusion from the surface. Makes harder outer layer and also introduces compressive stresses

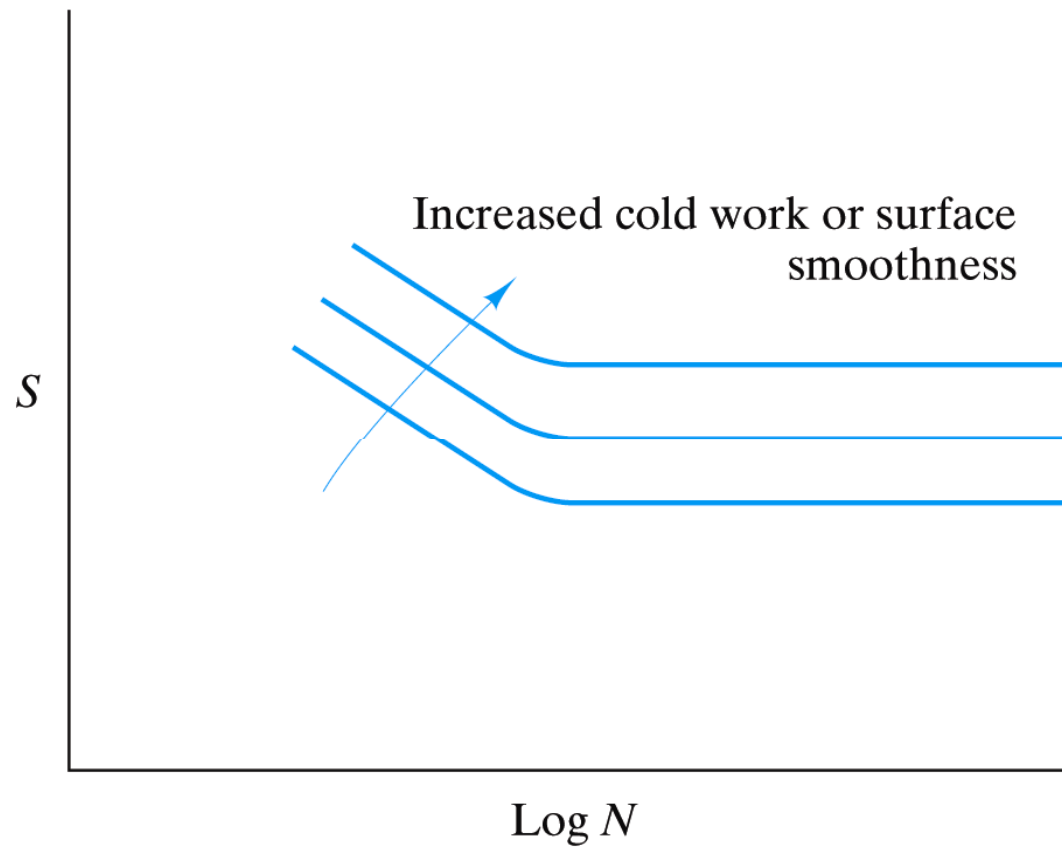- Optimizing geometry - avoid internal corners, notches etc.

Figure 8.17

Fatigue strength is increased by prior mechanical deformation or reduction of structural discontinuities.

Factors that affect fatigue life: environmental effects

- **Thermal Fatigue.** Thermal cycling causes expansion and contraction, hence thermal stress, if component is restrained.

  Solutions:

  - eliminate restraint by design

  - use materials with low thermal expansion coefficients

- **Corrosion fatigue.** Chemical reactions induce pits which act as stress raisers. Corrosion also enhances crack propagation.

  Solutions:

  - decrease corrosiveness of medium, if possible

  - add protective surface coating

  - add residual compressive stresses

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Fatigue Failures

Crack Growth Rate

To estimate whether a crack will grow, the stress intensity factor (ΔK), which characterizes the crack geometry and the stress amplitude can be used.
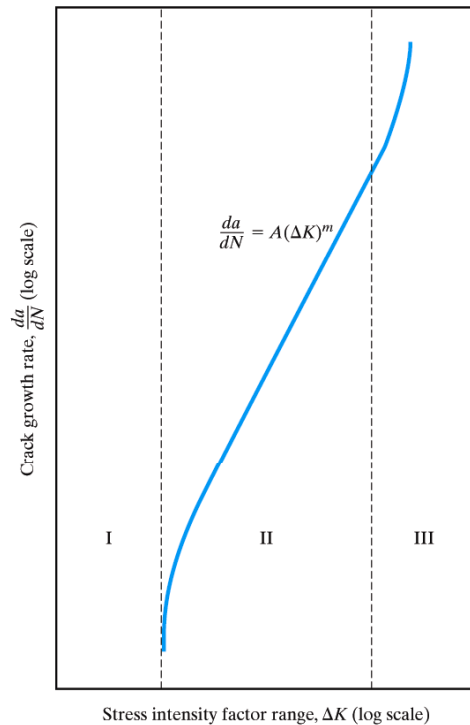
Below a threshold ΔK a crack doesn't grow.

Figure 8.13

Illustration of the logarithmic relationship between crack growth rate, da/dN, and the stress intensity factor range, ΔK. Region I corresponds to nonpropagating fatigue cracks. Region II corresponds to a linear relationship between log da/dN and log ΔK. Region III represents unstable crack growth prior to catastrophic failure.

For higher stress-intensities a crack grows at a rate given by:

$$\frac{da}{dN} = A(\Delta K)^m$$

$$\Delta K = K_{max} - K_{min}$$

$$\Delta K = f(\sigma_{max} - \sigma_{min})\sqrt{\pi a}$$

Where A and m are empirical constants that depend on the material.

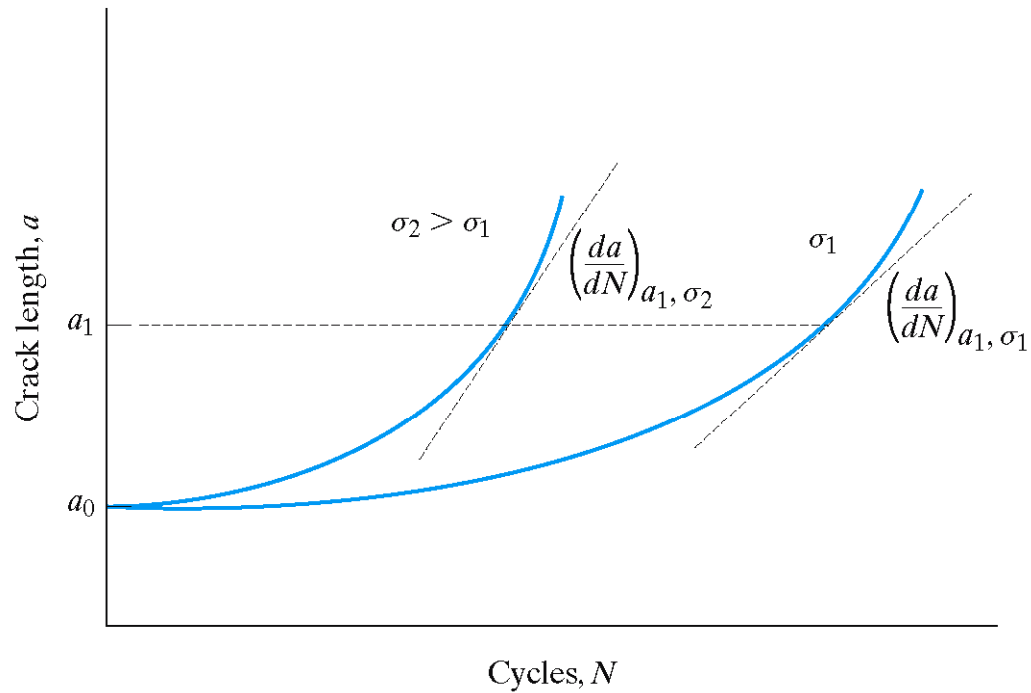**When ΔK is high, the cracks grow in a rapid and unstable manner until fracture occurs.** 58

Figure 8.12

Illustration of crack growth with number of stress cycles, N, at two different stress levels. Note that, at a given stress level, the crack growth rate, da/dN, increases with increasing crack length, and, for a given crack length such as a_1, the rate of crack growth is significantly increased with increasing magnitude of stress.
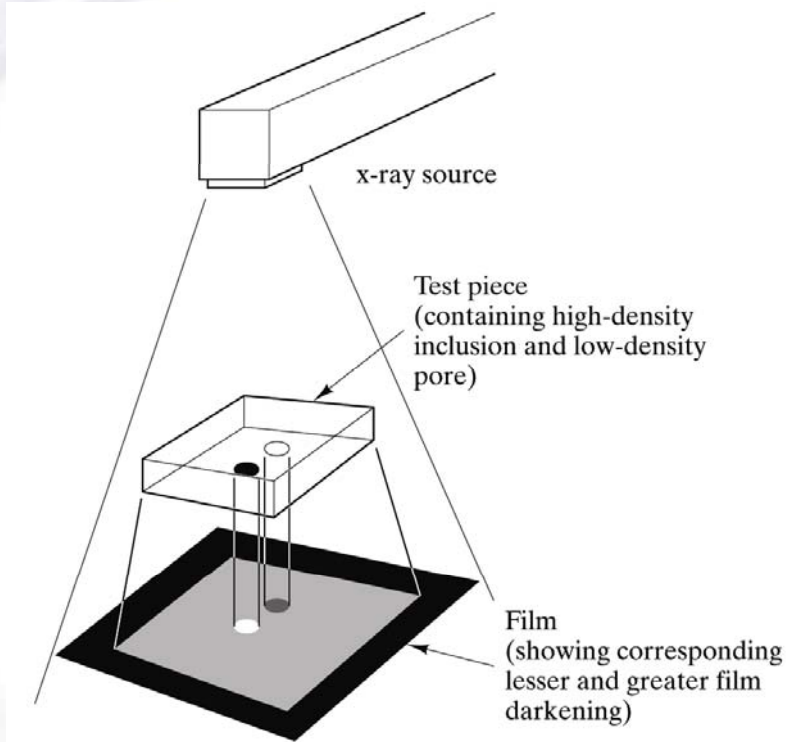
Figure 8.22
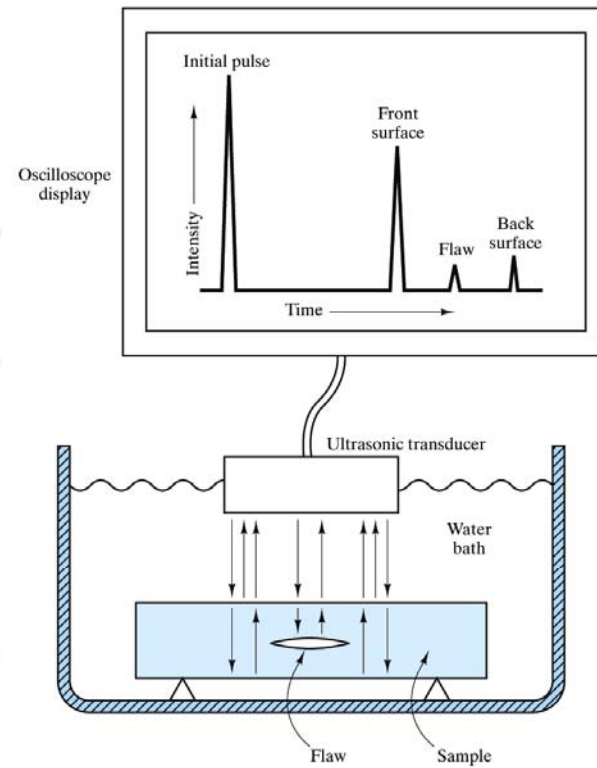
A schematic of x-radiography.

Figure 8.23

A schematic of a pulse echo *ultrasonic test.*

Element	Atomic number	μ (mm^{-1})
Aluminum	13	0.0459
Titanium	22	0.124
Iron	26	0.293
Nickel	28	0.396
Copper	29	0.410
Zinc	30	0.356
Tungsten	74	8.15
Lead	82	6.20

Source: Selected data from D. E. Bray and R. K. Stanley, *Nondestructive Evaluation*, McGraw-Hill Book Co., NY, 1989.

Table 8.6

Linear Absorption Coefficient of Various Elements for an X-Ray Beam with Energy = 100 keV (= 0.1 MeV).

$$I = I_o e^{-\mu x}$$

$I_o \rightarrow$ **intensity of the incident beam**

$\mu \rightarrow$ **linear absorption coefficient**

Thermal Behavior

Figure 7.0

Refractories are high-temperature resistant ceramics used in applications such as metal casting. The most effective refractories have low values of thermal expansion and thermal conductivity.

(Courtesy of R. T. Vanderbilt Company, Inc.)

Heat Capacity

- Both heat capacity and specific heat indicate the ability of a material to absorb heat from its surroundings.

- Heat capacity is defined as the amount of heat required to raise the temperature of a material by one Kelvin or Celcius.

- Heat capacity at constant volume c_v and heat capacity at constant pressure c_p. The magnitude of the c_p is greater than c_v. The difference is very small for solids at room temperature or below.

- We use in this lecture c_p because for most of the processes, the pressure is fixed (atmospheric pressure)

$$C = \frac{Q}{\Delta T}, \ or \ c = \frac{q}{m\Delta T}$$

- Energy absorption mechanism that contribute to the magnitude of the heat capacity: Atomic vibrations, and Energy absorption by free electrons in metals.
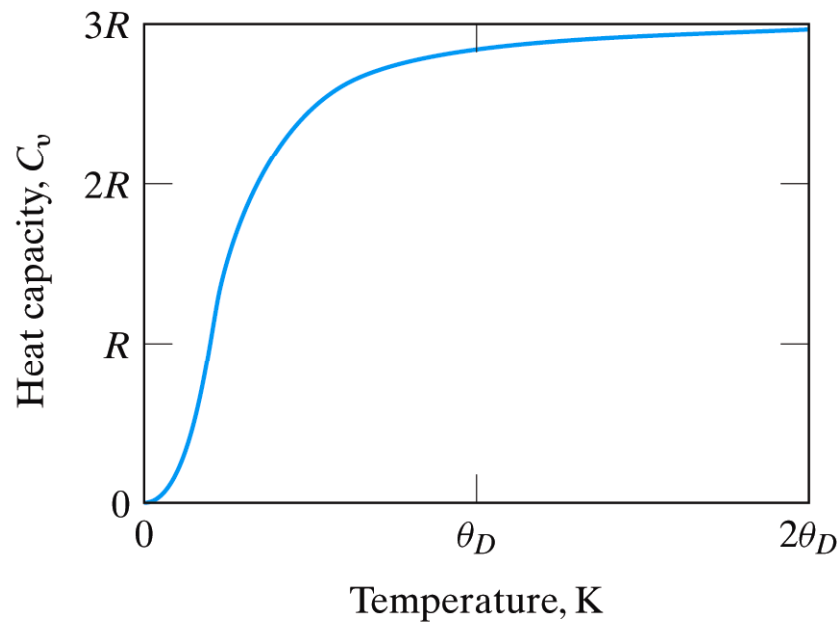
Figure 7.1

The temperature dependence of the heat capacity at constant volume, C_v*. The magnitude of* C_v *rises sharply with a temperature near 0 K and above the Debye temperature (*θ_D*) levels off at a value of approximately 3R.*

Material	c_p [J/kg·K]
Metals[a]	
Aluminum	900
Copper	385
Gold	129
Iron (α)	444
Lead	159
Nickel	444
Silver	237
Titanium	523
Tungsten	133
Ceramics[a, b]	
Al_2O_3	160
MgO	457
SiC	344
Carbon (diamond)	519
Carbon (graphite)	711
Polymers[a]	
Nylon 66	1260–2090
Phenolic	1460–1670
Polyethylene (high density)	1920–2300
Polypropylene	1880
Polytetraflouroethylene (PTFE)	1050

Source: Data from [a]J. F. Shackelford and W. Alexander, *The CRC Materials Science and Engineering Handbook*, 3rd ed., CRC Press, Boca Raton, FL, 2001, and [b]W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics*, 2nd ed., John Wiley & Sons, Inc., NY, 1976.

Table 7.1

*Values of Specific Heat for a Variety of Materials.*

Thermal Expansion

- The energy addition to a material in the form of heat increases the thermal vibration of the atoms in their lattice sites.

- The thermal expansion is a direct result of a greater separation distance between the centers of adjacent atoms as the thermal vibration of individual atoms increases with increasing temperature.

$$\alpha = \frac{dL}{LdT} \ [mm/mm.^oC] \rightarrow \textbf{linear coefficient of thermal expansion}$$

- α for ceramics and glasses < α for metals due to the shape of the energy well.

- The ceramics and glasses generally have deeper wells (higher bonding energies) due to their ionic and covalent bond natures; therefore less atomic separation with the increasing temperature.

- The elastic modulus is directly related to the derivative of the bonding energy curve near the bottom of the well. The deeper the well, the larger derivative and greater the elastic modulus.

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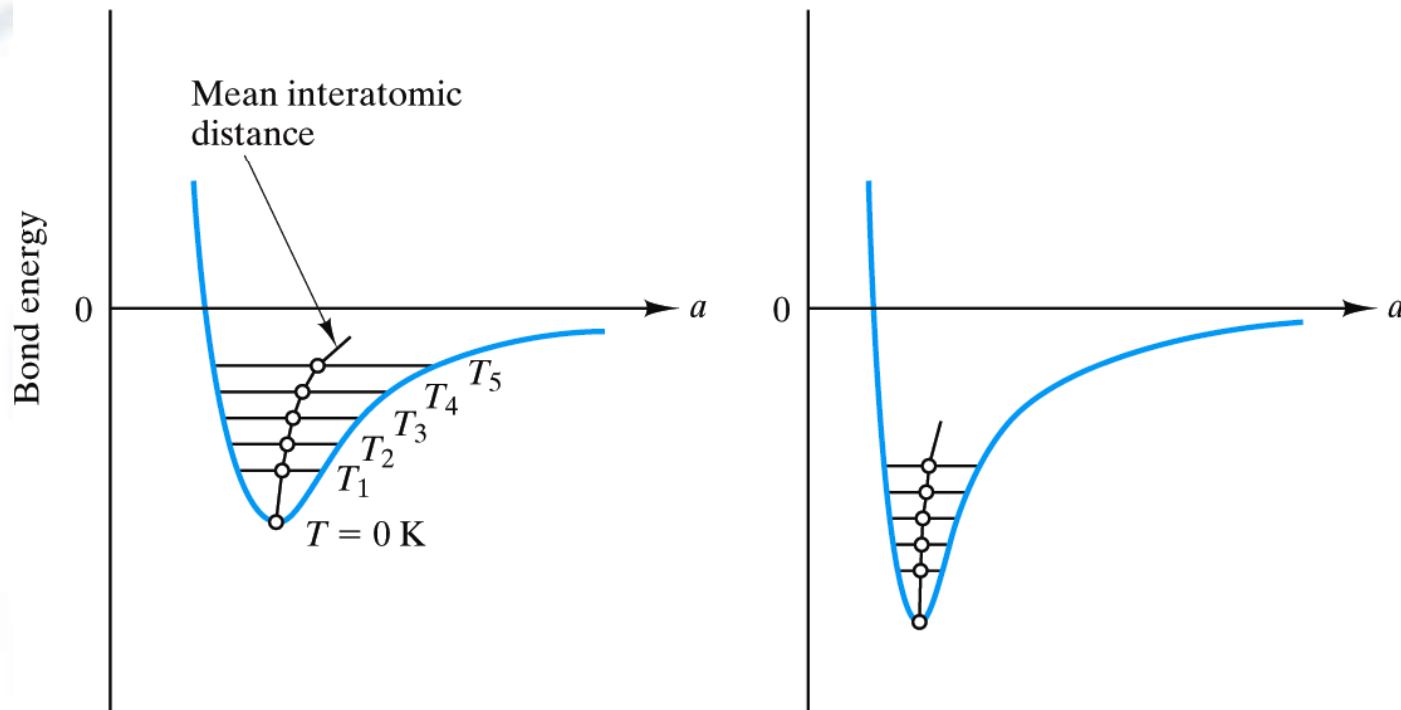
Thermal Expansion

Plot of atomic bonding energy versus interatomic distance for (a) a weakly bonded solid and (b) a strongly bonded solid. Thermal expansion is the result of a greater interatomic distance with increasing temperature. The effect (represented by the coefficient of thermal expansion in Equation 7.4) is greater for the more asymmetrical energy well of the weakly bonded solid. As shown in Table 7.3, melting point and elastic modulus increase with increasing bond strength.

Material	α [mm/(mm·°C)$\times 10^6$]		
	Temperature = 27°C (300 K)	527°C (800 K)	0–1,000°C
Metals[a]			
Aluminum	23.2	33.8	
Copper	16.8	20.0	
Gold	14.1	16.5	
Nickel	12.7	16.8	
Silver	19.2	23.4	
Tungsten	4.5	4.8	
Ceramics and glasses[a, b]			
Mullite ($3Al_2O_3 \cdot 2SiO_2$)			5.3
Porcelain			6.0
Fireclay refractory			5.5
Al_2O_3			8.8
Spinel ($MgO \cdot Al_2O_3$)			7.6
MgO			13.5
UO_2			10.0
ZrO_2 (stabilized)			10.0
SiC			4.7
Silica glass			0.5
Soda–lime–silica glass			9.0
Polymers[a]			
Nylon 66	30–31		
Phenolic	30–45		
Polyethylene (high-density)	149–301		
Polypropylene	68–104		
Polytetrafluoroethylene (PTFE)	99		

Source: Data from [a] J. F. Shackelford and W. Alexander, *The CRC Materials Science and Engineering Handbook*, 3rd ed., CRC Press, Boca Raton, FL, 2001, and [b] W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics*, 2nd ed., John Wiley & Sons, Inc., NY, 1976.

Table 7.2

Values of Linear Coefficient of Thermal Expansion for a Variety of Materials.

Weakly bonded solids	Strongly bonded solids
Low melting point	High melting point
Low elastic modulus	High elastic modulus
High thermal-expansion coefficient	Low thermal-expansion coefficient

Table 7.3

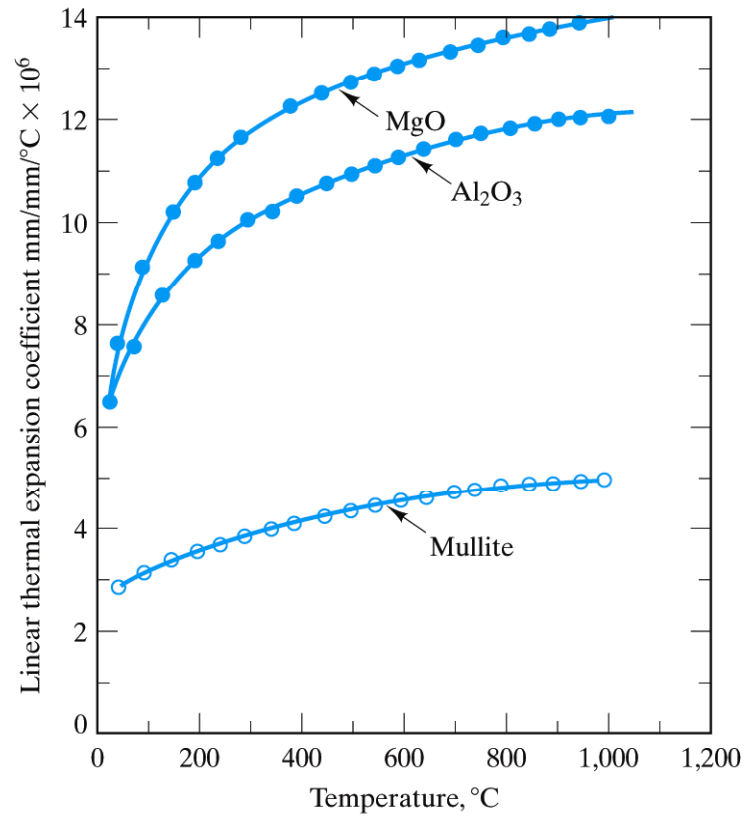*Correlation of Bonding Strength with Material Properties.*

Figure 7.3

*Linear thermal-expansion coefficient as a
function of temperature for three ceramic oxides
(mullite = 3Al$_2$O$_3$ · 2SiO$_2$). (From W. D. Kingery,
H. K. Bowen, and D. R. Uhlmann,* Introduction to
Ceramics, *2nd ed., John Wiley & Sons, Inc., NY, 1976.)*

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Thermal conductivity

$$\underset{\underset{\dfrac{1}{A}\dfrac{dQ}{dt}}{\smile}}{q} = -K\frac{\partial T}{\partial x}$$

The conduction of heat: two main mechanisms atomic vibration

the conduction of free electrons.

For poor electrical conductors such as ceramics and polymers, thermal energy is mainly transported by the vibrations of electrons.

For metals, the kinetic energy of the conducting or free electrons transport contributes to the transfer of heat more than atomic vibrations

$$k = -\frac{(dQ/dt)}{A(dT/dx)}$$
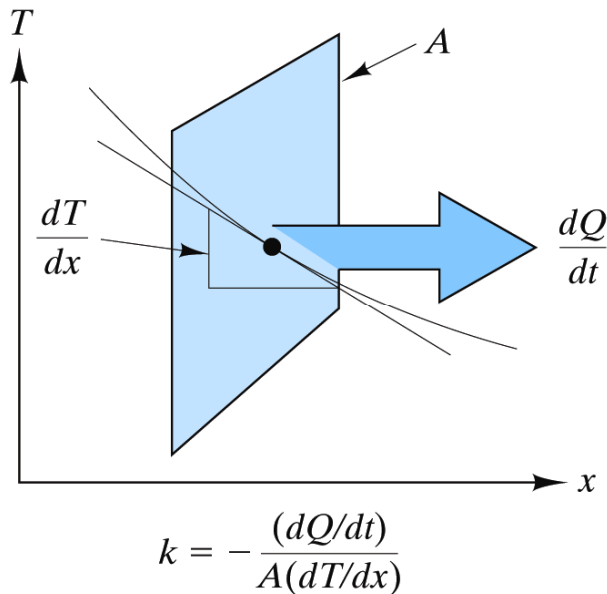
Figure 7.4

Heat transfer is defined by Fourier's law (Equation 7.5).

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Thermal conductivity

- Electrons can be viewed as a particle as well as a wave. For a wave, any structural disorder can behave as an obstacle for the movement of the waveform. The increasing vibration of the crystal lattice at increasing temperature results in a decrease in thermal conductivity.

- Similarly, the structural disorder due to chemical impurities results in a decrease in thermal and electrical conductivities. As result metal alloys tend to have lower thermal conductivities than pure metals.

- For ceramics and polymers, lattice vibrations, also wave-like in nature, are similarly impeded by structural disorder. Thermal conductivities for amorphous polymers are lower than crystalline polymers

- The thermal conductivities of ceramics and polymer are further reduced due to the presence of porosities.

Material	k [J/(s · m · K)]			
	Temperature =27°C (300 K)	100°C	527°C (800 K)	1,000°C
Metals[a]				
Aluminum	237		220	
Copper	398		371	
Gold	315		292	
Iron	80		43	
Nickel	91		67	
Silver	427		389	
Titanium	22		20	
Tungsten	178		128	
Ceramics and glasses[a, b]				
Mullite ($3Al_2O_3 \cdot 2SiO_2$)		5.9		3.8
Porcelain		1.7		1.9
Fireclay refractory		1.1		1.5
Al_2O_3		30.0		6.3
Spinel ($MgO \cdot Al_2O_3$)		15.0		5.9
MgO		38.0		7.1
ZrO_2 (stabilized)		2.0		2.3
TiC		25.0		5.9
Silica glass		2.0		2.5
Soda–lime–silica glass		1.7		—
Polymers[a]				
Nylon 66	2.9			
Phenolic	0.17–0.52			
Polyethylene (high-density)	0.33			
Polypropylene	2.1–2.4			
Polytetrafluoroethylene (PTFE)	0.24			

Source: Data from [a] J. F. Shackelford and W. Alexander, *The CRC Materials Science and Engineering Handbook*, 3rd ed., CRC Press, Boca Raton, FL, 2001, and [b] W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics*, 2nd ed., John Wiley & Sons, Inc., NY, 1976.

Table 7.4

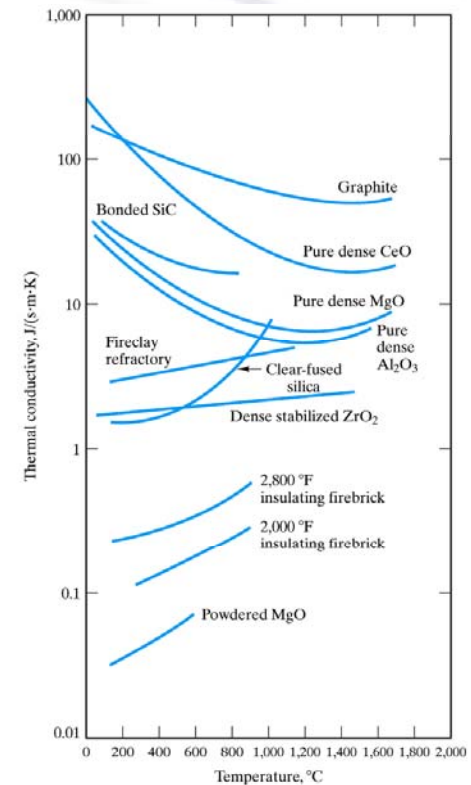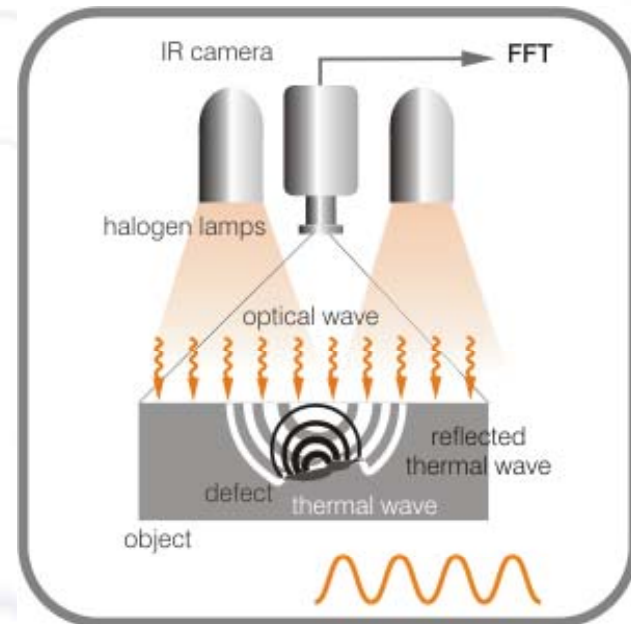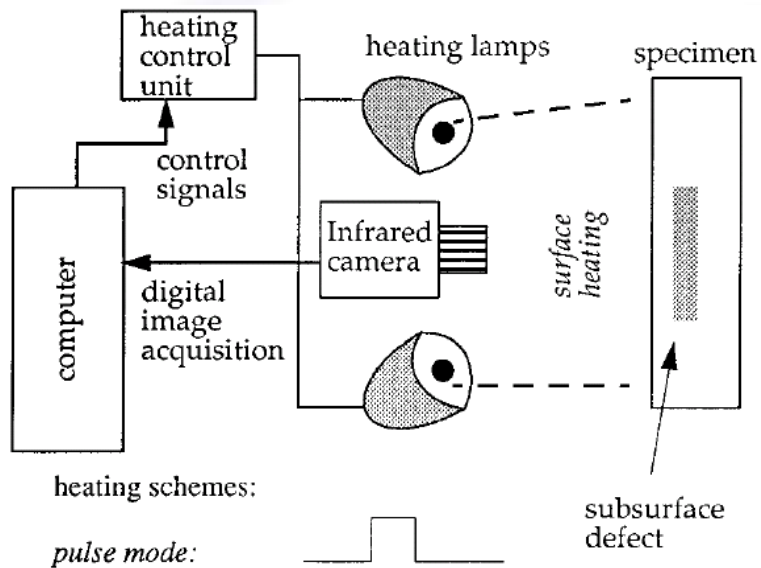*Values of Thermal Conductivity for a Variety of Materials.*

Figure 7.5

Thermal conductivity of several ceramics over a range of temperatures. (From W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, Introduction to Ceramics, *2nd ed., John Wiley & Sons, Inc., NY, 1976.)*

Thermograph

higher surface temperature just over the defect

Infrared thermography with pulse heating mode

Thermal shock

•Thermal shock: Fracture of materials due to a temperature change, usually sudden cooling.
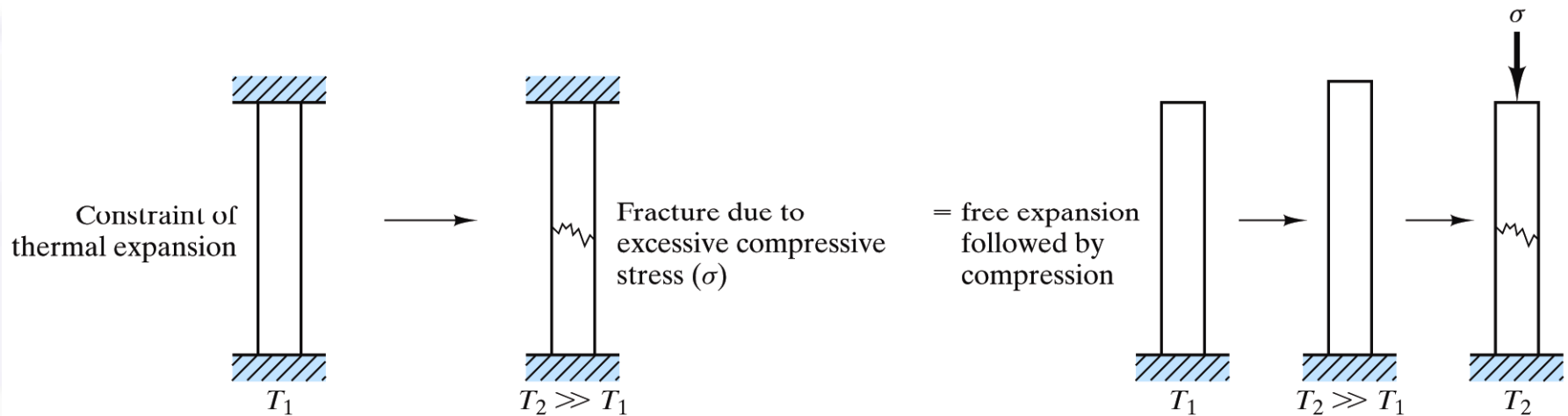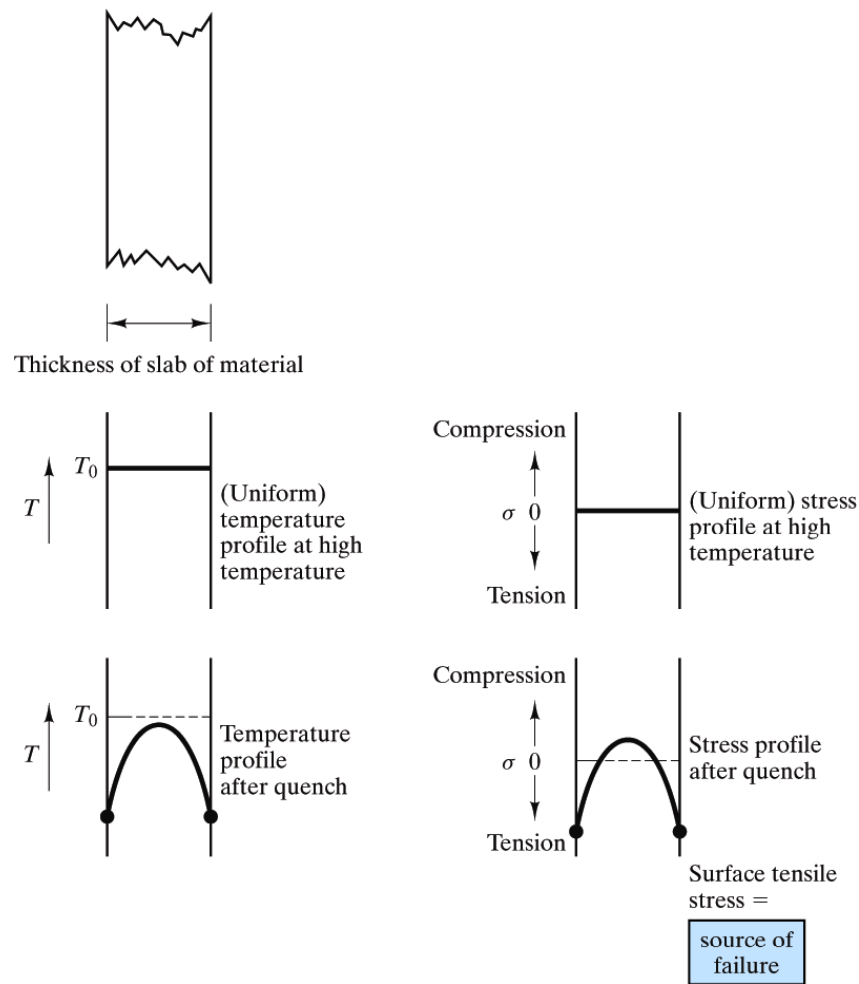

Figure 7.6

Thermal shock resulting from constraint of uniform thermal expansion. This process is equivalent to free expansion followed by mechanical compression back to the original length.

With the inevitable presence of flaws at the surface, the created tensile stress at the surface will cause a brittle fracture of the material

Thickness of slab of material

T_0

T

(Uniform) temperature profile at high temperature

Compression

σ 0

Tension

(Uniform) stress profile at high temperature

T_0

T

Temperature profile after quench

Compression

σ 0

Tension

Stress profile after quench

Surface tensile stress =

source of failure

Figure 7.7

Thermal shock resulting from temperature gradients created by a finite thermal conductivity. Rapid cooling produces surface tensile stresses.