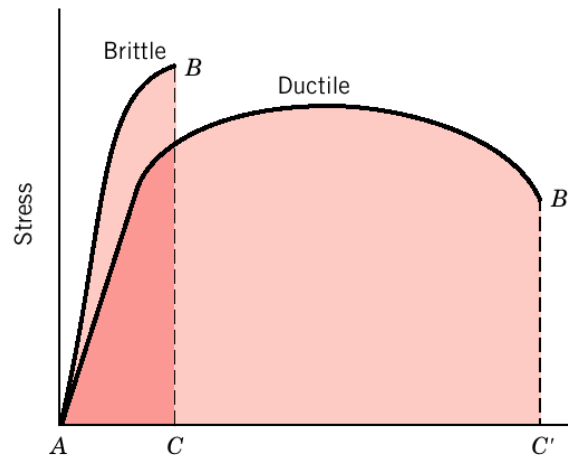


Mat E 272
Fall 2001 – Lectures 13 & 14
Fundamentals of Fracture

Introduction:

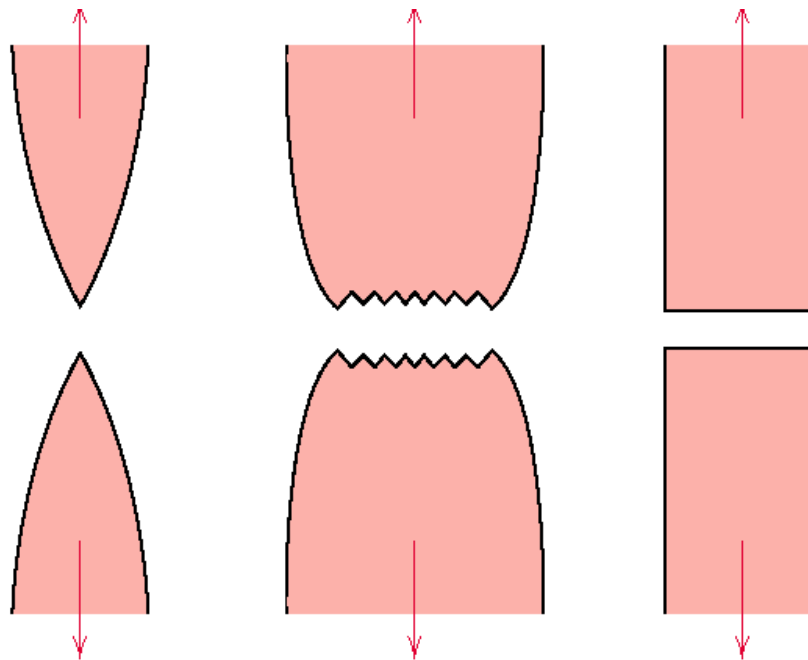
One of the most important concepts in Materials Science and Engineering is fracture. In its simplest form, fracture can be described as a single body separated into pieces by an imposed stress. For engineering materials there are two possible modes of fracture, ductile and brittle. In general, the main difference between brittle and ductile fracture can be attributed to the amount of plastic deformation (i.e., dislocation motion) that the material undergoes before fracture occurs. Ductile materials demonstrate large amounts of plastic deformation while brittle materials show little or no plastic deformation before fracture. Recall from Fig. 6.13 (Chapter 6 in the Callister text), that a tensile stress-strain curve represents the degree of plastic deformation exhibited by both brittle and ductile materials before fracture.



Fundamentals of Fracture

- **Definition:** A separation of an object into two or more pieces in response to active stresses below the melting temperature of the material.
- **Atoms on any surface of a material give rise to a *surface energy*, γ**
 - Work is required in order to create new surfaces
 - γ originates from unsatisfied bonds on the outer atoms
 - Grain boundaries also contain a surface energy due to the large number of unsatisfied bonds

- **Two steps in the process of fracture:**
 - Crack initiation
 - Crack propagation
- **Simple fracture may occur by one of two methods, ductile or brittle**
 - Dependent upon the plastic deformation of the material
 - Properties which influence the plastic deformation of a material:
 - Modulus of elasticity
 - Crystal structure
 - Temperature (for many BCC metals and alloys)
 - Ductile fracture:
 - characterized by the occurrence of necking
 - fracture produces a “cup-and-cone” structure
 - most common form of ductile fracture
 - Brittle fracture
 - Absence of plastic deformation



**Highly ductile fracture (left)
moderate ductility (center)
brittle fracture (right)**

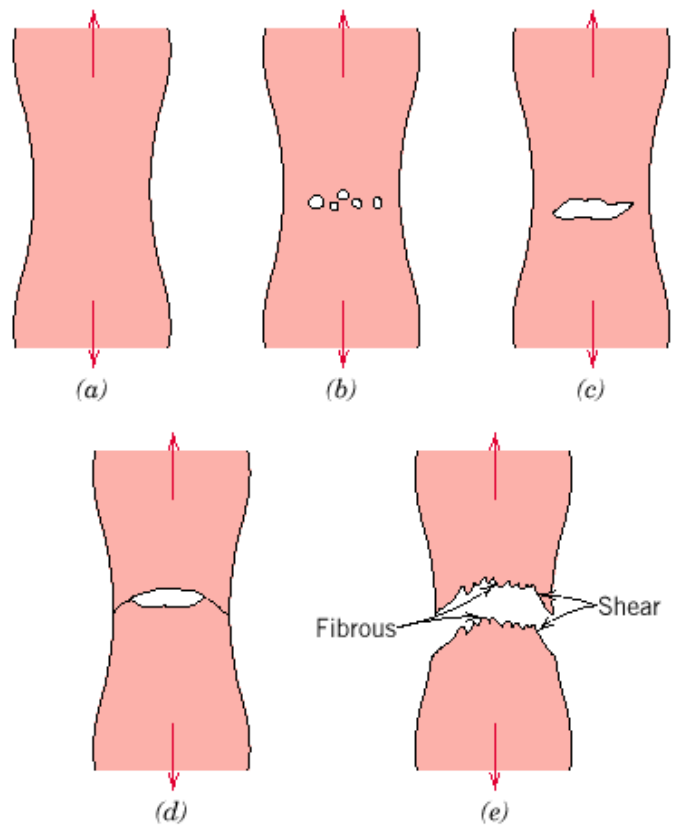
Ductile Fracture

Involves a substantial amount of plastic deformation and energy absorption before failure.

- Crack propagation occurs slowly as the length the crack grows.
- Often termed a stable crack, in that it will not grow further unless additional stress is applied

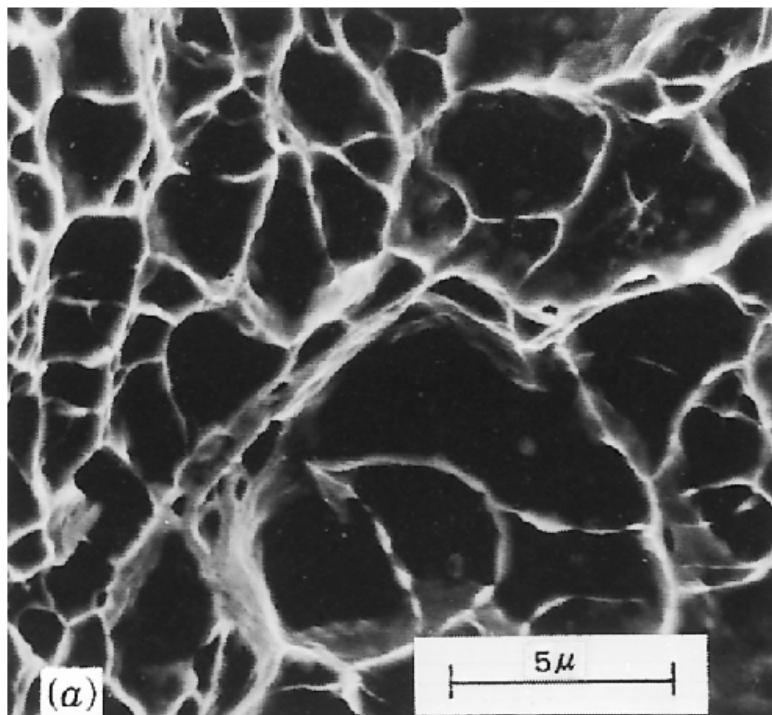
The fracture process usually consists of several stages:

- (a) Initial necking
- (b) Cavity formation
- (c) Cavities form a crack
- (d) Crack propagation
- (e) Final shear
occurs at an angle of 45° ,
where shear stress is at a
maximum





Ductile fracture in an Al rod



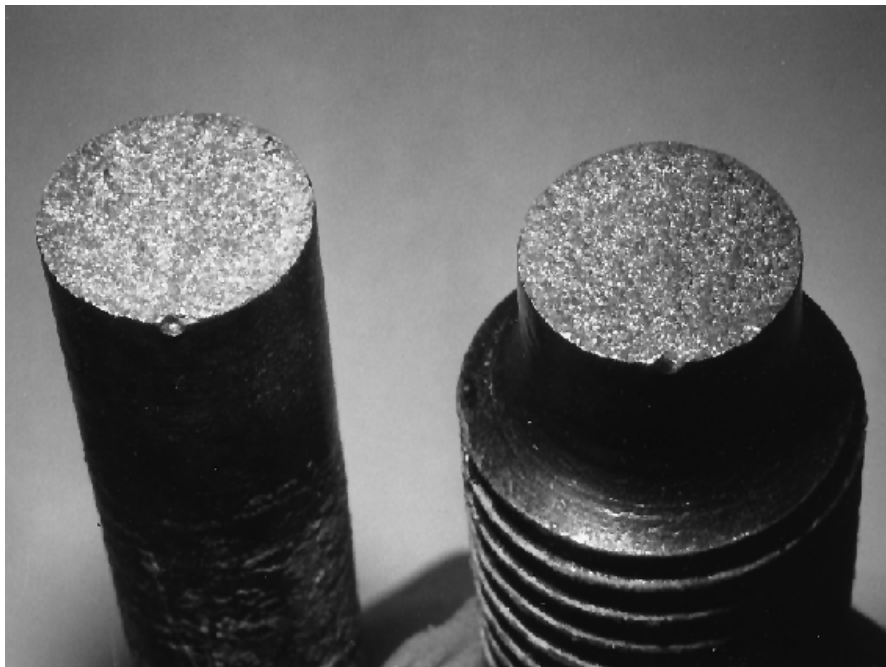
Surface morphology after ductile fracture (3,300x)
(note the presence of “dimples,” each of which represents one half of a microvoid)

Brittle Fracture

Little or no plastic deformation and low energy absorption before failure.

- A rapid propagation of cracks through a stressed material.
- The cracks usually travel so fast that you can't tell when the material is about to break
 - little or no plastic deformation before failure
- Crack propagation is spontaneous and rapid
 - propagation is perpendicular to the direction of the applied stress, forming an almost flat fracture surface
- Crack is *unstable*, since it continues to grow without the aid of additional stresses

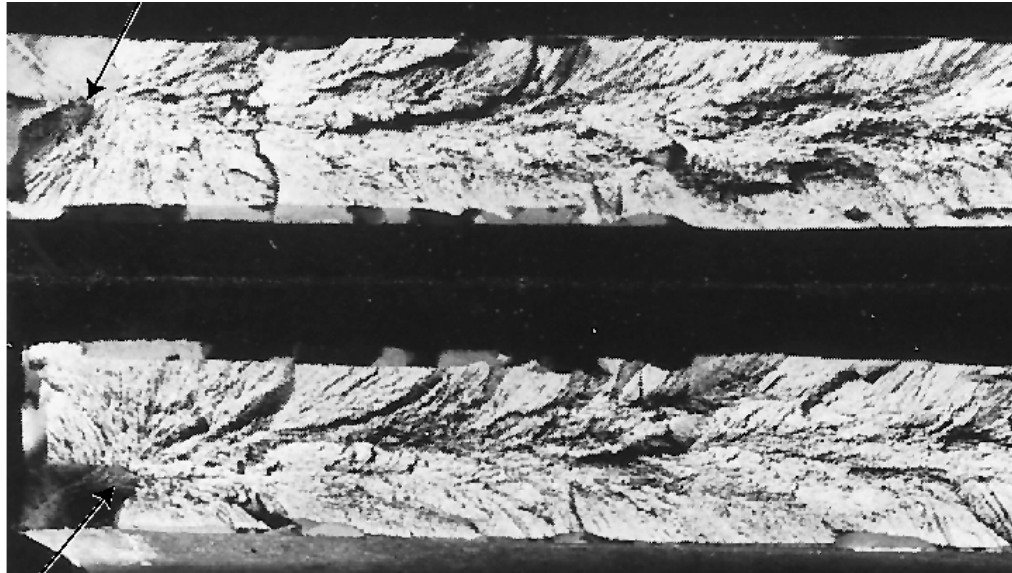
This is the worst type of fracture because you can't repair visible damage in a part or structure before it breaks:



Brittle fracture in mild steel

- In brittle fracture, cracks run perpendicular to the applied stress.
- This results in a relatively flat surface at the break.
- Brittle materials usually contain a pattern on their fracture surfaces.

- Some brittle materials have lines and ridges beginning at the origin of the crack and spreading out across the crack surface.
- Other materials, like some steels, have back to back V-shaped markings pointing to the origin of the crack.
- These V-shaped markings are called **chevrons**:



Chevron markings indicating brittle fracture

- Very hard or fine grained materials have no special pattern on their fracture surface, and amorphous materials like ceramic glass have shiny smooth fracture surfaces.

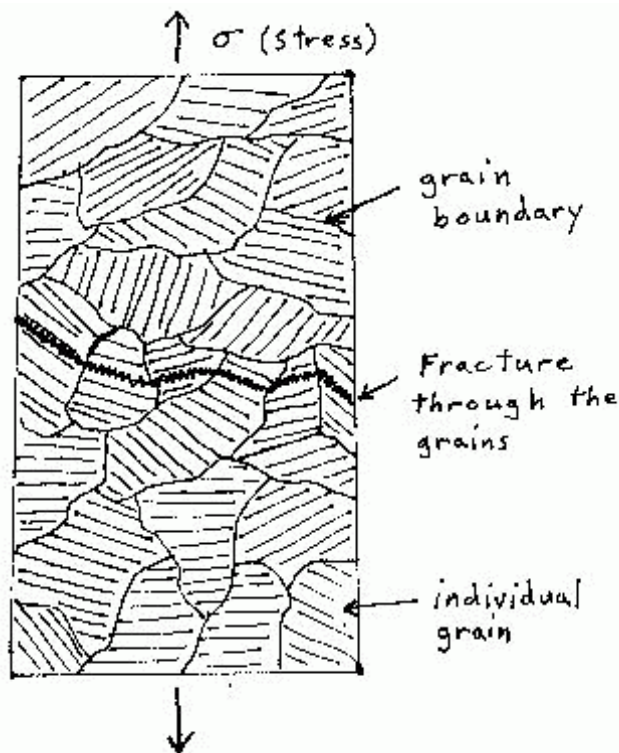
Crack Initiation and Propagation

- **Cracks usually initiate at some point of stress concentration**
 - Typical culprits include scratches, fillets, threads, and dents
 - Pre-existing internal cracks play a major role
- **Crack propagation occurs in two stages:**
 - **Stage I**: propagates slowly along crystallographic planes of high shear stress and may constitute either a large or small fraction of the fatigue life of a specimen
 - **Stage II**: the crack growth rate increases and changes direction, moving perpendicular to the applied stress

Crack propagation across grain boundaries is known as transgranular, while propagation along grain boundaries is termed intergranular

- **Transgranular fracture:**

- The fracture travels **through the grain** of the material.
- The fracture changes direction from grain to grain due to the different lattice orientation of atoms in each grain.
 - when the crack reaches a new grain, it may have to find a new path or plane of atoms to travel on because it is easier to change direction for the crack than it is to rip through.
 - Cracks choose the path of least resistance. You can tell when a crack has changed in direction through the material, because you get a slightly bumpy crack surface.



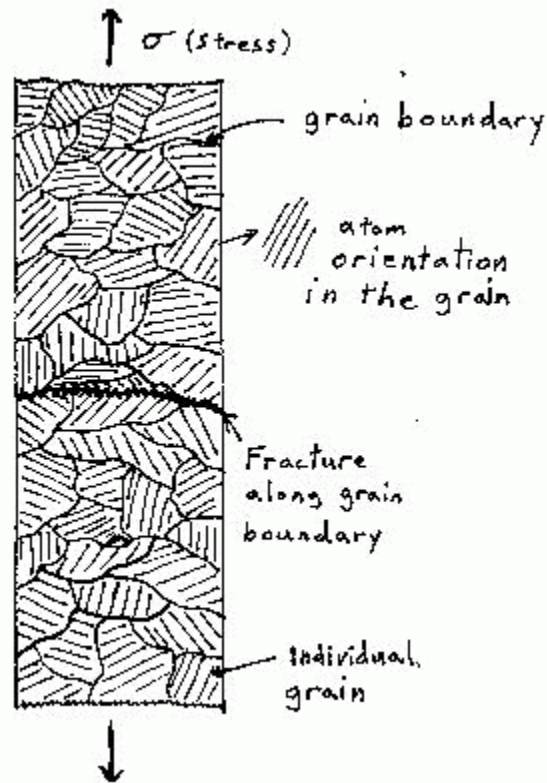
A schematic drawing illustrating **transgranular** fracture

The second type of fracture is intergranular fracture.

- **Intergranular fracture**

- The crack path **follows the grain boundaries**, and not through the actual grains.

- Usually occurs when the grain boundary is weak and brittle
 - i.e., cementite in Iron's grain boundaries.



A schematic drawing illustrating intergranular fracture

Think of a metal as a 3-D puzzle. Transgranular fracture cuts through the puzzle pieces, while intergranular fracture travels along the puzzle pieces pre-cut edges.

Fracture Mechanics

- Use of fracture analysis to determine the critical stress at which a crack will propagate and lead to failure
- The stress at which fracture occurs is termed fracture strength
 - For a brittle elastic solid the theoretical fracture strength is around $E/10$, where E is the modulus of elasticity
 - This strength is a function of the cohesive forces between the atoms
 - Experimental values lie between 10 and 1000 times below this value
 - This is due to the presence of small flaws occurring throughout the material, referred to as **stress raisers** (Griffith theory of fracture).

- If one assumes that the crack is elliptical with its long axis perpendicular to the applied stress, the maximum stress at the crack tip is:

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

σ_0 is the nominal applied tensile stress

ρ_t is the radius of curvature of the crack tip

a is the length of a surface crack (becomes $a/2$ for an internal crack)

- Note that as the ratio (a/ρ) becomes smaller, the stress around the tip increases...
 - ... and exceeds the applied stress
 - The effect is most pronounced for short, sharp cracks
- Fracture will occur when the stress level exceeds this maximum value .
- The stress concentration factor, K , is given by

$$K = \frac{\sigma_m}{\sigma_0} = 2 \sqrt{\frac{a}{\rho_t}}$$

and gives the degree to which an applied load is amplified at the tip of a crack

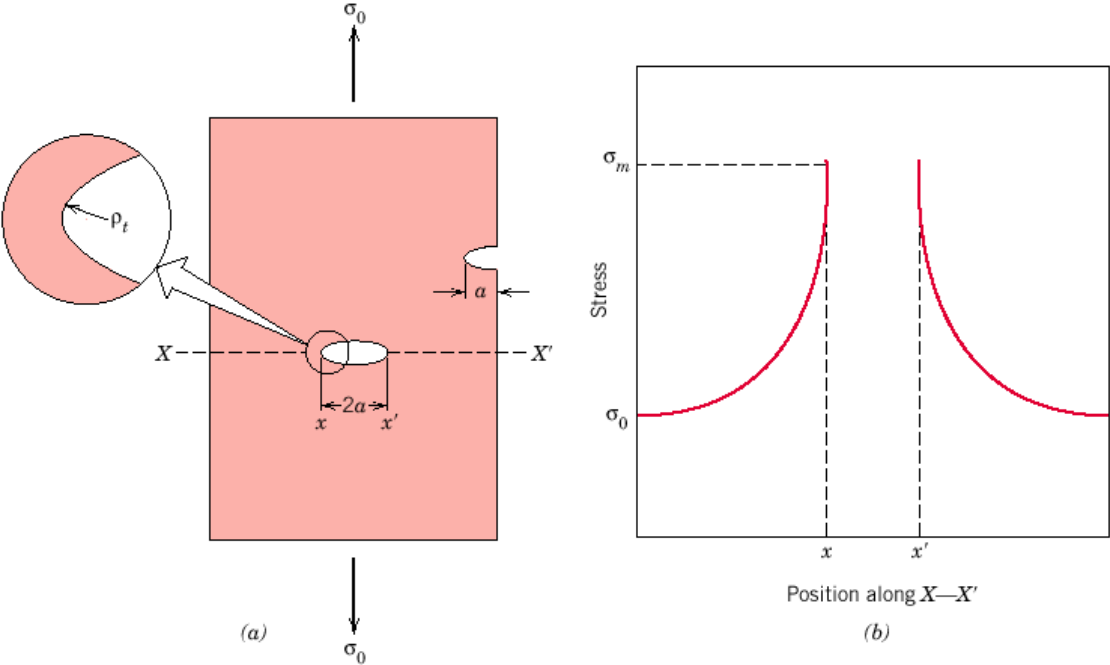
Griffith theory:

all brittle materials contain small cracks and flaws

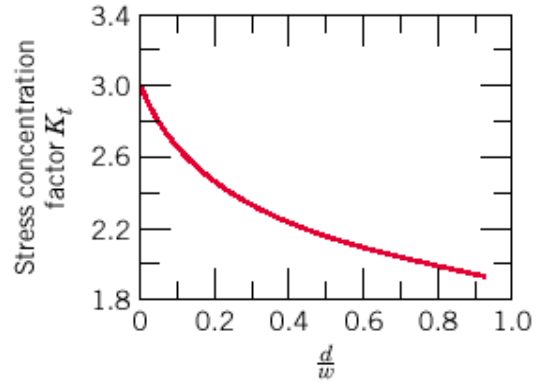
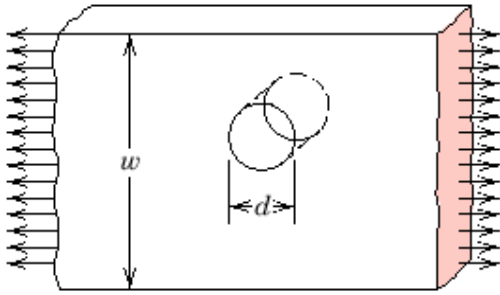
these flaws act as stress risers, increasing the local applied stress around sharp corner or discontinuities

fracture occurs when the local stress exceeds the material's cohesive strength.

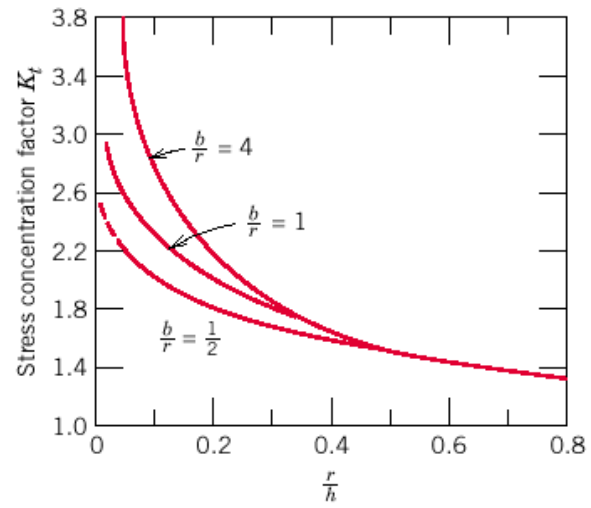
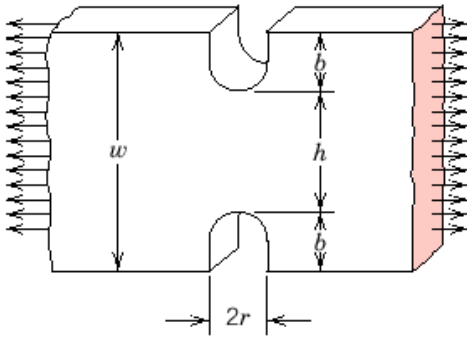
Qualitative picture of stress enhancement:



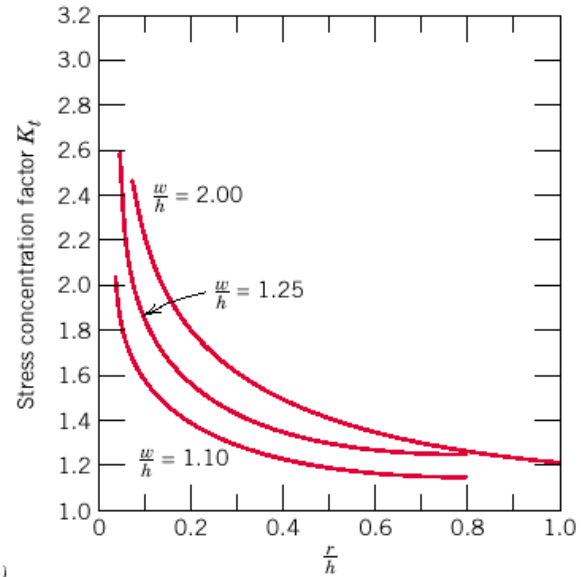
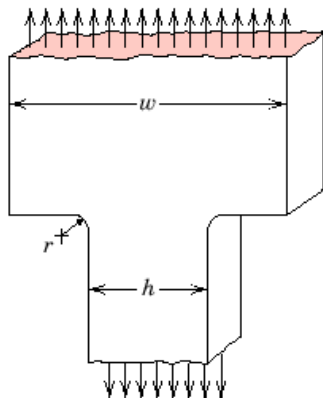
Magnitude of stress concentration:



(a)



(b)



(c)

Griffith Theory of Brittle Fracture

Describes crack propagation in brittle materials containing internal flaws

The critical stress required for crack propagation in a brittle material is given by:

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

Stress req'd for crack propagation is higher for high modulus and high surface energy materials.

- E = modulus of elasticity
- γ_s = specific surface energy
 - (creation of nascent surfaces requires energy)
- a = half the length of an internal crack

This is based on an energy balance between a decrease in lattice strain energy and the energy req'd to create (2) surfaces

Applies only in cases where there is no plastic deformation present.

- A similar expression is obtained for ductile materials

How do we quantitatively specify conditions for brittle fracture?

Fracture Toughness:

Stresses near the crack tip of a material can be characterized by the stress intensity factor, K,

A critical value of K exists, similar to the value σ_c , known as fracture toughness given by:

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

σ is the critical stress for crack propagation, a is the crack length, and Y is a dimensionless parameter that depends on both the crack and specimen geometries (=a/W).

“K” assumes the units of $psi\sqrt{in}$ ($MPa\sqrt{m}$)

fracture toughness is a property that describes a material’s resistance to brittle fracture when a crack is present

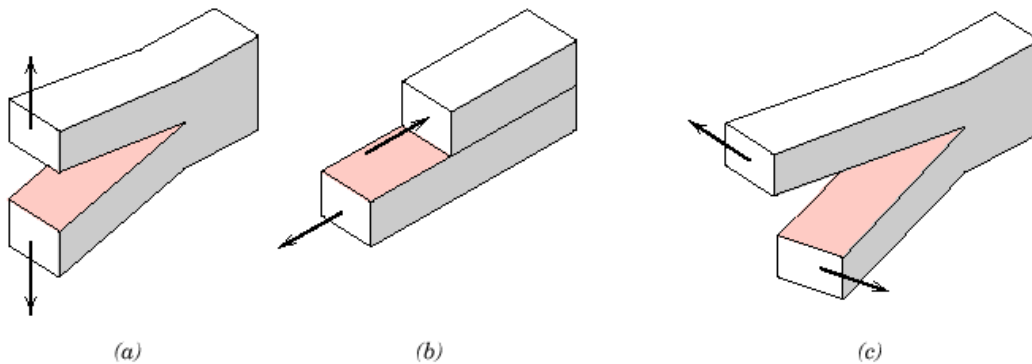
Plane Strain Fracture Toughness

K_{Ic} depends on the thickness of plate up to a certain point above which it becomes constant

- This constant value is known as the plane strain fracture toughness denoted by:

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

- The I subscript corresponds to a “mode I” crack displacement:



(a) Mode I = opening (or tensile) mode

(b) Mode II = sliding mode

(c) Mode III = tearing mode

- K_{Ic} values are used most often because they represent the worst case scenario
 - *Brittle materials have low K_{Ic} values, leading to catastrophic failure*
 - *ductile materials usually have much larger K_{Ic} values*
- K_{Ic} depends on temperature, strain rate, and microstructure
 - *Increases as grain size decreases*
 - *Decreases with increasing strain rate*
 - *Decreases with decreasing temperature....*

Ductile vs. Brittle Fracture

- “Brittle fracture” and “ductile fracture” are general terms describing two opposite extremes of the fracture spectrum.
- What are the factors that make a material lean toward one type of fracture as opposed to the other type?
- The first and foremost factor is temperature.
- higher temperatures → yield strength is lowered and the fracture is more ductile in nature

As temperature increases, the atoms in the material vibrate with greater frequency and amplitude. This **increased vibration** allows the atoms under stress to slip to new places in the material (i.e. break bonds and form new ones with other atoms in the material). This slippage of atoms is seen on the outside of the material as plastic deformation, a common feature of ductile fracture.

- lower temperatures → yield strength is greater while the fracture is more brittle in nature

When temperature decreases however, the exact opposite is true. **Atom vibration decreases**, and the atoms do not want to slip to new locations in the material. So when the stress on the material becomes high enough, the atoms just break their bonds and do not form new ones. This decrease in slippage causes little plastic deformation before fracture. Thus, we have a brittle type fracture.

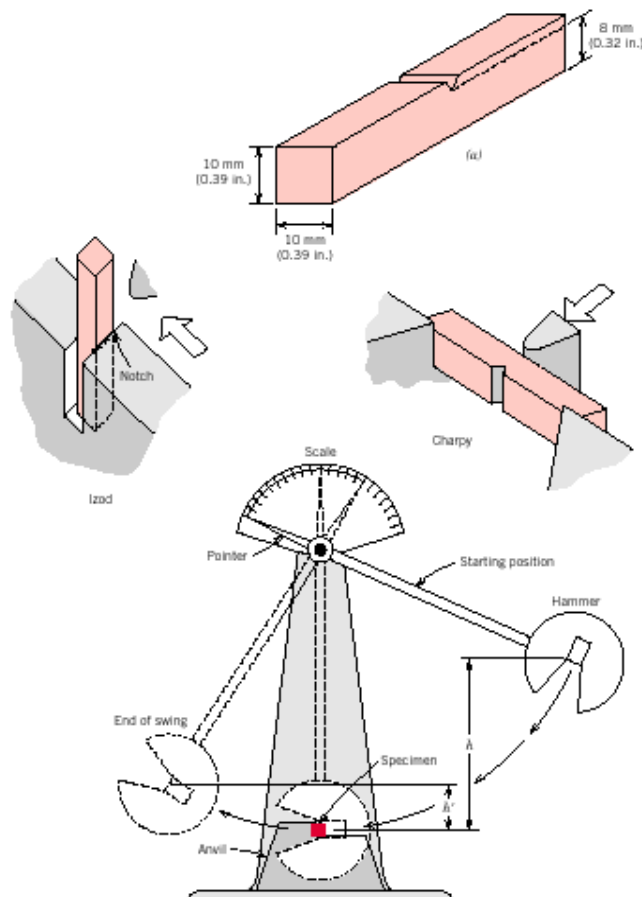
- At moderate temperatures (with respect to the material) the material exhibits characteristics of both types of fracture.
- Thus, temperature determines the amount of brittle or ductile fracture that can occur in a material (mainly in BCC, HCP but not so much for FCC).
- **Another factor is dislocation density.**
 - The higher the dislocation density, the more brittle the fracture will be in the material.
 - Recall how dislocations interact; as dislocation density increases due to applied stresses above the yield point, it becomes

increasingly difficult for the dislocations to move because their strain fields interact with each other.

- A material that already has a high dislocation density can only deform but so much before it fractures in a brittle manner.
- **The third factor is grain size.**
 - As grains get smaller, fracture becomes more brittle.
 - This phenomena is due to the fact that in smaller grains, dislocations have less space to move before they hit a grain boundary.
 - When dislocations can not move very far before fracture, then plastic deformation decreases. Thus, the material's fracture is more brittle.

How do we characterize fracture?

Impact testing:





A Typical Charpy Impact Tester

Procedure:

1. A notched bar-shaped specimen is clamped in the holder
2. The weight is released from a known height
3. After breaking the specimen, the pendulum swings on, reaching a height (lower than the initial height)
4. The difference in potential energy of the pendulum gives the energy required to break the specimen

DBT (Ductile-to-Brittle Transformation):

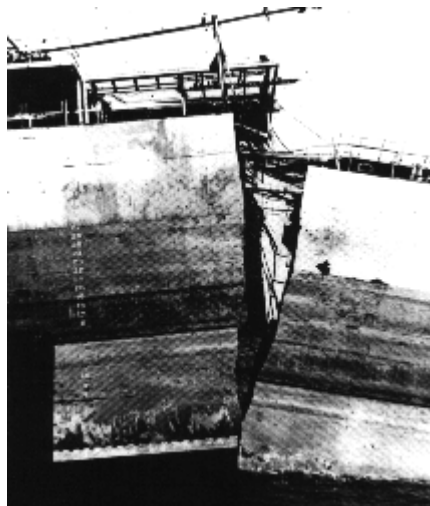
DBT is a consequence of slower dislocation mechanics in BCC metals compared with FCC.

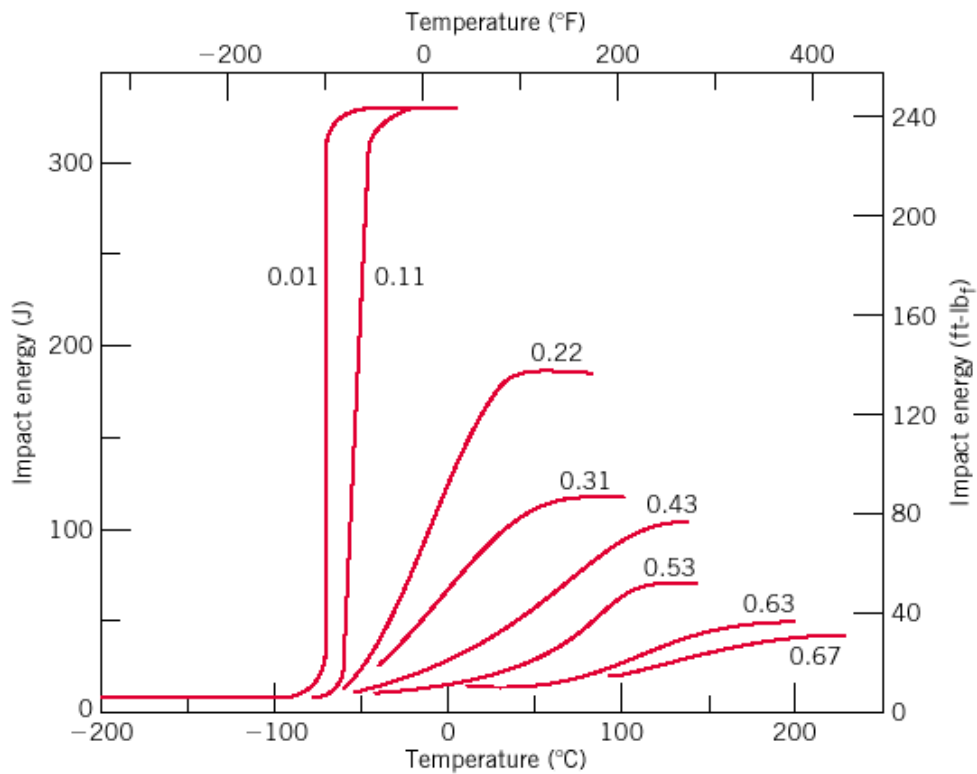
- a large number of structural steels are included in the BCC classification category
- DBTT can fall between -100°C (-148°F) and $+100^{\circ}\text{C}$ (212°F), depending on composition
- Cold water temperatures, about 35 degrees Fahrenheit, can cause certain steels to crack in a brittle manner, like glass, instead of the normal ductile, twisting, tearing manner.
 - During the first half 20th century, the temperature below which typical high grade ship steel changed from ductile to brittle failure mode was 50 degrees Fahrenheit.
 - Not until 1963, over 50 years after the TITANIC sank in cold arctic water, was the first authoritative documentation published by researchers from the U. S. Naval Research Laboratory providing a comprehensive, quantitative analysis describing the phenomenon of ductile to brittle crack propagation in steel.
- Over 5000 Liberty ships were mass produced during World War II without accounting for D-B-T
 - Of these, 1000 suffered significant failures between 1942-1946 because of low temperatures
 - 200 suffered serious fractures between 1942-1952.
- The failure rate of the welded Liberty ships in the North Atlantic was statistically astronomical, while literally NON-EXISTENT in the warm waters of the South Pacific
 - How many lost ships in the North Atlantic were falsely classified as lost to German U-Boat torpedo attacks?



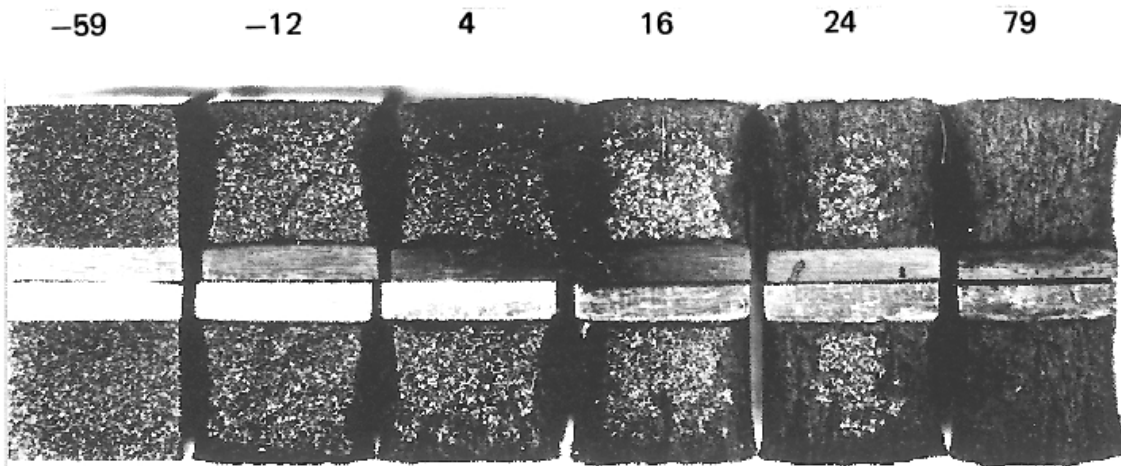
Jeremiah O'Brien – One of Two Remaining Operational WWII Liberty Ships

- Not until 1947, when a ship literally broke into two pieces while tied to a dock in the cold water of Boston Harbor, was enough evidence, left accessible and dramatic enough, that the problem was taken seriously:





Effect of Carbon Concentration on the DBTT in Steel



CVN Fracture Surfaces of A36 Steel as a Function of Test Temperature (°C) (note the bright surface (left) resulting from the lowest temperature, (indicated above) suggestive of brittle fracture. In contrast, the surface reflectivity of the specimen fractured at high temperature (right) is low, corresponding to fibrous, or ductile fracture)

A Footnote about Titanic:

Some years ago, Canadian scientists compared samples of the Titanic's steel to a modern alloy using the Charpy impact test. They took cigarette-length chunks of both metals, supported them at either end and whacked them each in the middle with equal force. The modern alloy bent while the Titanic piece snapped.

We learn from these earlier disasters how to engineer improved materials that are more resistant to catastrophic fracture. The study of crack initiation and propagation based on pre-existing flaws has evolved into the science of Fracture Mechanics.

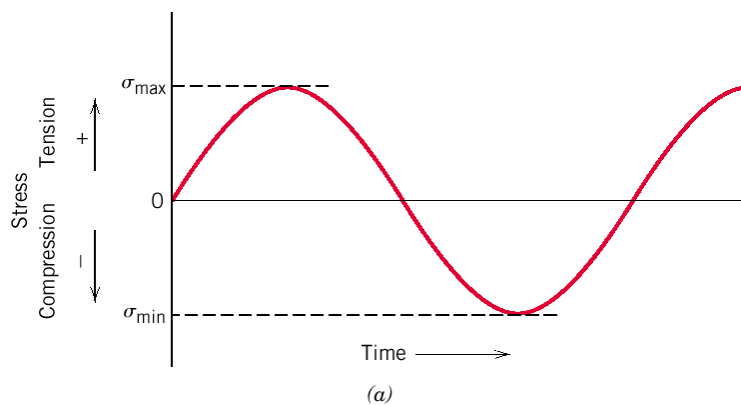
Fatigue:

Definition: Nucleation and growth of cracks in a material undergoing time-varying loading (at levels below the yield strength)

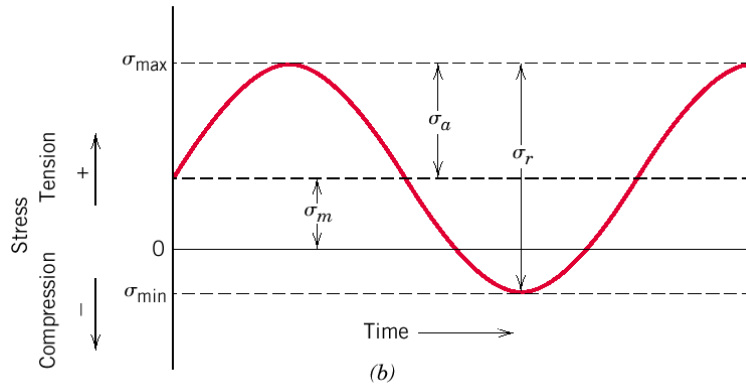
Estimated to be responsible for ~ 90% of all failures in metals

- **As a result of fatigue, materials can fracture at stress levels well below yield strength.**
- **Fatigue is insidious**
 - Little, if any, large-scale plastic deformation before failure
- **Types of fatigue loading:**

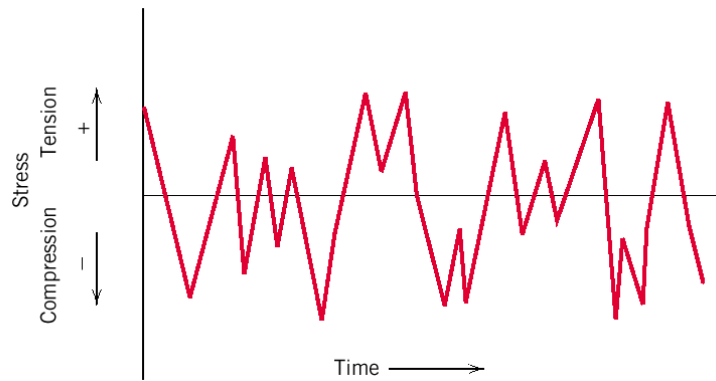
I. Reversed stress cycle:



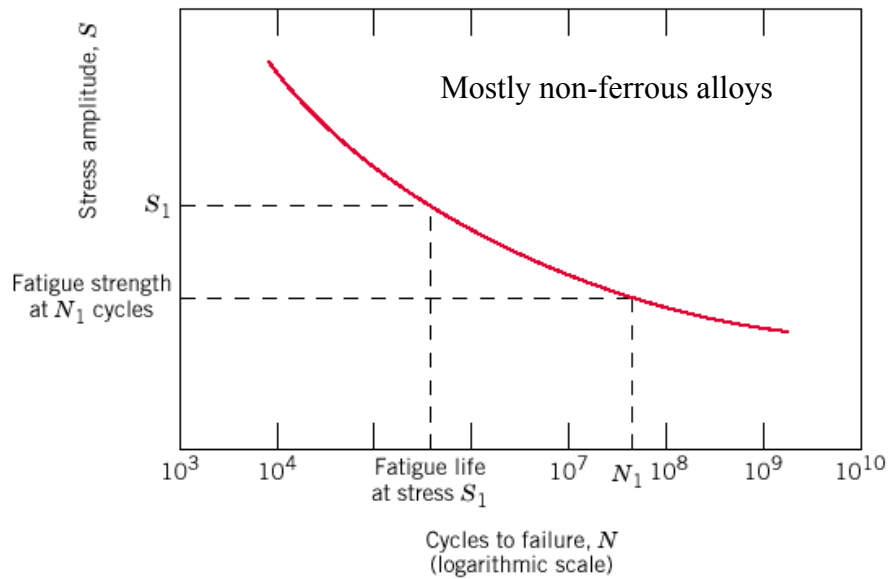
II. Repeated stress cycle:



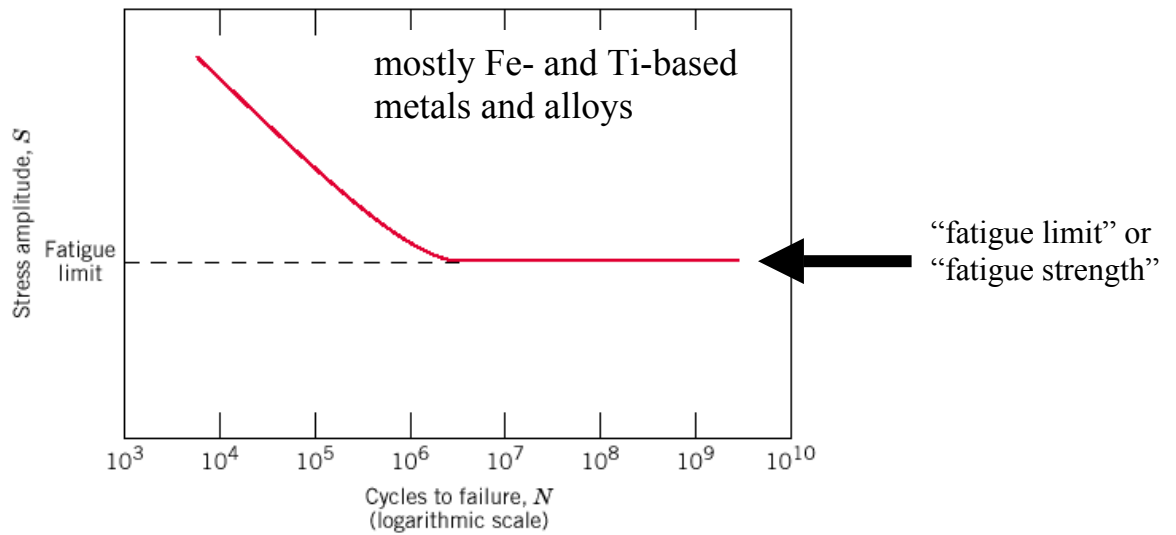
III. Random stress cycle:



Reporting of fatigue data -- the S-N curve:

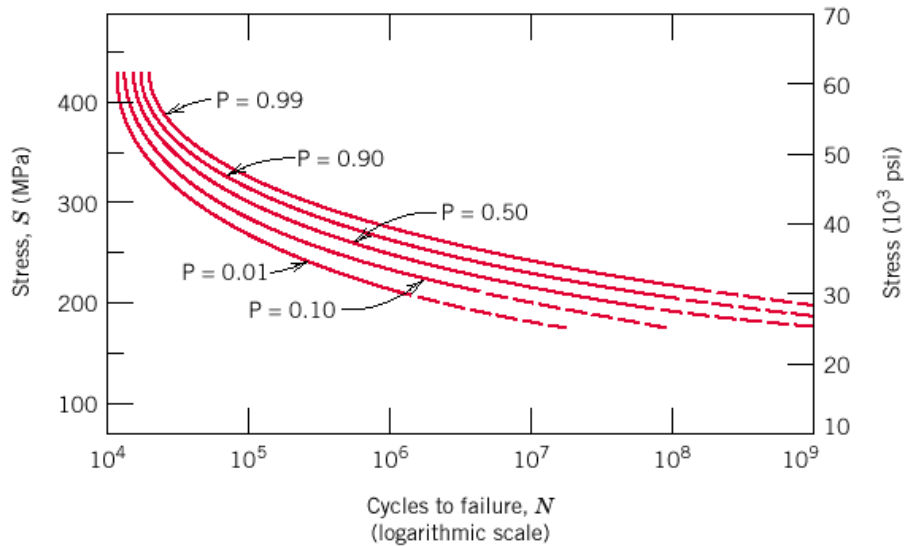


- Some materials exhibit a “**fatigue limit.**”



- Below some minimum stress level, fatigue does not occur

- Another useful parameter: **fatigue probability**



probability curves give the likelihood of fatigue failure for a given stress amplitude (the above example is for 7075-T6 Al alloy)

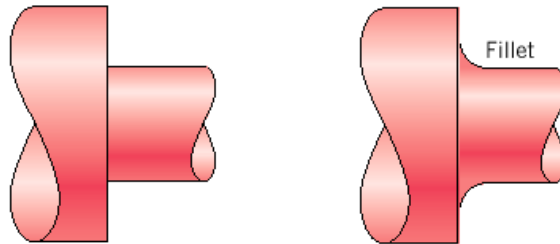
- **Factors that affect fatigue life:**

I. Mean stress

increasing the mean stress decreases fatigue life

II. Design factors –

The presence of notches, sharp edges or corners, or any feature with a small radius of curvature acts as stress concentrators and exacerbates the effects of fatigue. (Example, window curvature on early Comet aircraft)



The part on the left is more likely to suffer fatigue failure after a given number of cycles than the part on the right. Do you understand why?

III. Surface treatment –

Grooves, scratches, and other surface imperfections resulting from machining can act as stress risers. Surface polishing can reduce this effect.

Placing a surface layer in a state of compressive stress can offset imposed tensile loading and reduce crack formation. (shot peening)

IV. Case hardening –

Esp. for steel alloys; C or N diffusion into a thin surface layer of steel. This results in a hard surface layer less prone to crack initiation.

To summarize:

Fracture mechanisms and their surface characteristics.

Mode of Fracture	Typical fracture surface Characteristics
Ductile	Cup and Cone, Dimples, Dull Surface, Inclusion at the bottom of the dimple
Brittle Intergranular	Shiny, Grain Boundary cracking
Brittle Transgranular	Shiny Cleavage fractures Flat
Fatigue	Beachmarks, Striations (SEM), Initiation sites, Propagation area Zone of final fracture

Detection of Flaws:

Commonly used nondestructive tests and capabilities in detecting defects.

NDT Method	Capabilities
Radiography	<ul style="list-style-type: none">• Measures differences in radiation absorption.• Inclusions, Porosity, Cracks
Ultrasonic	<ul style="list-style-type: none">• Uses high frequency sonar to find surface and subsurface defects.• Inclusions, porosity, thickness of material, position of defects.
Dye Penetrate	<ul style="list-style-type: none">• Uses a die to penetrate open defects.• Surface cracks and porosity
Magnetic Particle	<ul style="list-style-type: none">• Uses a magnetic field and iron powder to locate surface and near surface defects.• Surface cracks and defects• Based on magnetic induction.
Eddy Current	<ul style="list-style-type: none">• Measures conductivity, magnetic permeability, physical dimensions, cracks, porosity, and inclusions.

Creep

“Creep” refers to permanent deformation caused by static loading at elevated temperature

- Examples: Turbine blades in jet engines and steam generators
Furnace heater elements

Creep is most pronounced at temperatures $> 0.4 T_m$, where T_m is the absolute melting temperature

Creep mechanisms:

1. Grain boundary sliding
2. Dislocation motion
3. Grain boundary diffusion
4. Vacancy diffusion

Of these, grain boundary sliding is the most common

Material property considerations:

Creep can be minimized by careful consideration of the following properties:

1. Melting temperature

High melting temperature alloys tend to offer improved creep resistance than their lower melting point counterparts.
(slower diffusion kinetics)

2. Elastic modulus

High modulus materials are usually more creep resistant than low modulus materials
(stronger bonding → higher activation energy for creep)

3. Grain size

Large-grained materials are more creep resistant than fine-grained materials (all other factors being equal)
(smaller grains permit more grain boundary sliding)

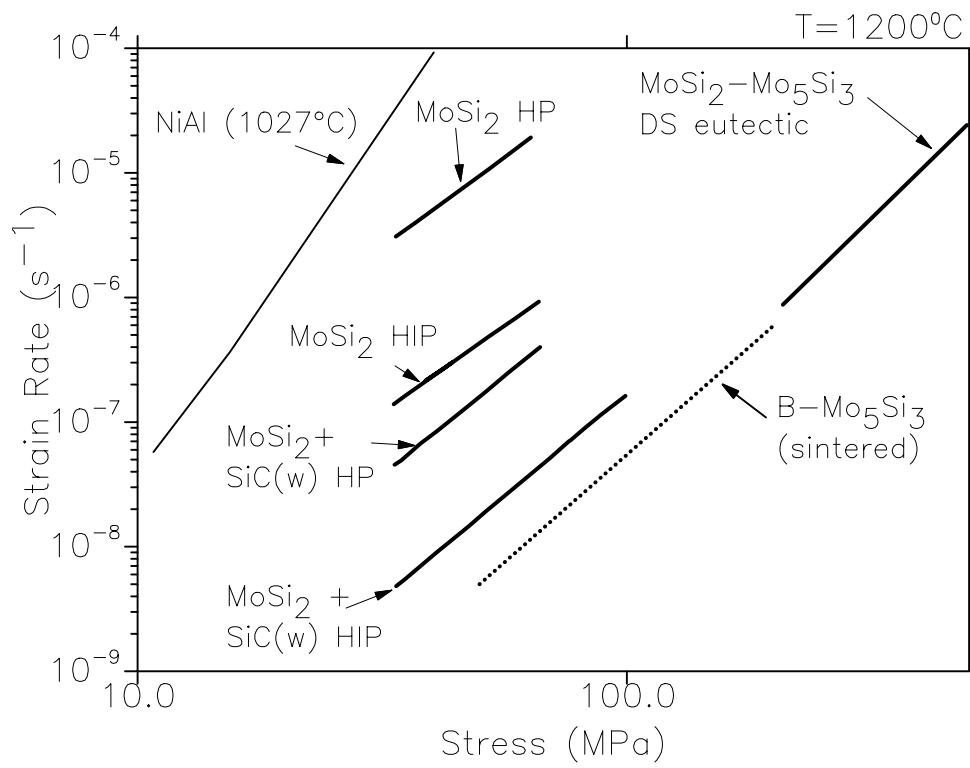
Control of grain morphology: e.g., use of oriented, columnar grains in turbine blades via directional solidification to minimize creep.

note: large-grained materials tend to be weaker than fine-grained materials. Proper materials selection usually involves consideration of operational trade-offs.

An example of “real-world” creep studies:

Advanced $\text{Mo}_5\text{Si}_3\text{-B}$ for high temperature heat exchanger and heater element applications

(Ames Laboratory -- Akinc, Cook, Thom, Kramer, Ünal):



note the dramatic reduction in isothermal creep rate in boron-doped Mo_5Si_3 compared with existing MoSi_2 materials.

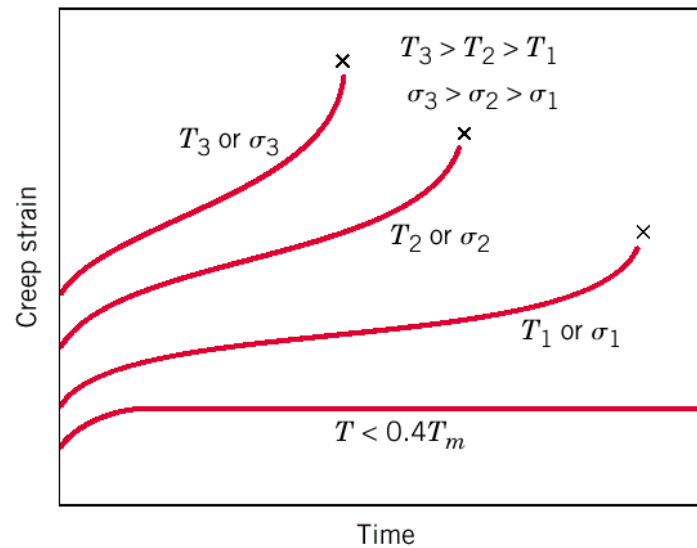
Testing for creep behavior:

Typical set-up involves imposing a constant (tensile) load on a specimen while positioned in a furnace at elevated temperature.

Relevant variables: creep strain (ϵ) vs. time (while Temp = const.)

Creep strain, ϵ , is just $\frac{\Delta l}{l_0}$, where Δl = change in length

What do typical creep curves look like as a function of test temperature?



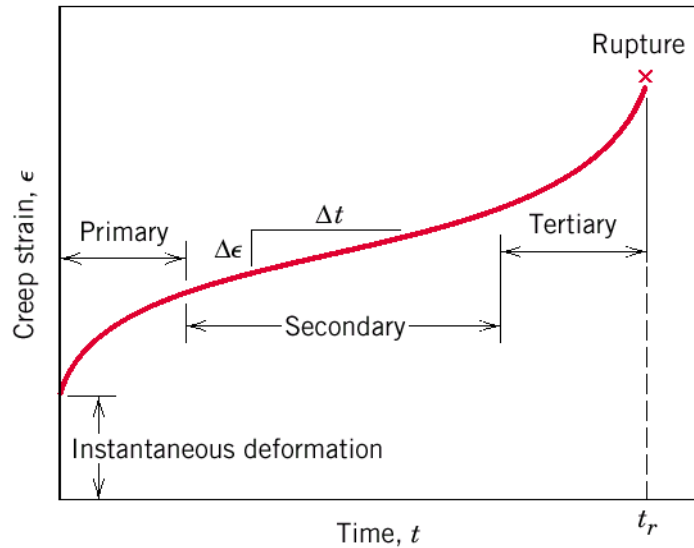
note that at low homologous temperatures ($< 0.4T_m$), there is negligible strain (or extension) over time. (initial deformation is due to the static load)

Stages of creep: creep rate is given by $\dot{\epsilon}$

Primary: continually decreasing $\dot{\epsilon}$ due to strain hardening

Secondary (steady-state): $\dot{\epsilon}$ is constant due to balance between strain hardening and recovery.

Tertiary: $\dot{\epsilon}$ increases up to the point of rupture; large-scale sliding and deformation



creep rate is parameterized as

•
 $\dot{\epsilon} = K_1 \sigma^n$, where **n = creep exponent**

(provides information about the mechanism responsible for creep)

temperature dependence:

•
 $\dot{\epsilon} = K_2 \sigma^n \exp\left\{\frac{-Q_c}{RT}\right\}$

where Q_c is the activation energy for creep.

Example (low carbon – nickel alloy)

