

Materials for Automobiles

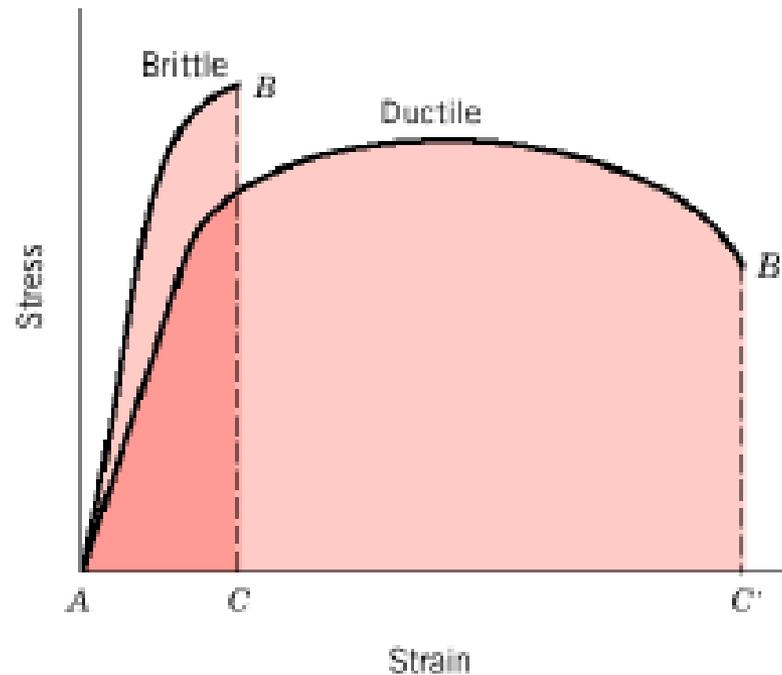
Lec 8

29 August 2011

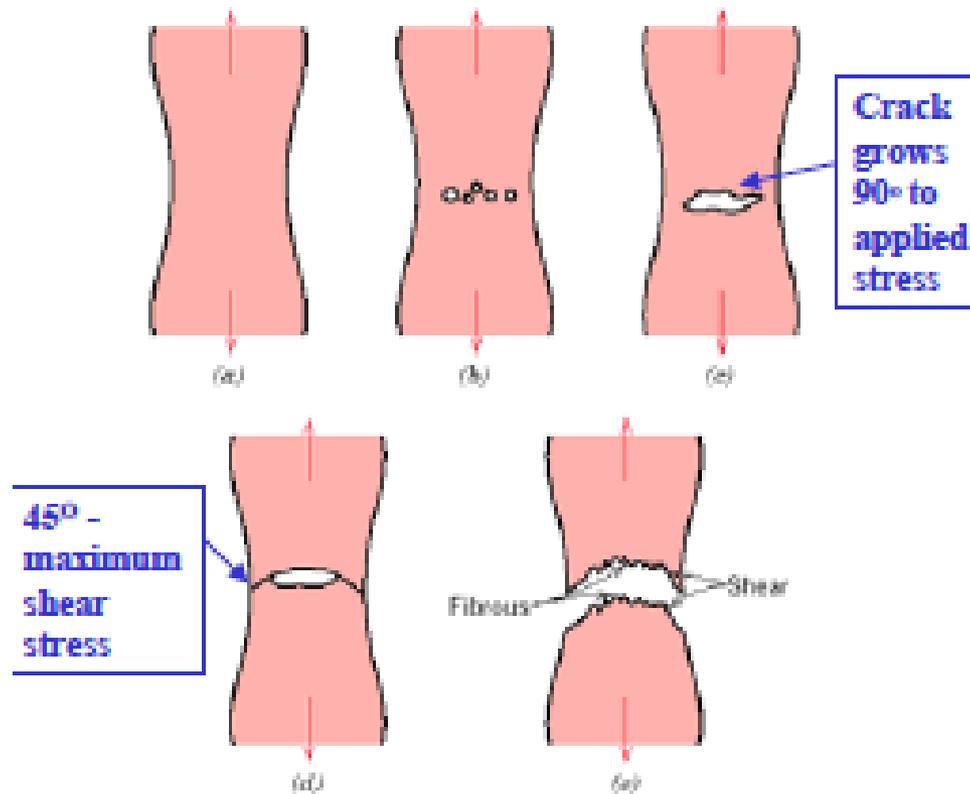
Fracture & Fatigue

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

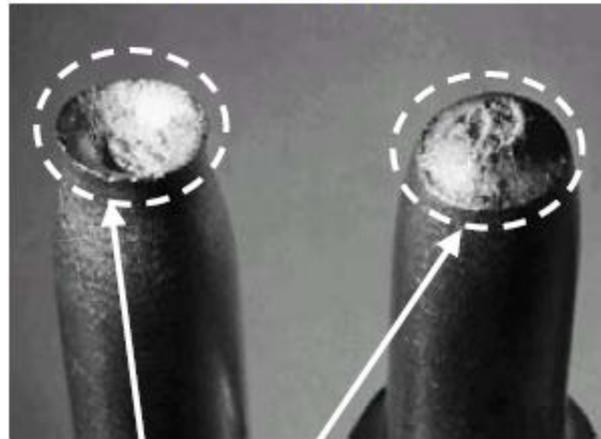


Ductile Fracture (Dislocation Mediated)

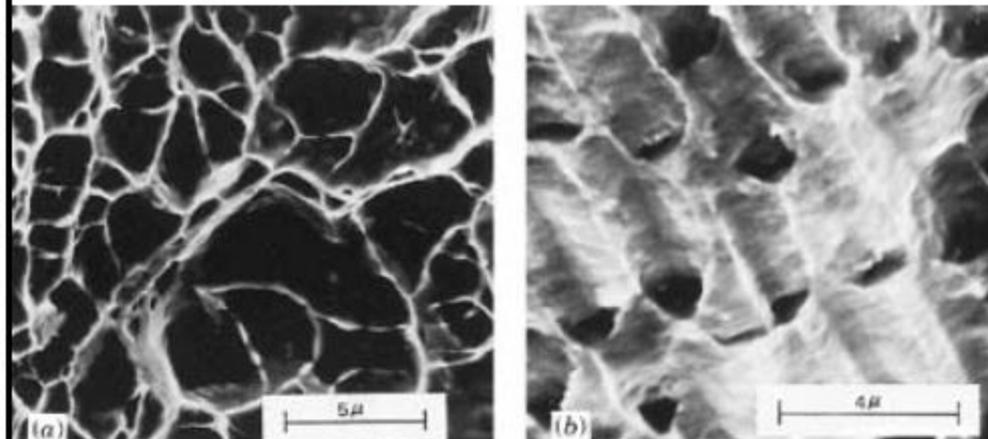


- (a) Necking, (b) Cavity Formation,
(c) Cavity coalescence to form a crack,
(d) Crack propagation, (e) Fracture

Ductile Fracture



Typical Cup-and-Cone fracture in ductile Al



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

Ductile Fracture



Fig. 14 Scanning electron micrographs of AISI 4130 steel. (a) and (b) Fractures of resulfurized steel that had been quenched and tempered to 1400 MPa. (c) Low-sulfur AISI 4130 steel that had been spheroidized to 600 MPa. In all three photographs, particles can be found in the dimples. Source: *Metals Handbook*, 9th ed., Vol 8

Ductile Fracture

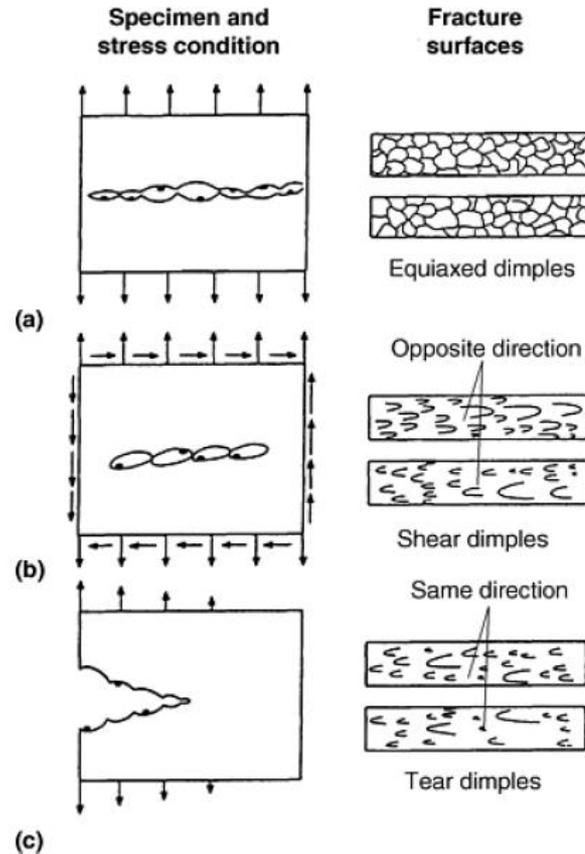
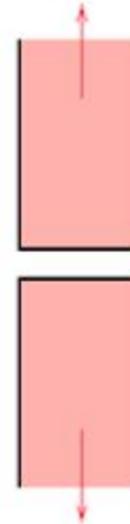


Fig. 8 Different dimple geometries to be expected from three possible loading conditions. The dimple geometry can be valuable to the failure analyst in determining the loading conditions present at the time of failure. Courtesy of Martinus Nijhoff Publishers. Source: Ref 21

Brittle Fracture (Limited Dislocation Mobility)

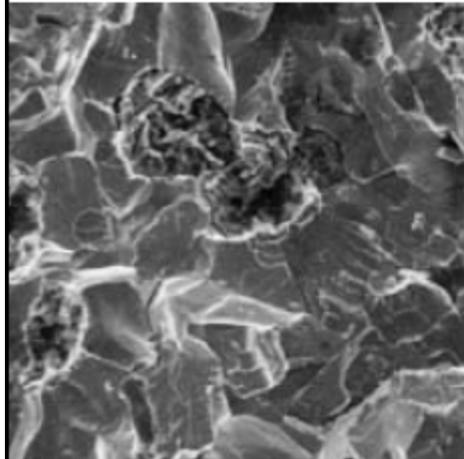
- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by **cleavage** - breaking of atomic bonds along specific crystallographic planes (**cleavage planes**).



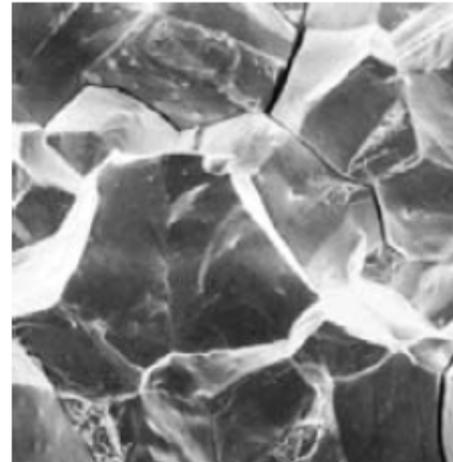
Brittle fracture in a mild steel

Brittle Fracture

- A. Transgranular fracture:** Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.
- B. Intergranular fracture:** Fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.)



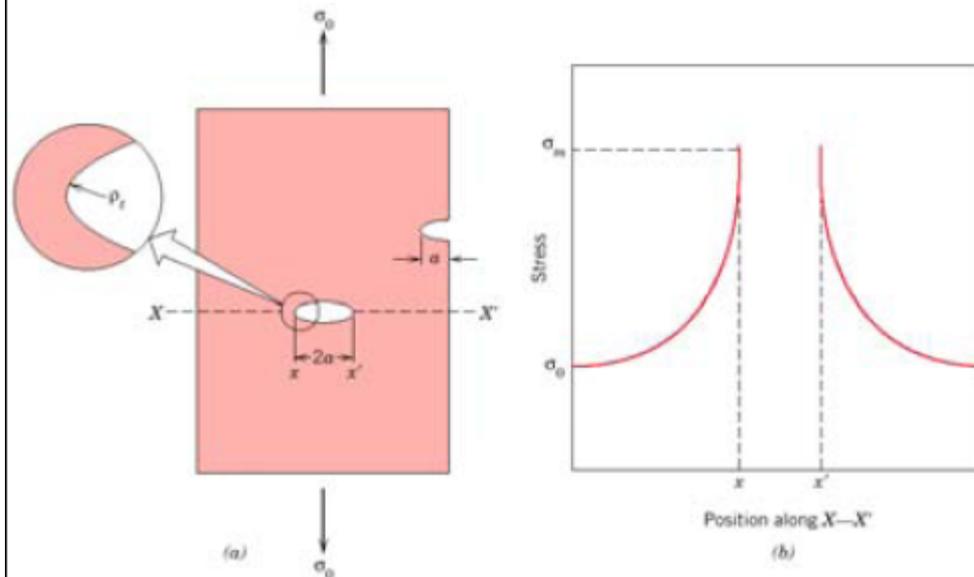
A



B

	Instantaneous		Progressive
METHOD	Ductile Overload	Brittle Overload	Fatigue
VISUAL 1 TO 50× (FRACTURE SURFACE)	NECKING OR DISTORTION IN DIRECTION CONSISTENT WITH APPLIED LOADS · DULL, FIBROUS FRACTURE · SHEAR LIPS	LITTLE OR NO DISTORTION · FLAT FRACTURE · BRIGHT OR COARSE TEXTURE, CRYSTALLINE, GRAINY · RAYS OR CHEVRONS POINT TO ORIGIN	FLAT PROGRESSIVE ZONE WITH BEACH MARKS · OVERLOAD ZONE CONSISTENT WITH APPLIED LOADING DIRECTION · RATCHET MARKS WHERE ORIGINS JOIN
SCANNING ELECTRON MICROSCOPY, 20 TO 10,000× (FRACTURE SURFACE)	MICROVOIDS (DIMPLES) ELONGATED IN DIRECTION OF LOADING · SINGLE CRACK WITH NO BRANCHING · SURFACE SLIP BAND EMERGENCE	CLEAVAGE OR INTERGRANULAR FRACTURE · ORIGIN AREA MAY CONTAIN AN IMPERFECTION OR STRESS CONCENTRATOR	PROGRESSIVE ZONE: WORN APPEARANCE, FLAT, MAY SHOW STRIATIONS AT MAGNIFICATIONS ABOVE 500× · OVERLOADZONE: MAY BE EITHER DUCTILE OR BRITTLE
METALLOGRAPHIC INSPECTION, 50 TO 1000× (CROSS SECTION)	· GRAIN DISTORTION AND FLOW NEAR FRACTURE · IRREGULAR, TRANSGRANULAR FRACTURE	· LITTLE DISTORTION EVIDENT INTERGRANULAR OR TRANSGRANULAR · MAY RELATE TO NOTCHES AT SURFACE OR BRITTLE PHASES INTERNALLY	PROGRESSIVE ZONE: USUALLY TRANSGRANULAR WITH LITTLE APPARENT DISTORTION · OVERLOAD ZONE: MAY BE EITHER DUCTILE OR BRITTLE
CONTRIBUTING FACTORS	LOAD EXCEEDED THE STRENGTH OF THE PART · CHECK FOR PROPER ALLOY AND PROCESSING BY HARDNESS CHECK OR DESTRUCTIVE TESTING, CHEMICAL ANALYSIS · LOADING DIRECTION MAY SHOW FAILURE WAS SECONDARY · SHORT-TERM, HIGH TEMPERATURE, HIGH-STRESS RUPTURE HAS DUCTILE APPEARANCE	EXCEEDED THE DYNAMIC STRENGTH OF THE PART · CHECK FOR PROPER ALLOY AND PROCESSING AS WELL AS PROPER TOUGHNESS, GRAIN SIZE · LOADING DIRECTION MAY SHOW FAILURE WAS SECONDARY OR IMPACT INDUCED · LOW TEMPERATURES	EXCEEDED THE ENDURANCE LIMIT OF THE MATERIAL · CHECK FOR PROPER STRENGTH, SURFACE FINISH, ASSEMBLY, AND OPERATION · PRIOR DAMAGE BY MECHANICAL OR CORROSION MODES MAY HAVE INITIATED CRACKING · ALIGNMENT, VIBRATION, BALANCE · HIGH CYCLE, LOW STRESS, LARGE FATIGUE ZONE/ LOW CYCLE HIGH STRESS LOW FATIGUE ZONE

Stress Concentration



For a long crack oriented perpendicular to the applied stress the maximum stress near the crack tip is:

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

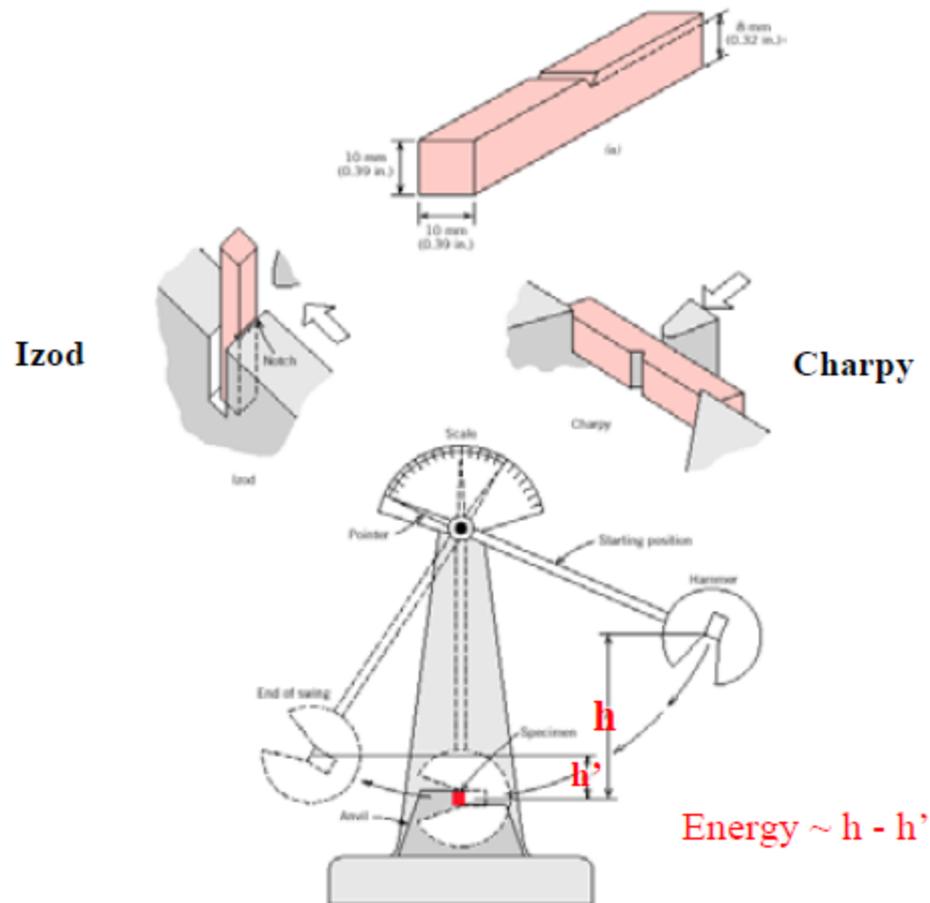
where σ_0 is the applied external stress, a is the **half-length** of the crack, and ρ_t the radius of curvature of the crack tip. (note that a is half-length of the internal flaw, but the full length for a surface flaw).

The **stress concentration factor** is: $K_t = \frac{\sigma_m}{\sigma_0} \approx 2 \left(\frac{a}{\rho_t} \right)^{1/2}$

Impact Fracture Testing

(testing fracture characteristics under high strain rates)

Two standard tests, the **Charpy** and **Izod**, measure the **impact energy** (the energy required to fracture a test piece under an impact load), also called the **notch toughness**.



Fatigue

(Failure under fluctuating / cyclic stresses)

Under fluctuating / cyclic stresses, failure can occur at loads considerably lower than tensile or yield strengths of material under a static load: **Fatigue**

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!

Applied stresses causing fatigue may be axial (tension or compression), flextural (bending) or torsional (twisting).

Fatigue failure proceeds in three distinct stages: crack initiation in the areas of stress concentration (near stress raisers), incremental crack propagation, final catastrophic failure.

Three Stages of Fatigue Failure

- Crack Initiation
- Crack Propagation
 - oscillating stress... crack grows, stops growing, grows, stops growing... with crack growth due to tensile stresses
- Fracture
 - sudden, brittle-like failure

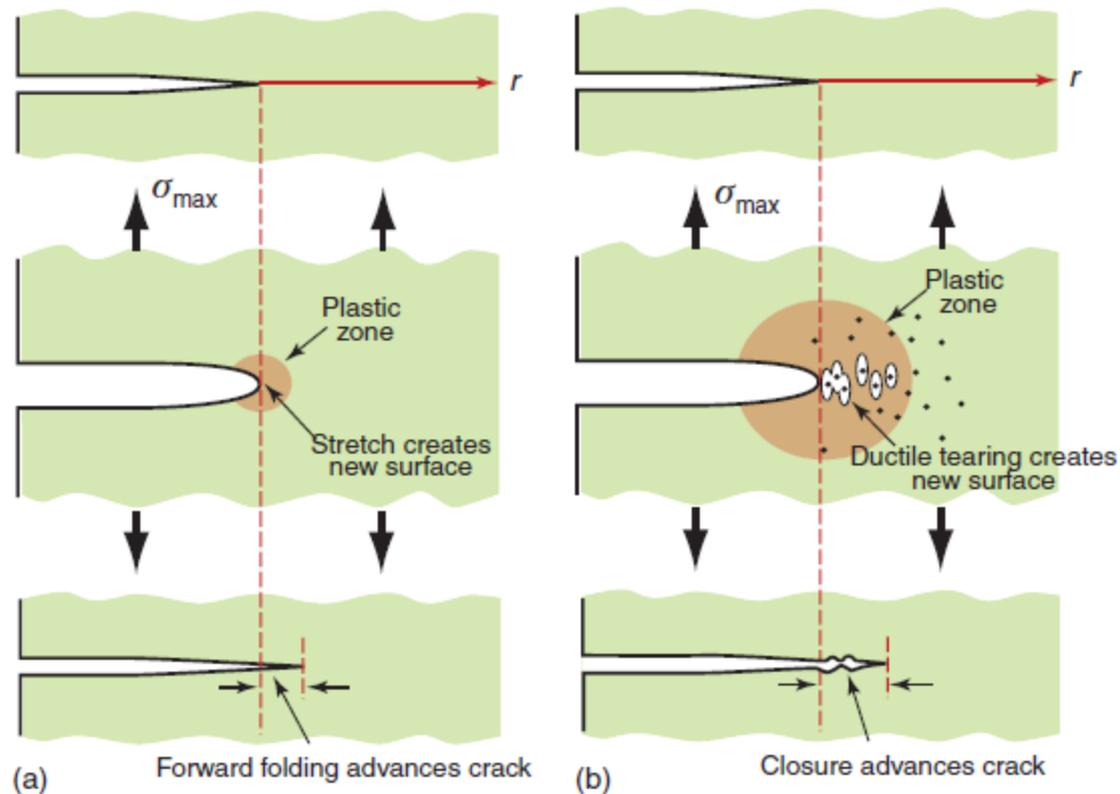


Figure 9.9 (a) In high-cycle fatigue a tiny zone of plasticity forms at the crack tip on each tension cycle; on compression the newly formed surface folds forwards. (b) In low-cycle fatigue the plastic zone is large enough for voids to nucleate and grow within it. Their coalescence further advances the crack.

Fatigue: Cyclic Stresses (I)

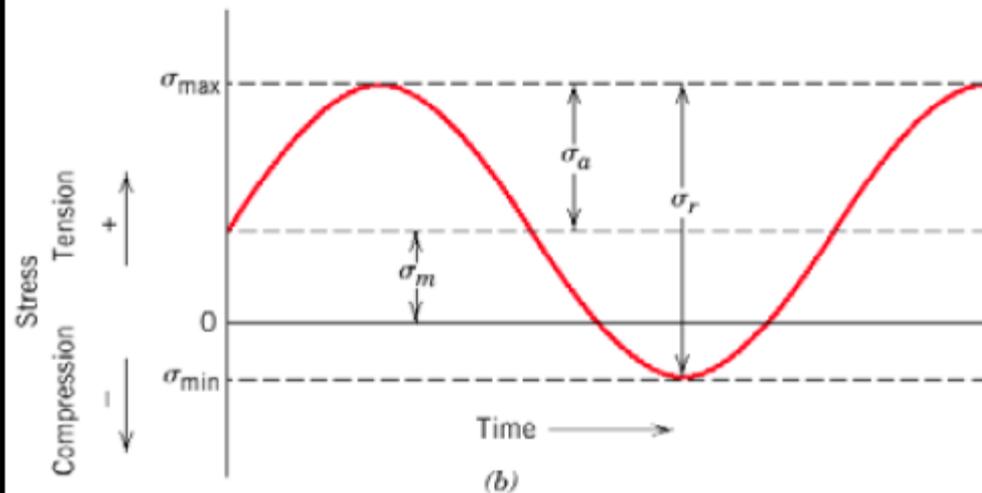
Cyclic stresses are characterized by maximum, minimum and mean stress, the range of stress, the stress amplitude, and the stress ratio

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

Endurance Limit

$S_{e'}$

A stress level below which a material can be cycle infinitely without failure

Many materials have an endurance limit:

low-strength carbon and alloy steels, some stainless steels, irons, molybdenum alloys, titanium alloys, and some polymers

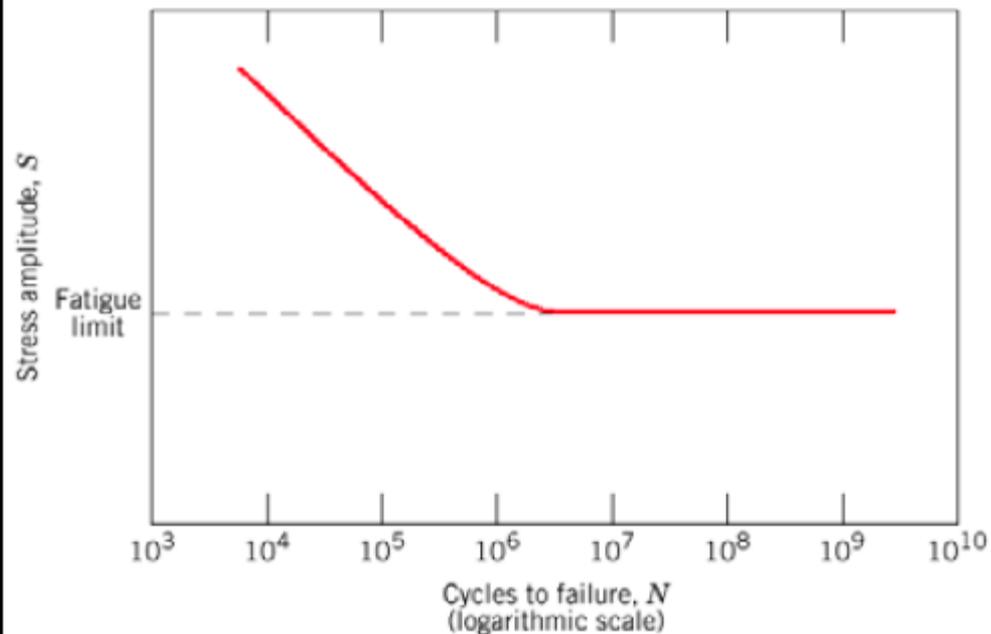
Many other materials DO NOT have an endurance limit:

aluminum, magnesium, copper, nickel alloys, some stainless steels, high-strength carbon and alloy steels

$S_{f'}$

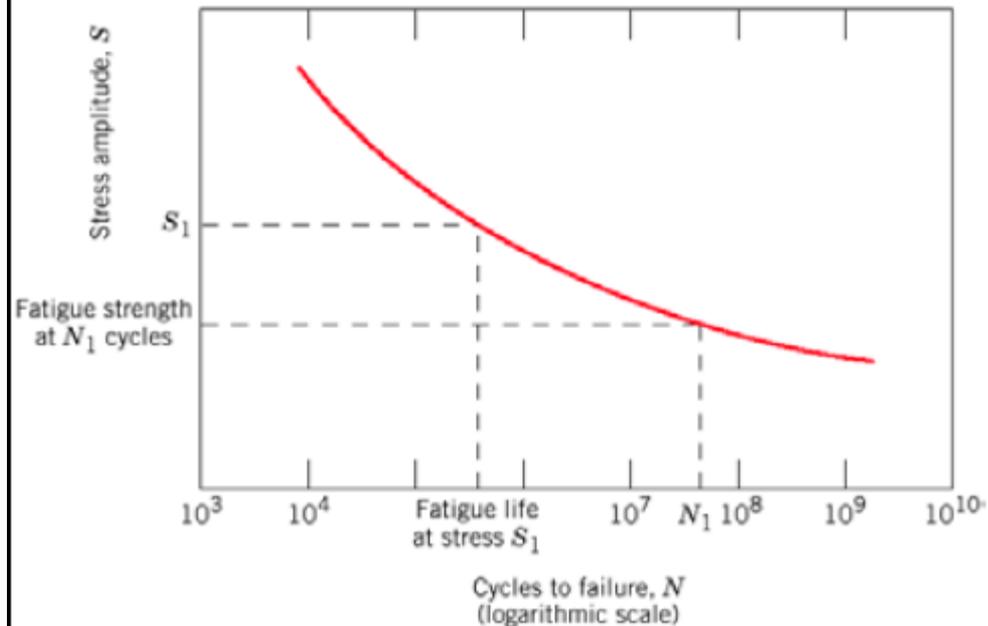
for these, we use a **FATIGUE STRENGTH** defined for a certain number of cycles (5E8 is typical)

Fatigue: S—N curves (II)



Fatigue limit (endurance limit) occurs for some materials (some Fe and Ti alloys). In this case, the S—N curve becomes horizontal at large N . The fatigue limit is a maximum stress amplitude below which the material never fails, no matter how large the number of cycles is.

Fatigue: S—N curves (III)



In most alloys, S decreases continuously with N . In these cases the fatigue properties are described by

Fatigue strength: stress at which fracture occurs after specified number of cycles (e.g. 10^7)

Fatigue life: Number of cycles to fail at specified stress level

The most important single property characterizing fatigue strength is the endurance limit, σ_e , at 10^7 cycles and zero mean stress (an R -value of -1). Given this and the ability to scale it to correct for mean stress, and sum contributions when stress amplitude changes (equations (9.7) and (9.8)), enables design to cope with high-cycle fatigue.

Not surprisingly endurance limit and strength are related. The strongest correlation is with the tensile strength σ_{ts} , shown in the chart of Figure 9.8. The data for metals and polymers cluster around the line

$$\sigma_e \approx 0.33 \sigma_{ts}$$

shown on the chart. For ceramics and glasses

$$\sigma_e \approx 0.9 \sigma_{ts}$$

CRACK INITIATION AND PROPAGATION

- Process of fatigue failure:

1. Crack initiation
2. Crack propagation
3. Final failure

➤ Crack nucleation



scratches

sharp fillets



keyways



threads



➤ Cyclic loading
discontinuities

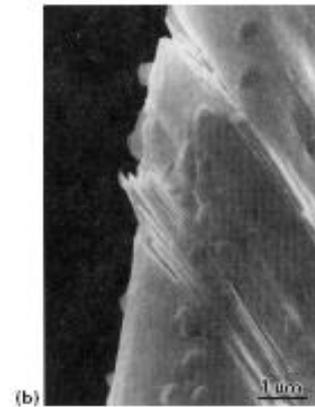
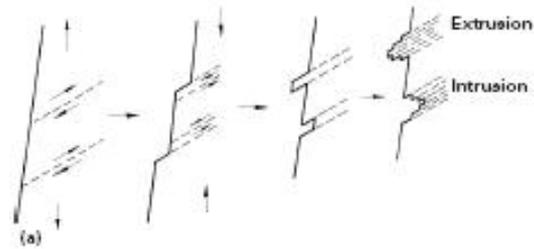
produce
slips steps

microscopic

surface

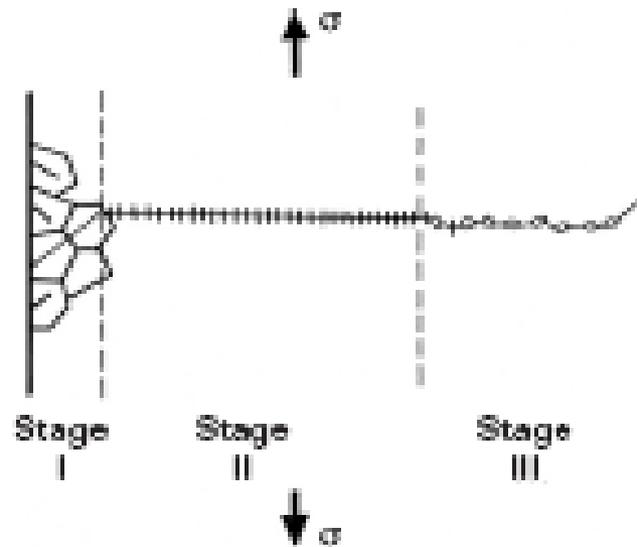


Fatigue Crack Nucleation at Slip Bands

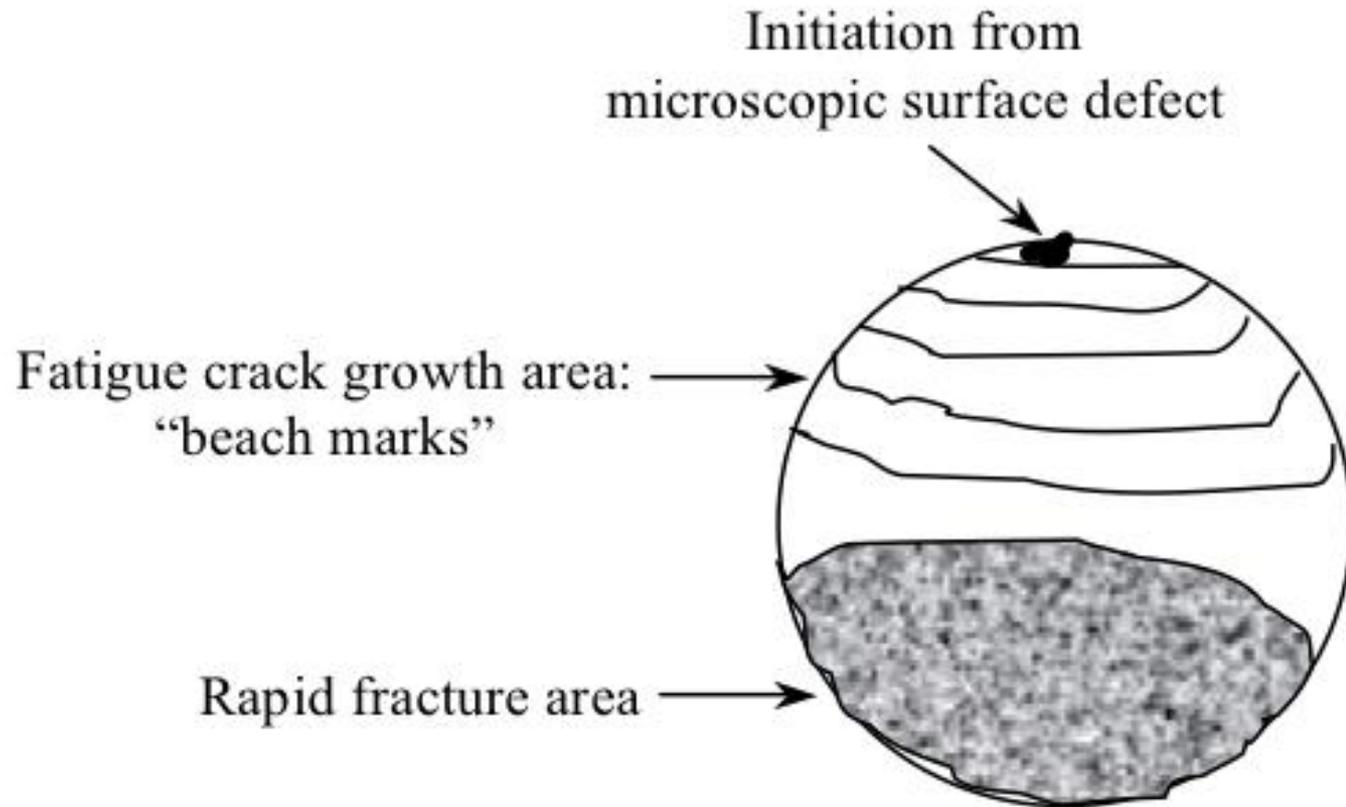


(a) Fatigue crack nucleation at slip bands. (b) SEM of extrusions and intrusions in a copper sheet. (Courtesy of M. Judelwicz and B. Ilchner.)

Stages I, II, and III of fatigue crack propagation



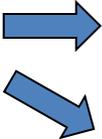
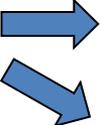
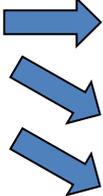
CRACK INITIATION AND PROPAGATION



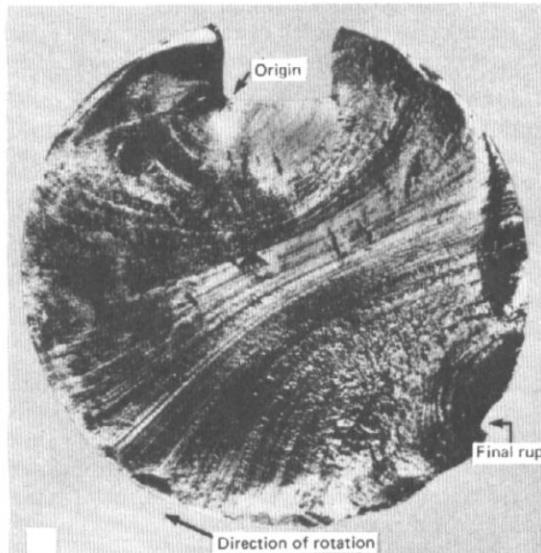
Fatigue Fracture Surface



CRACK INITIATION AND PROPAGATION

- Fracture surface  beachmarks
striations
- Indicates the position of the crack tip and appear as concentric ridges that expand away from the crack initiation sites.
- Beachmarks  Macroscopic dimensions
Short cycles
- Striations  Microscopic size
Single load cycle
to > stress range > striation width

CRACK INITIATION AND PROPAGATION



BEACHMARK RIDGES
OF A ROTATING STEEL SHAFT

CRACK INITIATION AND PROPAGATION



The total width of this SEM picture is only $12\mu\text{m}$ (0.012mm). This specimen was cycled with alternating blocks of 10 cycles at high stress followed by 10 cycles at low stress, creating groups of striations with two different spacings.

STRIATIONS RIDGES

FATIGUE LIFE

◆ Factors



Mean stress level



Geometrical design



Surface effects



Metallurgical variables



Environment

1. MEAN STRESS:



S – N plot



to $>$ mean stress $<$ fatigue life

2. SURFACE EFFECTS



Maximum stress



Design criteria

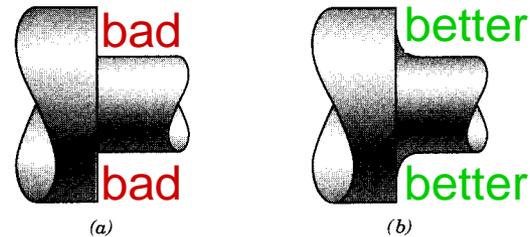


Surface treatments

IMPROVING FATIGUE LIFE

◆ Design factors

Remove stress concentrators.



➤ Surface treatments

- Scratches and grooves



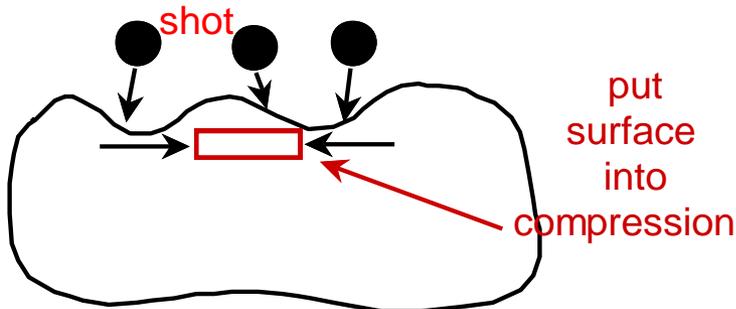
polishing

- Imposing residual compressive stresses

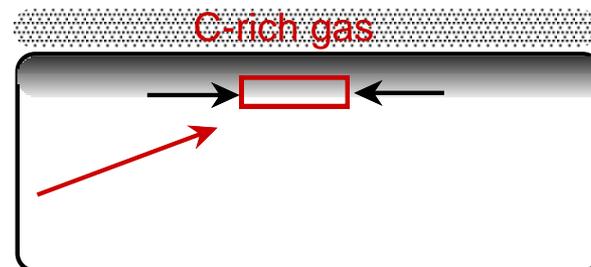


net effect

--Method 1: shot peening



--Method 2: carburizing



FATIGUE LIFE

3. ENVIRONMENTAL EFFECTS



Thermal fatigue



Corrosion fatigue

➤ Thermal fatigue :  T°
 $\sigma = \alpha_1 E \Delta T$

* solution =  T° or choose appropriate material

➤ Corrosion fatigue : Cyclic stress + chemical attack
Small pits

* solution: Apply protective surface coatings

Three Theories

Stress-Life

stress-based, for high-cycle fatigue, aims to prevent crack initiation

Strain-Life

useful when yielding begins (i.e., during crack initiation), for low-cycle fatigue

LEFM (Fracture Mechanics)

best model of crack propagation, for low-cycle fatigue

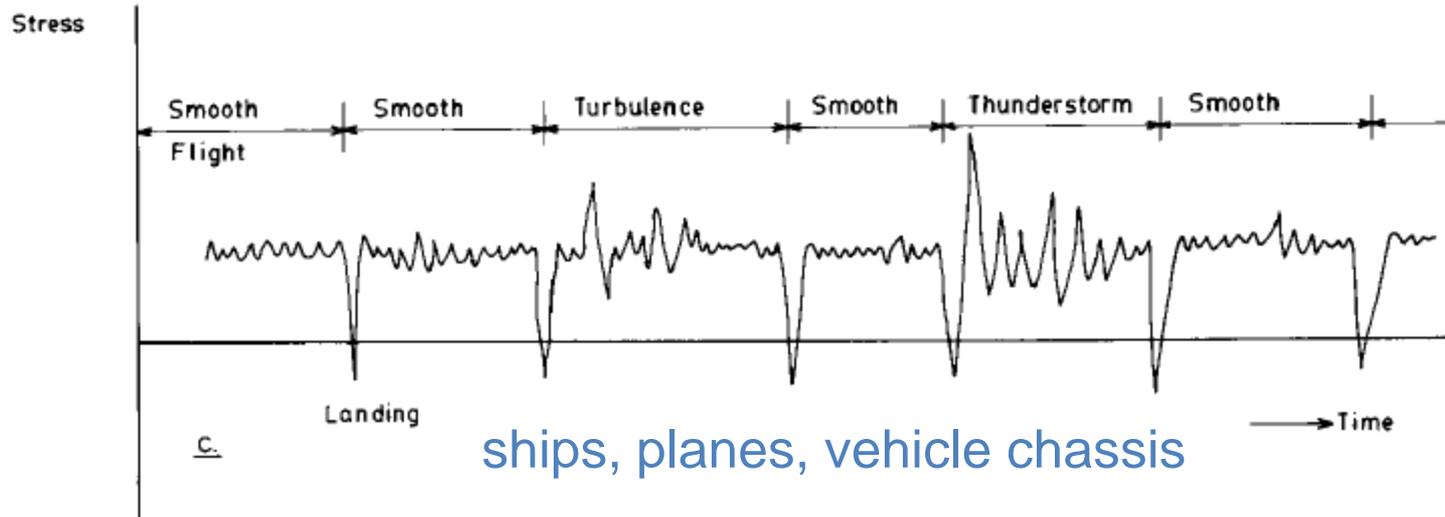
Low vs. High Cycle

>10³ cycles, high cycle fatigue

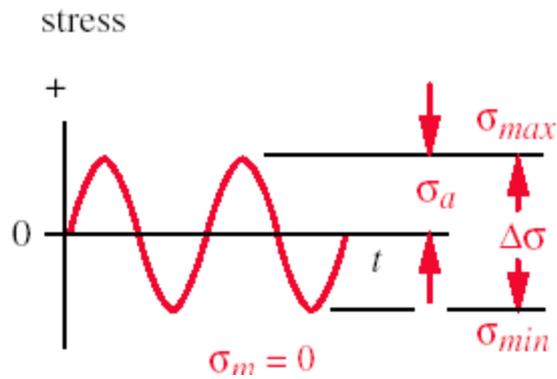
car crank shaft – ~2.5 E8 Rev/10⁵ miles

manufacturing equipment @ 100 rpm – 1.25 E8 Rev/year

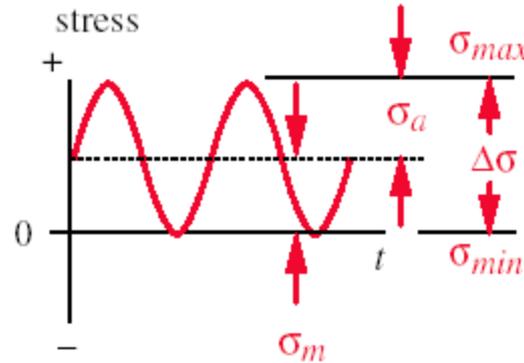
<10³ cycles, low cycle fatigue



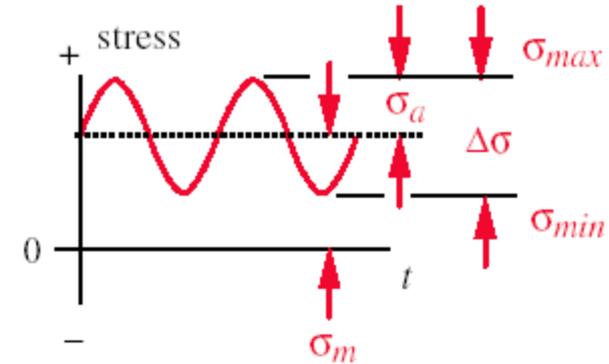
Types of Fatigue Loading



Fully Reversed



Repeated



Fluctuating

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min}$$

stress range

amplitude
ratio

$$A = \frac{\sigma_a}{\sigma_m}$$

$$\sigma_a = \frac{\Delta\sigma}{2}$$

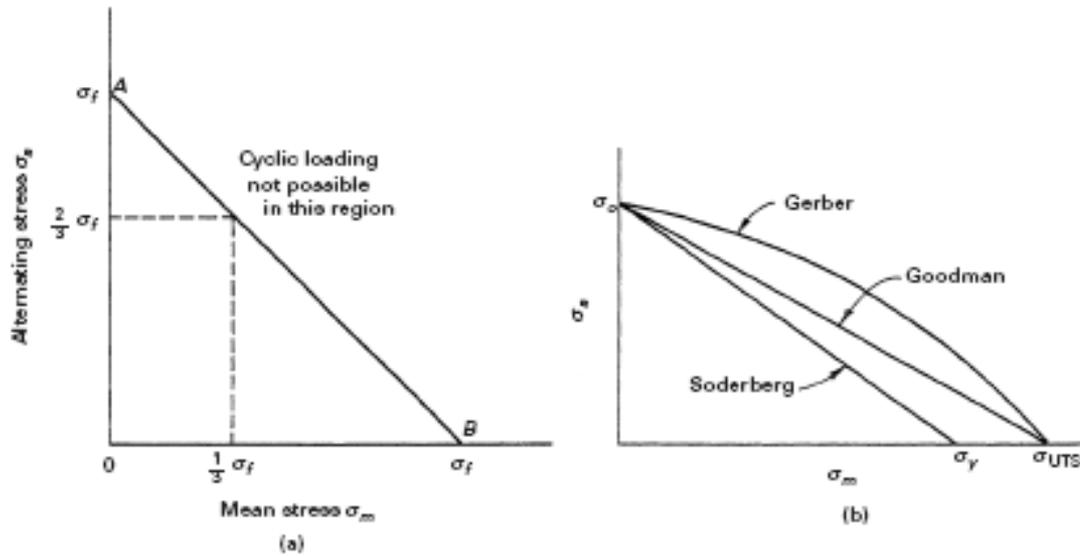
alternating
component

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

mean
component

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

Effect of Mean Stress on Fatigue Life



(a) Effect of mean stress on fatigue life. (b) Gerber, Goodman, and Soderberg diagrams, showing mean stress effect on fatigue life.

Testing Fatigue Properties

- Rotating Beam – most data is from this type
- Axial
 - lower or higher? Why?
- Cantilever
- Torsion

Fully Reversed Empirical Data

An S-N Curve

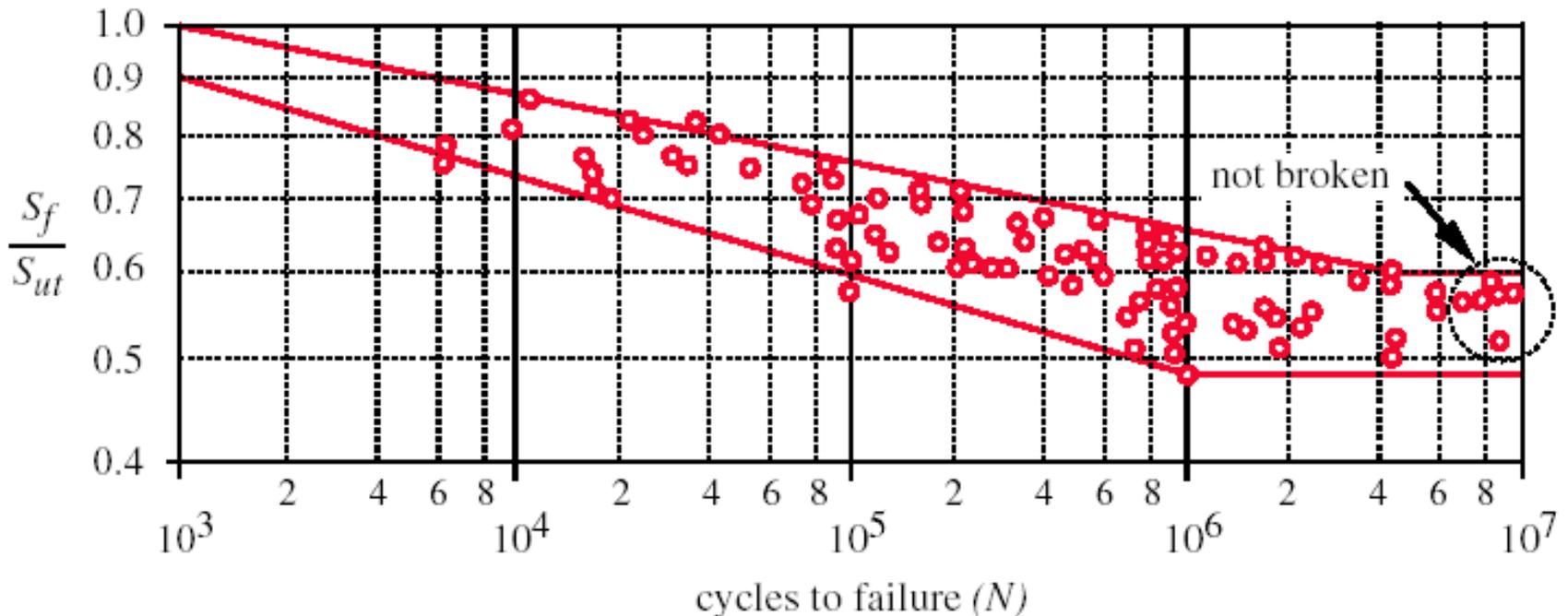


FIGURE 6-8

Log-Log Plot of Composite S-N Curves for Wrought Steels of $S_{ut} < 200$ ksi (From Fig. 11.7, p. 210, R. C. Juvinall, *Stress, Strain, and Strength*, McGraw-Hill, New York, 1967, with permission)

Wrought Steel

Fully Reversed Empirical Data

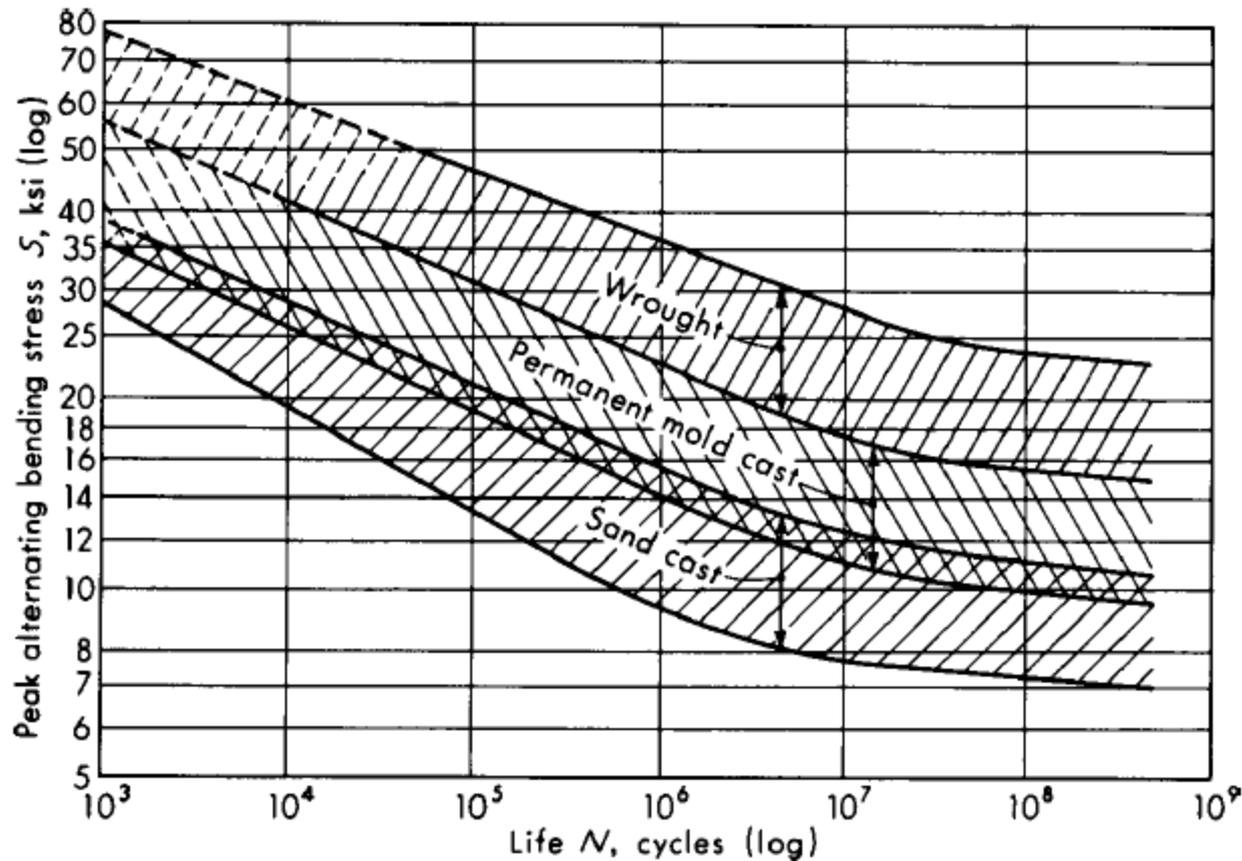


FIGURE 6-10

S-N Bands for Representative Aluminum Alloys, Excluding Wrought Alloys with $S_{ut} > 38$ kpsi (From Fig. 11.13, p. 216, R. C. Juvinall, *Stress, Strain, and Strength*, McGraw-Hill, New York, 1967, with permission)

Aluminum

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2} \quad (9.1)$$

and a mean stress σ_m of

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \quad (9.2)$$

all defined in the figure. Fatigue data are usually reported for a specified R -value:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \quad (9.3)$$

An R -value of -1 means that the mean stress is zero; an R -value of 0 means the stress cycles from 0 to σ_{\max} . For many materials there exists a *fatigue* or *endurance limit*, σ_e (units: MPa). It is the stress amplitude σ_a , about zero mean stress, below which fracture does not occur at all, or occurs only after a very large number ($N_f > 10^7$) cycles. Design against high-cycle fatigue is therefore very similar to strength-limited design, but with the maximum stresses limited by the endurance limit σ_e rather than the yield stress σ_y .

Experiments show that the high-cycle fatigue life is approximately related to the stress range by what is called Basquin's law:

$$\Delta\sigma N_f^b = C_1 \quad (9.4)$$

where b and C_1 are constants; the value of b is small, typically 0.07 and 0.13. Dividing $\Delta\sigma$ by the modulus E gives the strain range $\Delta\varepsilon$ (since the sample is elastic):

$$\Delta\varepsilon = \frac{\Delta\sigma}{E} = \frac{C_1/E}{N_f^b} \quad (9.5)$$

or, taking logs,

$$\text{Log}(\Delta\varepsilon) = -b \text{Log}(N_f) + \text{Log}(C_1/E)$$

Low-cycle fatigue

In low-cycle fatigue the peak stress exceeds yield, so at least initially (before work hardening raises the strength), the entire sample is plastic. Basquin is no help to us here; we need another empirical law, this time that of Dr Lou Coffin:

$$\Delta\varepsilon^{\text{pl}} = \frac{C_2}{N_f^c} \quad (9.6)$$

where $\Delta\varepsilon^{\text{pl}}$ means the plastic strain range—the total strain minus the (usually small) elastic part. For our purposes we can neglect that distinction and plot it in Figure 9.4 as well, giving the left-hand branch. Coffin's exponent, c , is much larger than Basquin's: typically it is 0.5.

This is plotted in Figure 9.4, giving the right-hand, high-cycle fatigue part of the curve with a slope of $-b$.

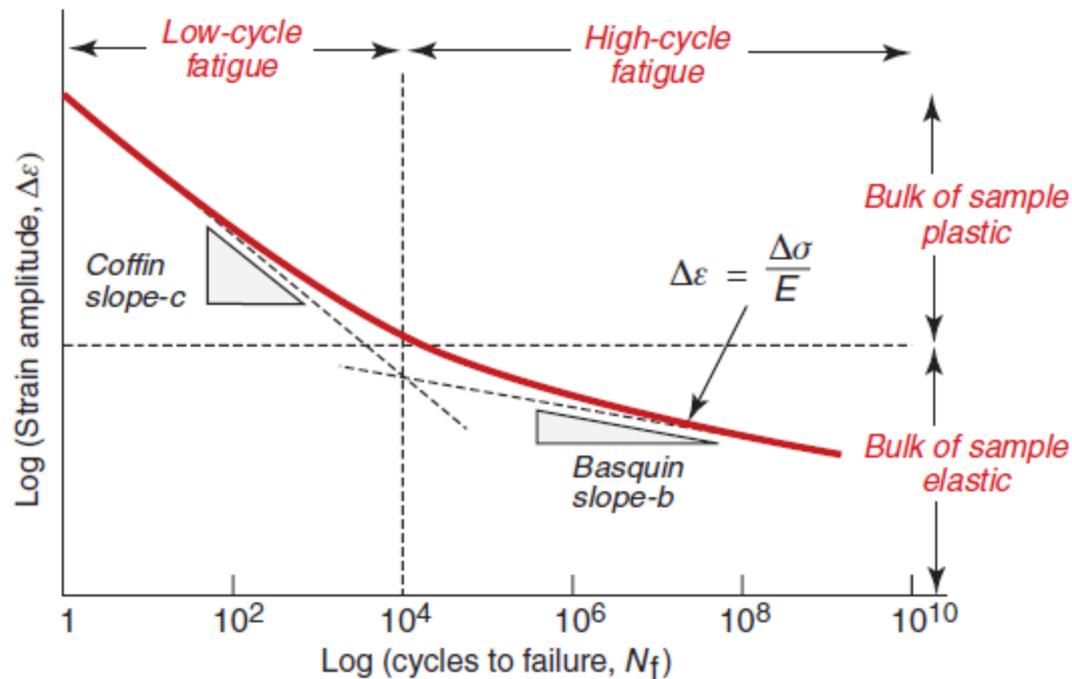


Figure 9.4 The low- and high-cycle regimes of fatigue and their empirical description of fatigue.

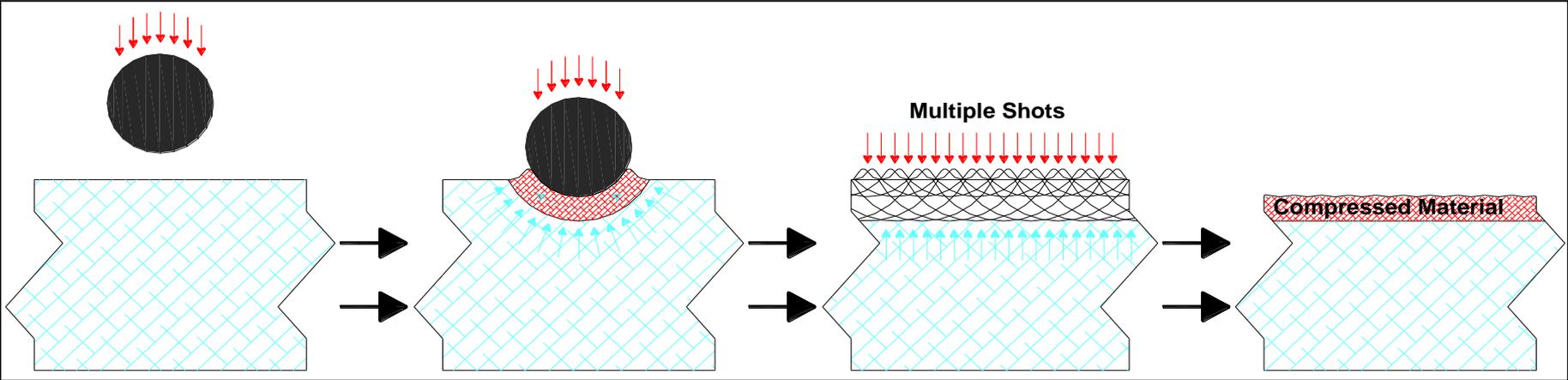
MINER'S RULE

N_1 cycles are spent at stress amplitude $\Delta\sigma_1$ a fraction $N_1/N_{f,1}$ of the available life is used up, where $N_{f,1}$ is the number of cycles to failure at that stress amplitude.

Miner's rule assumes that damage accumulates in this way at each level of stress. Then failure will occur when the sum of the damage fractions reaches 1—that is, when

$$\sum_{i=1}^n \frac{N_i}{N_{f,i}} = 1 \quad (9.8)$$

Shot Peening



Shot Peening Benefits

- Enhances fatigue strength (Figure 4)
- Improves ultimate strength (Figure 5)
- Prevents cracking due to wear
- Prevents hydrogen embrittlement
- Prevents corrosion
- Prevents galling
- Prevents fretting
- Can increase gear life more than 500%
- Can increase drive pinion life up to 400%
- Can increase spring life 400% to 1200%
- Can increase crankshaft life 100% to 1000% (Figure 6)
- Can permit the use of very hard steels by reducing brittleness
- Possible to increase the fatigue strength of damaged parts extending the wear
- Increases lubricity by creating small pores in which lubricants can accumulate
- Substitution of lighter materials can be possible without sacrificing strength and durability
- Leaves a uniformly textured, finished surface ready for immediate use or paint and coatings
- Can be used to curve metal or straighten shafts without creating tensile stress in a Peen forming process
- Shot Peening can be used in a number of specialized processes such as flow treatment of pipes used to transport polymer pellets used in oil and gas industries. Polymer pellets will slide against the inside of a smooth pipeline, melt and form streamers or angel hair. These long polymer fibers will contaminate the pellet flow and clog up the transfer system. When the inside of the pipeline is roughened by shot peening, the polymer pellets bounce or roll instead of sliding along the inside of the pipe. The pellets contact with the side of the pipe is shortened, and formation of angel hair is prevented.
- Optimal fatigue properties for machined steel components are obtained at approximately 700 MPa, any higher and the materials lose fatigue strength due to increased notch sensitivity and brittleness. When compressive stresses from shot peening are added fatigue strength increases proportionately to increased strength.

Methods of Shot Peening

Conventional (Mechanical) Shot Peening – Conventional shot peening is done by two methods. Method one involves accelerating shot material with compressed air. Shot is introduced into a high velocity air stream that accelerates the shot to speeds of up to 250 ft/s. The second method involves accelerating the shot with a wheel. The shot gets dropped onto the middle of the wheel and accelerates to the outer edge where it leaves on a tangential path.

Dual Peening – Dual peening further enhances the fatigue performance from a single shot peen operation by re-peening the same surface a second time with smaller shot and lower intensity. Large shot leaves small peaks and valleys in the material surface even after 100% coverage has been achieved. Peening the surface a second time drives the peaks into the valleys, further increasing the compressive stress at the surface.

Laser-shot Peening – Laser-shot peening utilizes shock waves to induce residual compressive stress. The primary benefit of the process is a very deep compressive layer with minimal cold working. Layer depths up to 0.40” on carburized steel and 0.100” on aluminum alloys have been achieved. Mechanical peening methods can only produce 35% of these depths. **Figure 4** shows the increase in fatigue life that laser-shot peening can create.

Strain Peening – Where dual peening increases the compressive stress on the outer surface of the compressive layer, strain peening develops a greater amount of compressive stress throughout the entire compressive layer. This additional stress is generated by preloading the part within its elastic limit prior to shot peening.. When the peening media impacts the surface, the surface layer is yielded further in tension because of the preloading. The additional yielding results in additional compressive stress when the metal's surface attempts to restore itself.

Media

Media control involves using high quality shot that is mostly round and of uniform size and shape. The diameter of the shot should be the same through out the media. If the shot diameter is not uniform, each individual shot will have a significantly different mass. This exposes the material surface to varying impact energies that create non uniformities. These non uniform layers will create inconsistent fatigue results.

Intensity

Intensity control involves changing the media size and shot velocity to control the energy of the shot stream. Using larger media or increasing the velocity of the shot stream will increase the intensity of the shot peening process. To determine what intensity has been achieved, Almen strips are mounted to Almen blocks and the shot peening process is performed on a scrap part. An Almen strip is a strip of SAE 1070 spring steel that, when peened on one side, it will deform into an arc towards the peened side due to the induced compressive stresses from the shot peening process. By measuring the height of the arc, the intensity can be reliably calculated. This process is done before the actual peening process on production parts to verify the peening process is correct.

The Almen strips also control how long the material is exposed to the shot peening process. The time to expose a material is determined from the saturation point on a saturation curve. The saturation curve is a plot of Almen strip arc height vs Time. The saturation point is defined as the point on the curve where doubling the exposure time produces no more than a 10% increase in arc height.

Coverage

Coverage is the measure of original surface area that has been obliterated by shot dimples. Coverage is crucial to high quality shot peening and should never be less than 100%. A surface that does not have 100% coverage is likely to develop fatigue cracks in the un-peened surface areas.

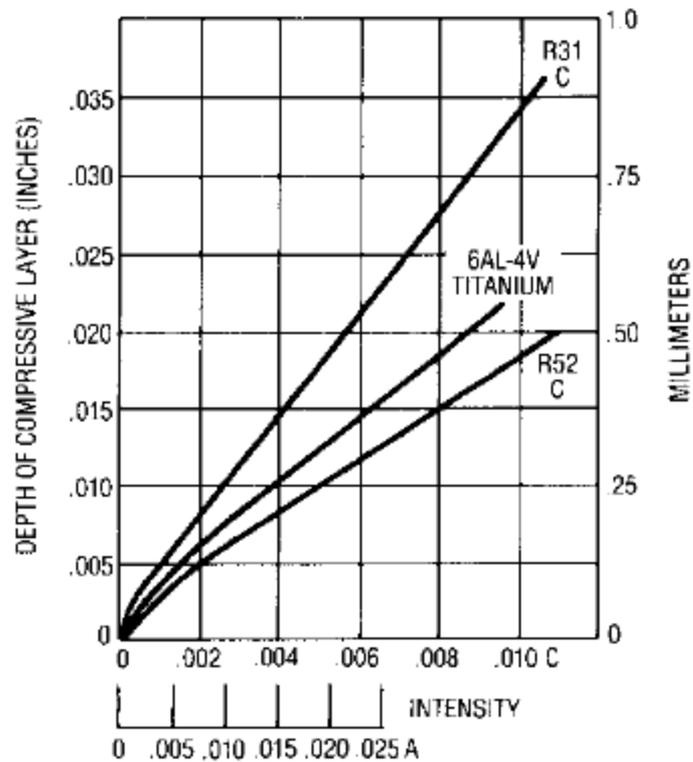


Fig. 2 Residual Stress Produced by Shot Peening vs. Tensile Strength of Steel

1.3.1 Smooth Specimen

Figure 3 illustrates the distribution of stress in a smooth beam with no external load applied which has been shot peened on both the upper and the lower surfaces. Since the beam is in equilibrium with no external forces, the area under the stress distribution curve in the regions of compressive stress must be equal to the corresponding area under the curve in the region of tensile stress. Further, the sum of the moments of these areas must be equal to zero.

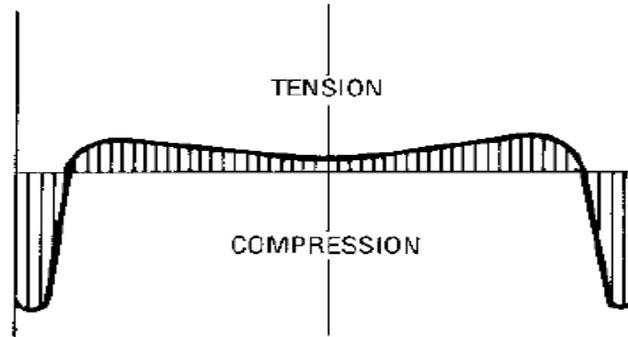
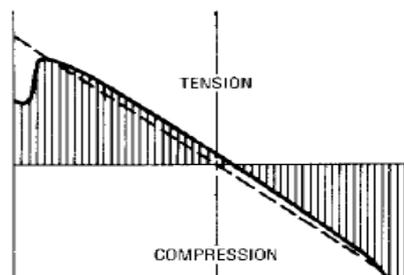


Fig. 3 Typical Residual Stress Distribution After Peening

Figure 4 shows the same beam after shot peening as in the above figure, but with an external bending moment being applied. The resultant stress at any depth will be equal to the algebraic sum of the residual stress and the stress due to the applied load at that depth. The resultant curve of the stress distribution is the solid line and the bending load is shown as a dashed line.

Note that even after loading, the stress at the peened surface is greatly reduced by the compressive stress of shot peening. This condition will help prevent initiation and, more importantly, the propagation of surface cracks.



1.3.2 Notched Specimen

Figure 5 illustrates the distribution of stress in a beam with a notch at the surface and under bending load ($K_t=2.0$). The notch dramatically concentrates and increases the effective stress experienced by the beam at the surface ($K_t=2.0$ effectively doubles the surface stress).

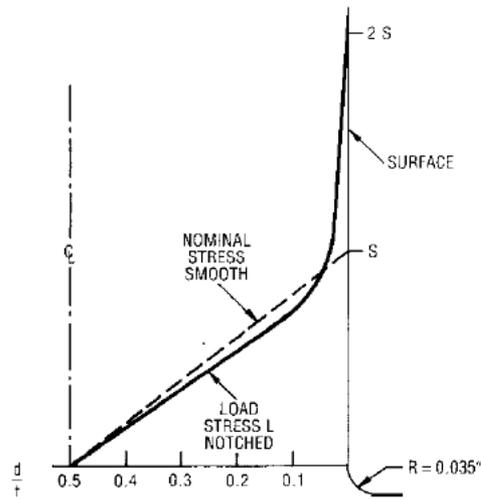


Fig. 5 Distribution of Bending Stress in a Notched Beam

Figure 6 shows the load/stress profile of the same beam but shot peened prior to the application of the bending load. Shot peening reduces the stress experienced at the surface of the beam by over fifty percent - essentially negating the detrimental stress concentration effect of the notch.

