UNIT IV

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- Theoretical cohesive strength of metals.
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- Effect of metallurgical variables and temperature.
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- Effect of some metallurgical variables.
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- Fracture
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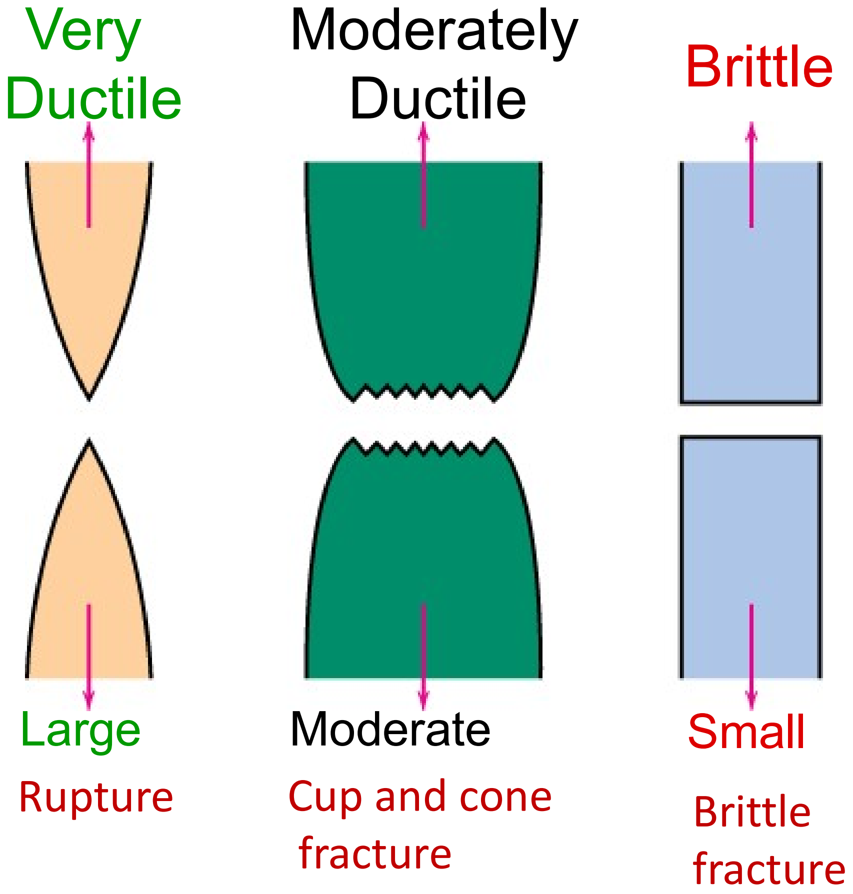
- Types of Fracture
  - Ductile fracture
  - Brittle fracture



Very Ductile

Moderately Ductile

Brittle

Large

Rupture

Moderate

Cup and cone fracture

Small

Brittle fracture

Stages in the cup and cone fracture

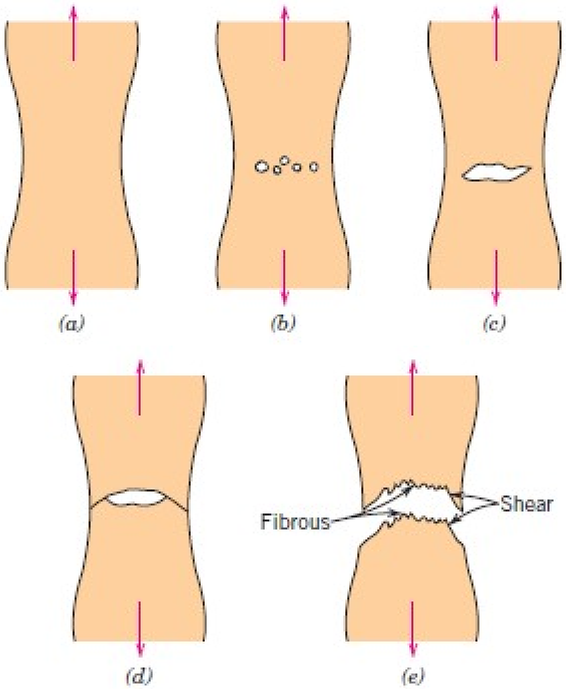
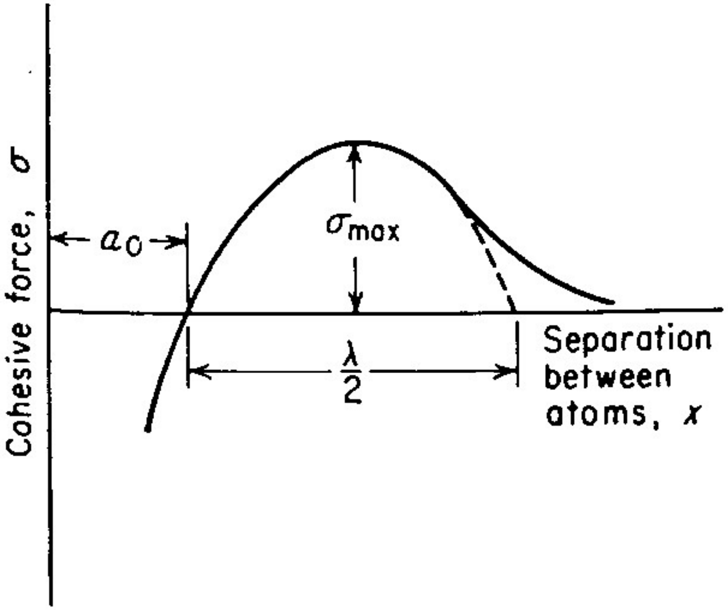


Figure 8.2 Stages in the cup-and-cone fracture. (*a*) Initial necking. (*b*) Small cavity formation. (*c*) Coalescence of cavities to form a crack. (*d*) Crack propagation. (*e*) Final shear fracture at a 45° angle relative to the tensile direction. (From K. M. Ralls, T. H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering,* p. 468. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Theoretical cohesive strength of metals

- The high strength of the materials due to the cohesive forces between atoms.
- The high cohesive forces are related to
  - large elastic constants,
  - high melting points and
  - small coefficients of thermal expansions.
- The cohesive force curve can be represented by as sine curve.

$$\sigma = \sigma_{max} \sin \frac{2\pi x}{\lambda}$$



σ_{max} is the theoretical cohesive strength

$x=a-a_o$ is the displacement in atomic spacing in a lattice with wave length λ.

For small displacements, *sinx* ≈ *x*

$$\sigma = \sigma_{max}\frac{2\pi x}{\lambda}$$

From Hooke's law,

$$\sigma = Ee = \frac{Ex}{a_o}$$

Substitute the above equation,

$$\sigma_{max} = \frac{\lambda}{2\pi}\frac{E}{a_o}$$

Assume $a_0=\lambda/2$, then

$$\sigma_{max} = \frac{E}{\pi}$$

Therefore, the potential exists for high values of cohesive strength.

- When fracture occurs in a brittle solid, all of the work expended in producing the fracture such as the creation of two new surfaces.
- Each of these surfaces has a surface energy of γ_s J m^{-2}.
- The work done per unit area of surface is creating the fracture which is the area under the stress-displacement curve.

$$U_o = \int_0^{\lambda/2} \sigma_{max} \sin \frac{2\pi x}{\lambda} dx = \frac{\lambda \sigma_{max}}{\pi}$$

- This energy is equal to the energy required to create the two new fracture surfaces.

$$\frac{\lambda \sigma_{max}}{\pi} = 2\gamma_s \qquad \lambda = \frac{2\pi\gamma_s}{\sigma_{max}}$$

- Substitute λ,

$$\sigma_{max} = \frac{\lambda}{2\pi} \frac{E}{a_o} \qquad \boxed{\sigma_{max} = \left(\frac{E\gamma_s}{a_o}\right)^{1/2}}$$

- The value of σ_{max} could lie between E/4 to E/15.

Determine the cohesive strength of a silica fiber, if $E=95GPa$, $\gamma_s=1$ Jm^{-2} and $a_0=0.16nm$

$$\boxed{\sigma_{max} = \left(\frac{E\gamma_s}{a_o}\right)^{1/2}}$$

$$\sigma_{max}=(95\times10^{9}\times1/0.16\times10^{-9})^{1/2}$$

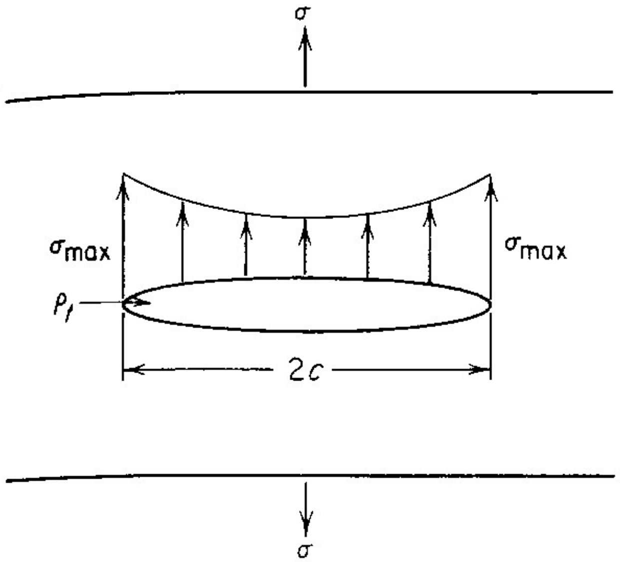
$$=24.4GPa$$

In practical, the value is very less.

Presence of crack reduces fracture strength.

The crack length is 2c and radius of curvature at its tips of ρ_t.

The max. stress at the tip of the crack σ_{max},



$$\sigma_{\max} = \sigma\left[1 + 2\left(\frac{c}{\rho_t}\right)^{1/2}\right] \approx 2\sigma\left(\frac{c}{\rho_t}\right)^{1/2}$$

The nominal fracture stress σ_f of the material having cracks,

$$\boxed{\sigma_f = \left(\frac{E\gamma_s\rho_t}{4a_0c}\right)^{1/2}}$$

The sharpest possible crack is, $\rho_t = a_o$,

$$\sigma_f = \left(\frac{E\gamma_s}{4c}\right)^{1/2}$$

Calculate the fracture stress for a brittle material with the following properties. E=100GPa, γ_s=1Jm^{-2}, a_o=0.25nm c=10^4

$$\boxed{\sigma_f = \left(\frac{E\gamma_s}{4c} \right)^{1/2}}$$

Stress Concentration

If a elliptical shape crack is oriented perpendicular to the applied stress σ_0, the max. stress at the crack tip is,

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

The ratio σ_m/σ_0 is denoted as stress concentration factor K_t.

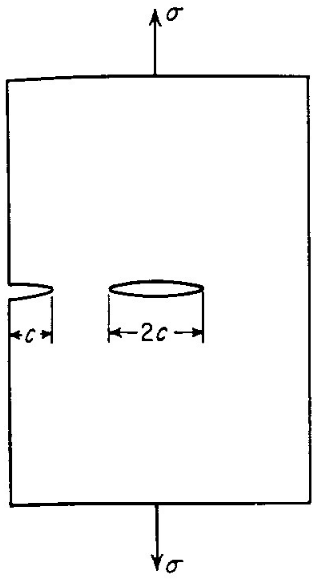
$$K_t = \frac{\sigma_m}{\sigma_0} = 2\left(\frac{c}{\rho_t} \right)^{1/2}$$

Griffth Theory of Brittle Fracture

Griffth proposed that

- A brittle materials contains a large number of fine cracks and flaws.
- These cracks are different sizes, geometries and orientations which act as stress concentration.
- Due to stress concentration, theoretical cohesive strength is reached in localized regions at a nominal stress .
- When crack spreads, it increases the surface area of the crack which required to overcome the cohesive force of the atoms.
- For opening a crack, it require surface energy which is obtained from the elastic strain energy which is released as the crack spreads.

Consider a crack model shown in figure.



The thickness of the plate is negligible (i.e. Plane stress)

Crack is assumed to be elliptical shape.

Crack length = interior = 2c

= edge = c

The crack on the surface and interior have same behaviour.

The elastic strain energy per unit of plat thickness is equal

$$U_E = -\frac{\pi c^2 \sigma^2}{E}$$

σ is the tensile stress acting normal to the crack. A negative sign is used because growth of the crack releases elastic strain energy.

The surface energy due to the presence of the crack is

$$U_s = 4c\gamma_s$$

The total change in potential energy resulting from the creation of the crack is

$$\Delta U = U_s + U_E$$

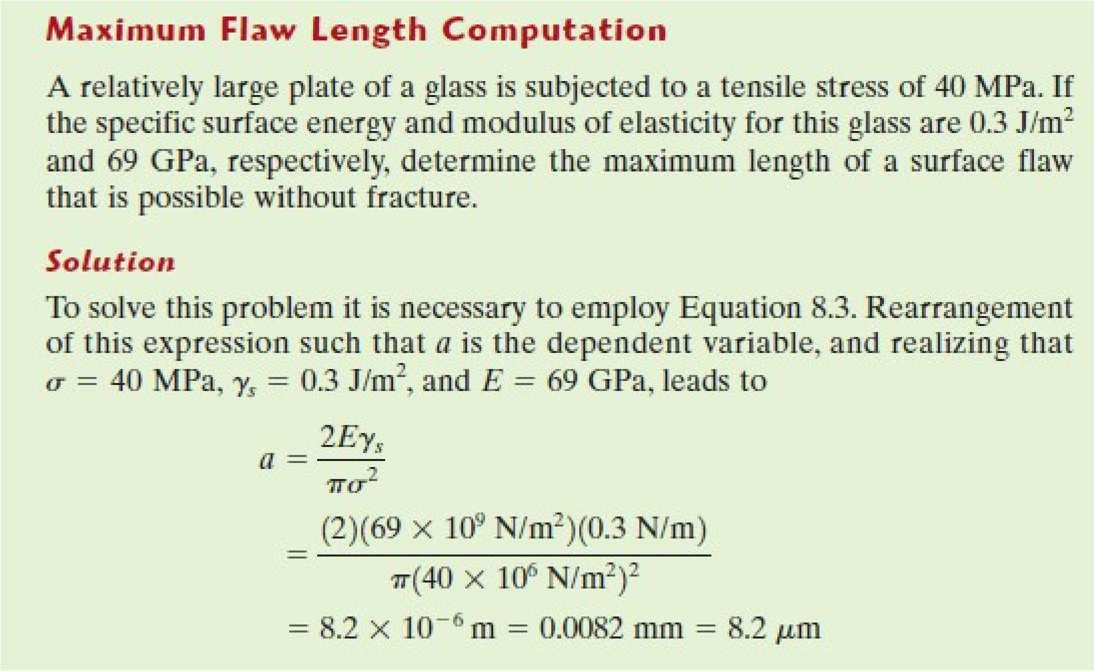
According to Griffith’s criterion, the crack propagates under constant applied stress σ if an incremental increases in crack length produces no change in the total energy of the system. The increased surface energy is compensated by a decrease in elastic strain energy.

$$\frac{d\Delta U}{dc} = 0 = \frac{d}{dc}\left(4c\gamma_s - \frac{\pi c^2\sigma^2}{E}\right)$$

$$4\gamma_s - \frac{2\pi c\sigma^2}{E} = 0$$

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

A relatively large plate of a glass is subjected to a tensile stress of 40MPa. If the specific surface energy and modulus of elasticity for this glass are 0.3 J/m^2 and 69GPa respectively



Maximum Flaw Length Computation

A relatively large plate of a glass is subjected to a tensile stress of 40 MPa. If the specific surface energy and modulus of elasticity for this glass are 0.3 J/m^2 and 69 GPa, respectively, determine the maximum length of a surface flaw that is possible without fracture.

Solution

To solve this problem it is necessary to employ Equation 8.3. Rearrangement of this expression such that a is the dependent variable, and realizing that $\sigma = 40$ MPa, $\gamma_s = 0.3$ J/m^2, and $E = 69$ GPa, leads to

$$
\begin{aligned}
a &= \frac{2E\gamma_s}{\pi\sigma^2} \\
&= \frac{(2)(69 \times 10^9\ \text{N/m}^2)(0.3\ \text{N/m})}{\pi(40 \times 10^6\ \text{N/m}^2)^2} \\
&= 8.2 \times 10^{-6}\ \text{m} = 0.0082\ \text{mm} = 8.2\ \mu\text{m}
\end{aligned}
$$

- For thin plate, fracture stress is

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

- For thick plate, fracture stress is represented as,

$$\sigma = \left(\frac{2E\gamma_s}{(1-\nu^2)\pi c} \right)^{1/2}$$

- Griffth theory applicable for brittle material like glass. In the case metal, before fracture material undergoes plastic deformation (even for brittle fracture)
- Orowan suggested to including the plastic work involved in extension of crack wall (γ_p).

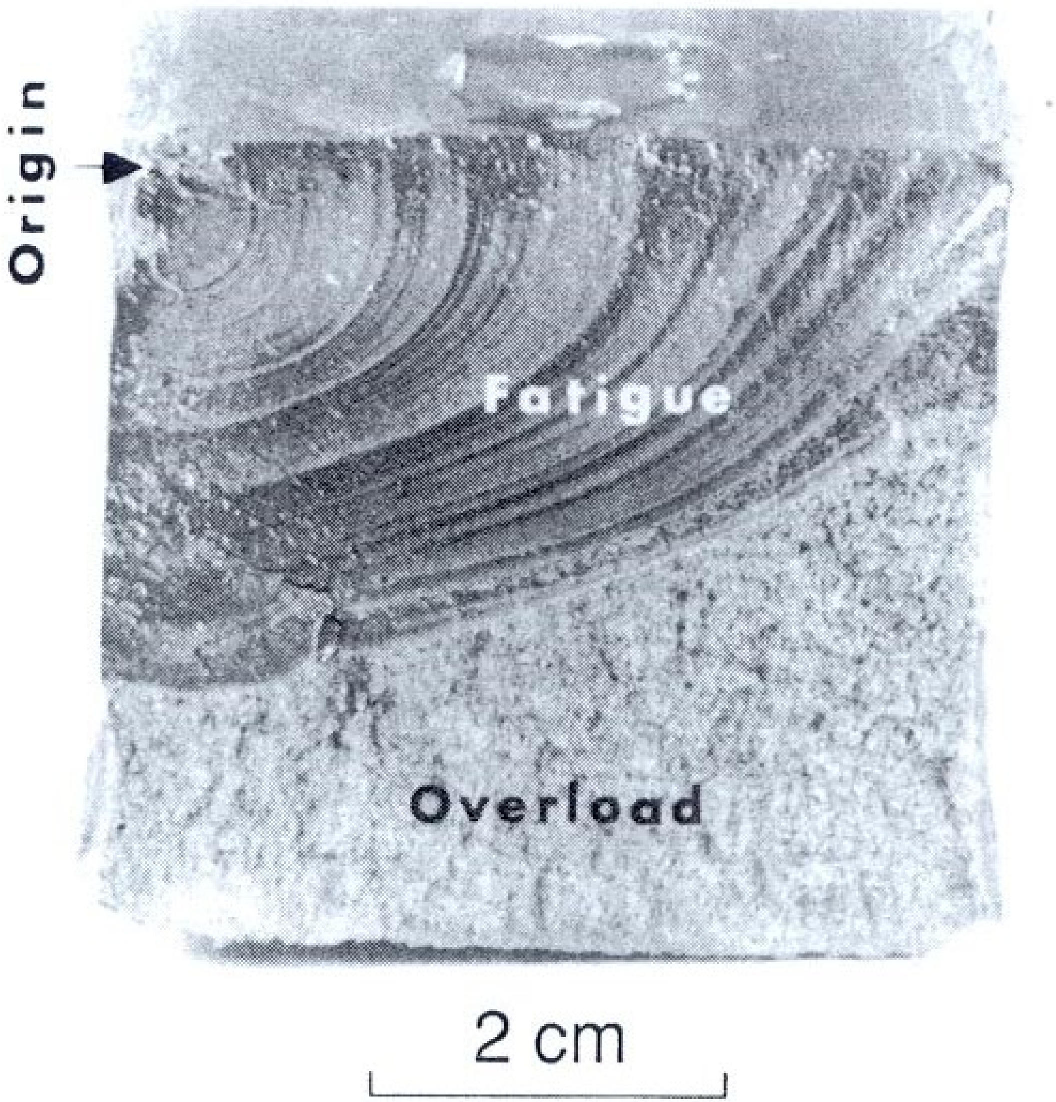
$$\sigma = \left(\frac{2E(\gamma_s + \gamma_p)}{\pi c} \right)^{1/2} \approx \left(\frac{E\gamma_p}{c} \right)^{1/2} \qquad \gamma_s << \gamma_p$$

Metallographic Aspects of Fracture

- The steps involved in brittle fracture (cleavage fracture)
  - Plastic deformation produces dislocation pile-ups
  - Crack initiation
  - Crack propagation
- Crack initiation
  - Presence and nature of second phase particles
  - Resistance to cracking increases if particle are well bonded with matrix.
  - Small particles ($r < 1\mu m$) and spherical particles give more resistance to cracking.
  - If the dislocation cut the particles, large dislocation pile up take place which leads to high stress, easy initiation of microcracks and brittle fracture.

- If the second phase particles are hard, bow the dislocation and increases the effective interfacial energy. Those precipitates increases the toughness.
- Most of the brittle fracture occur in a transgranular manner.
- If the grain boundary contain a film of brittle constitutes then facture occur an intergranular manner. Example
  - Sensitized austenitic stain less steel (deposition of chromium carbide at grain boundary),
  - Mo alloys containing O_2, N_2 and C,
  - Addition of Sb to Cu, and O2 to Fe leads embrittlement is produced.
- In the case of ductile fracture, initiation of voids take place at second phase particles. The particle geometry, size and bonding with the matrix are important parameters.

Fatigue



Fatigue: Failure due to dynamic or cyclic loading.

Example: aircraft, automobile parts such as axles, transmission parts and suspension systems, turbine blades, bridges etc.

Basic factor requires for fatigue failure,

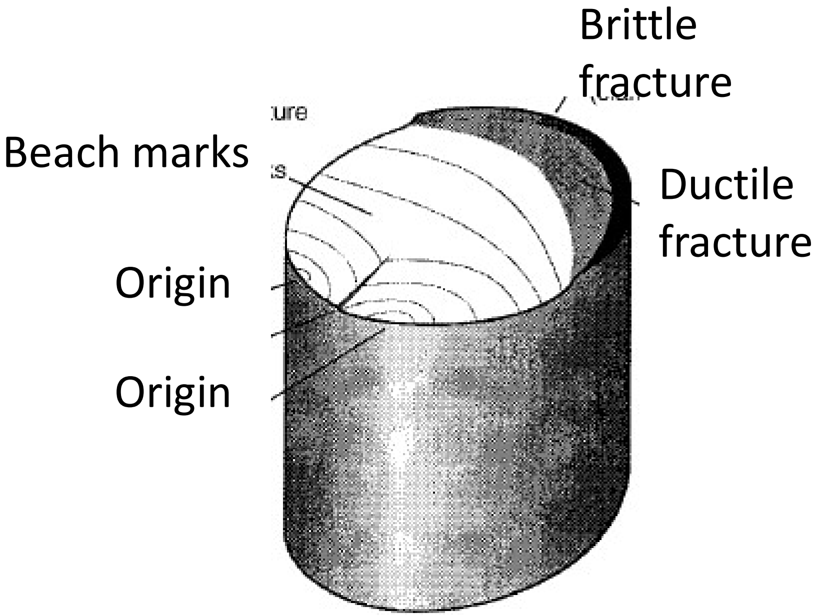
- Maximum tensile stress
- Large variation or fluctuation in applied stress
- Large number of cycles of applied stress

Other variables such as stress concentration, corrosion, temperature, overload, metallurgical structure, residual stresses and combines stresses alter the condition of fatigue.

Fatigue requires,

1. Cyclic loading
2. Tensile stresses and
3. Plastic strain on each cycle

If any of these are missing, there will be no failure



- Each cycle produces some permanent change, it may be very small.
- Metals and polymer fail by fatigue. Ceramic by fatigue failure is rare due to poor plastic deformation.

Stages of Fatigue:

1. **Crack nucleation** – where a small crack forms at high stress concentrated area such as sharp corner or notch or metallurgical stress concentration like an inclusion.
2. **Crack growth** – increment of crack length with each cycle
3. **Fracture** – sudden failure

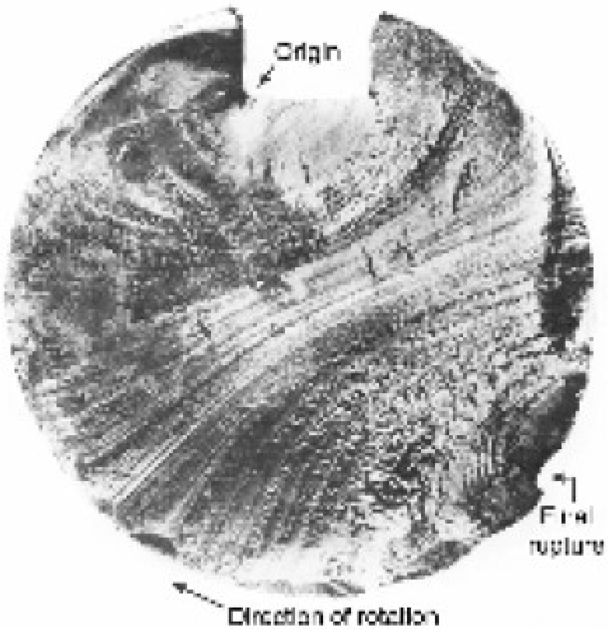


Fig.: Rotating bending fatigue failure of keyed medium-carbon steel shaft. Fatigue initiated at a corner of the keyway, as mraked. Beach marks in that vicinity are concentric about the origin

Fig.:Subsurface fatigue origin in-service failure of nitrided medium-carbon alloy steel crank pin.

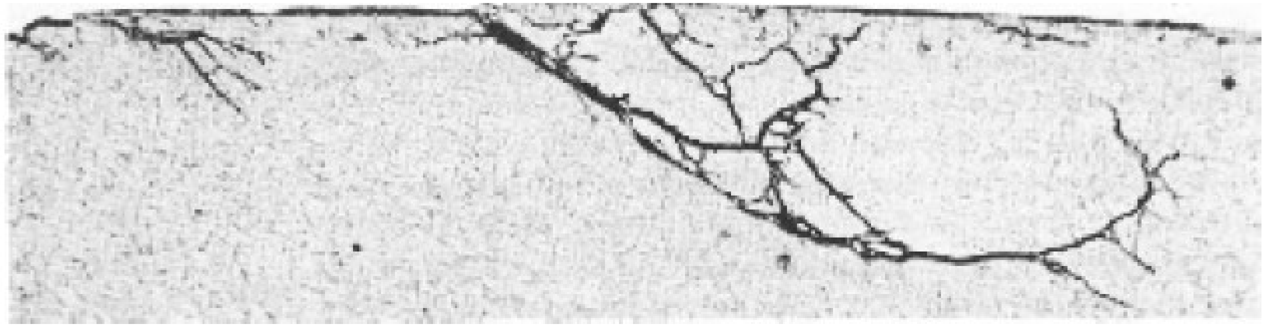
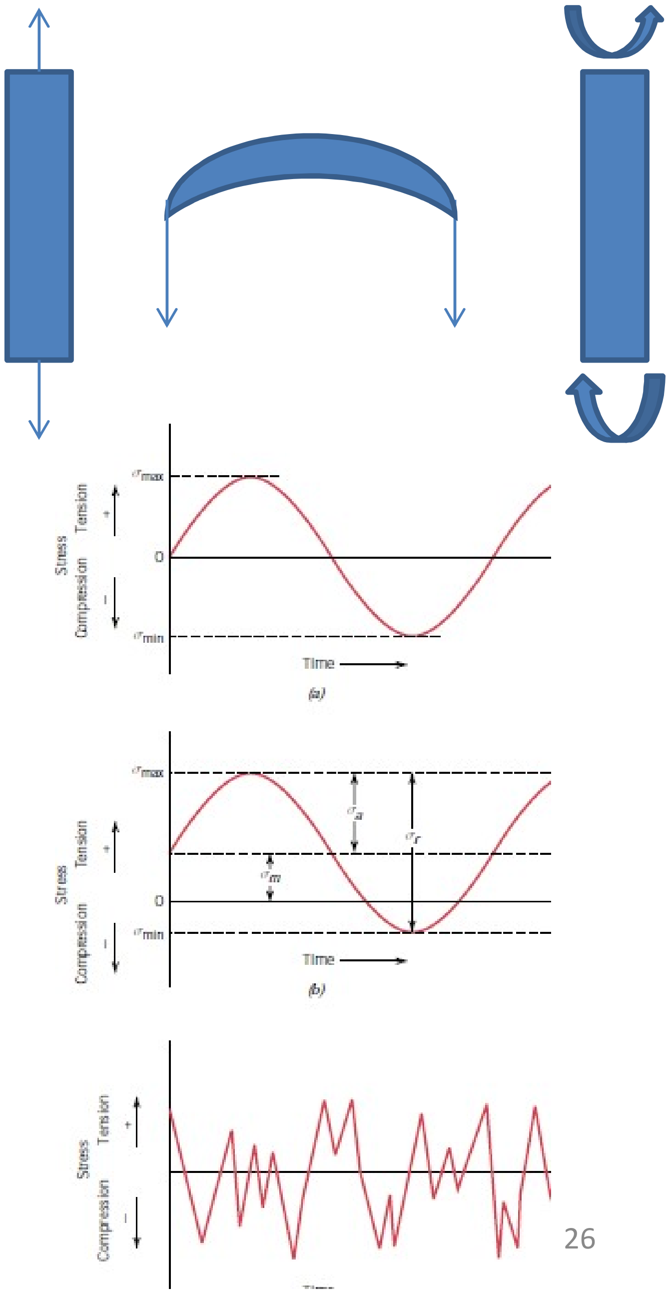


Fig.: Unetched metallographic cross section through hardened steel roller test specimen. Fatigue cracks initiate at surface

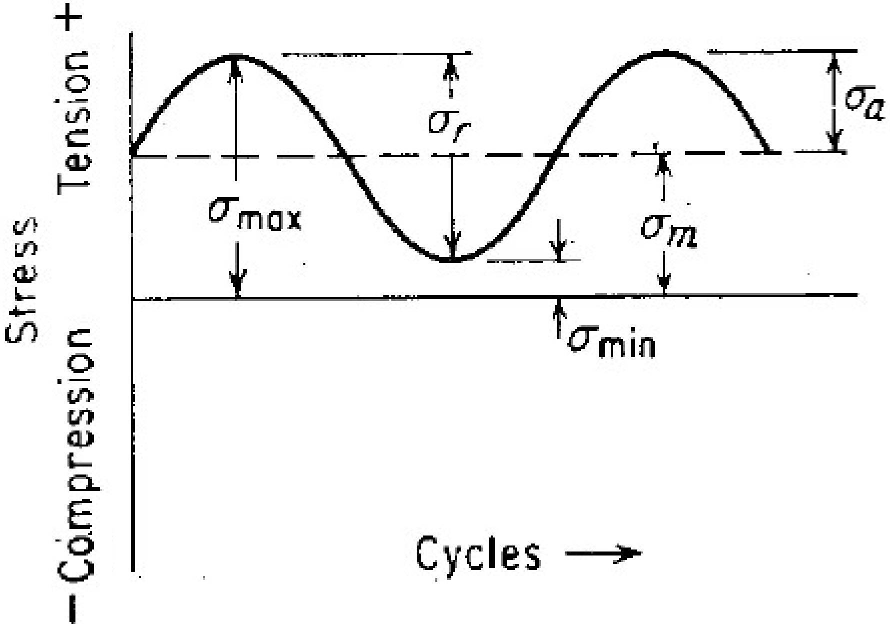
Stress Cycles

- The applied stress may be
  - axial (tension-compression),
  - flexural (bending),
  - torsion (twisting)

- There are three different fluctuating stress–time modes are possible.
  - Completely Reversed Cycle
  - Repeated Stress Cycle
  - Fluctuating Stress Cycle



Nomenclature of Fatigue Test



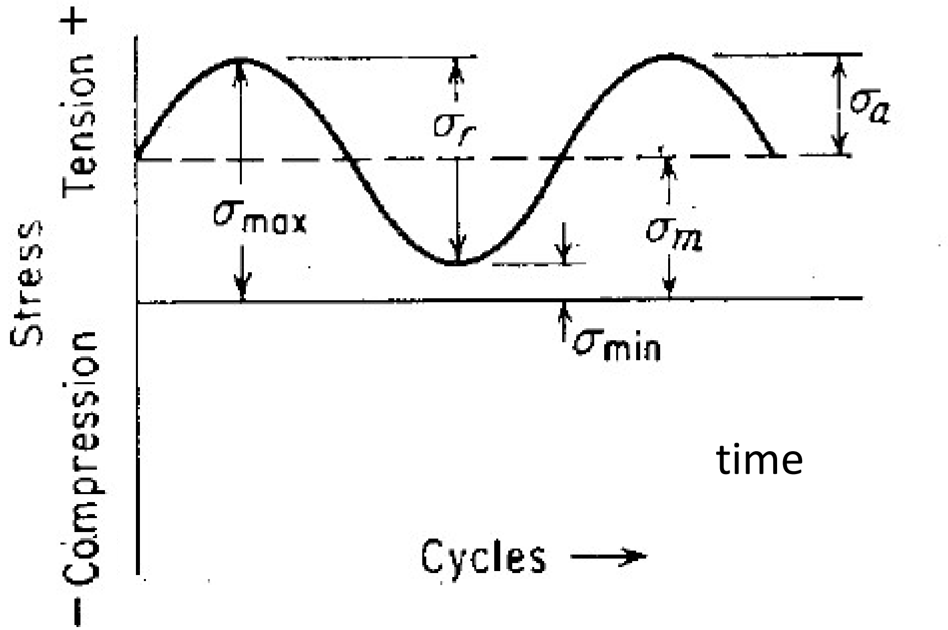
Nomenclature of Fatigue Test

Alternating or Variable or amplitude stress

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

Mean or steady stress

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



Stress Ratio

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

Range of stress

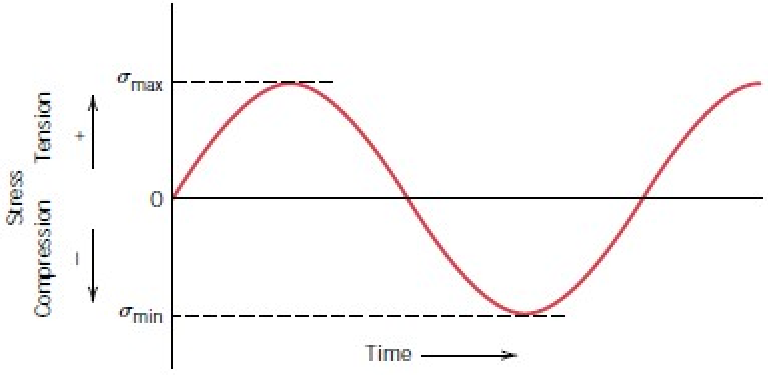
$$\sigma_r = \sigma_{\max} - \sigma_{\min}$$

Amplitude Ratio

$$A = \frac{\sigma_a}{\sigma_m} = \frac{1-R}{1+R}$$

Completely Reversed Cycle:

- Tensile stress is considered as +ve
- Compressive stress is considered as –ve
- In stress cycle the maximum and minimum stresses are equal
- Ex.: Rotating shaft operating at constant speed without overload



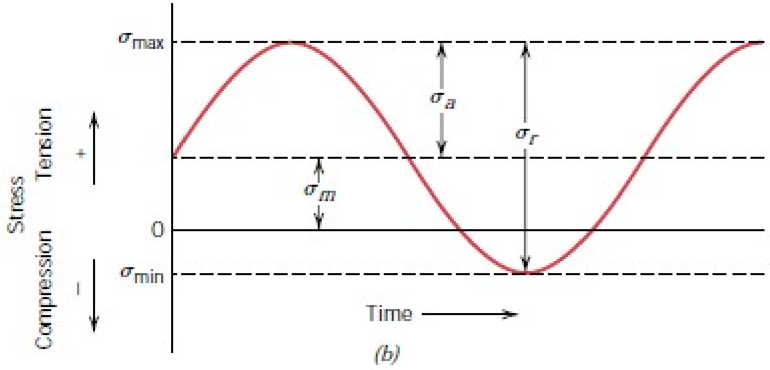
$$\sigma_a = \sigma_{max}$$

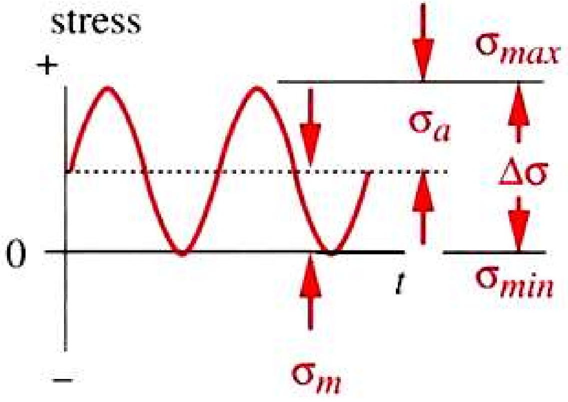
$$\sigma_{max} = -\sigma_{min}$$

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} = -1$$

Repeated stress cycle

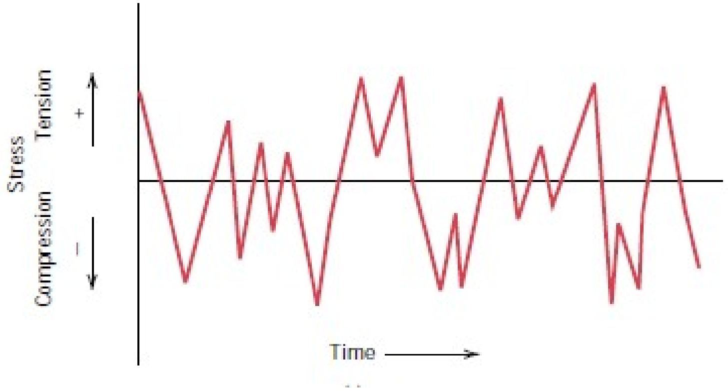
- The maximum and minimum stress cycles are asymmetrical relative to the zero stress level.



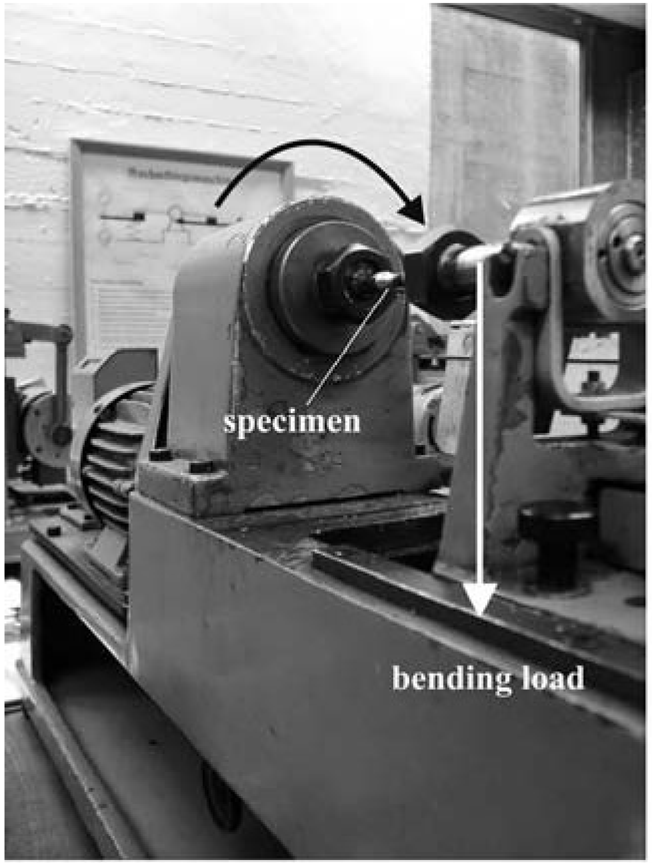


Fluctuating Stress Cycles

- The stress level vary randomly in amplitude and frequency .
- Ex: An aircraft wing which is subjected to periodic unpredictable overloads due to gusts.



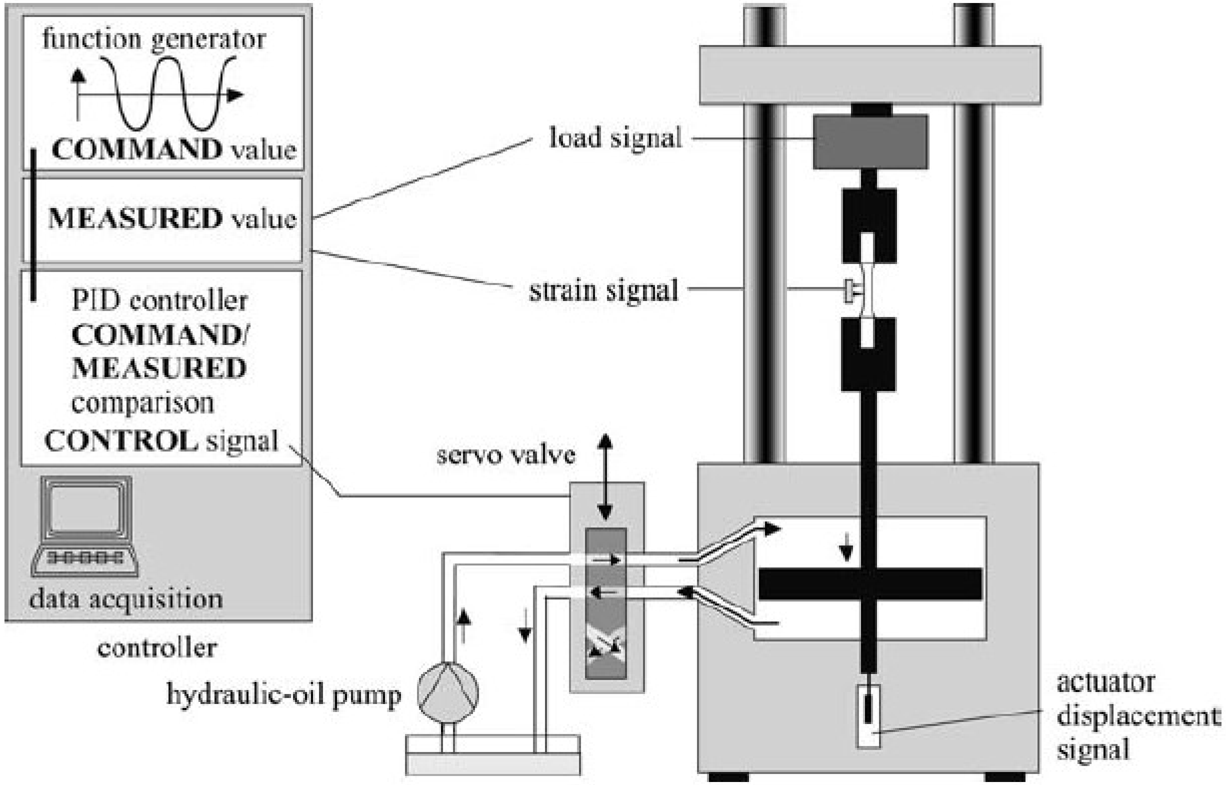
Fatigue Test



Rotating–bending testing machine

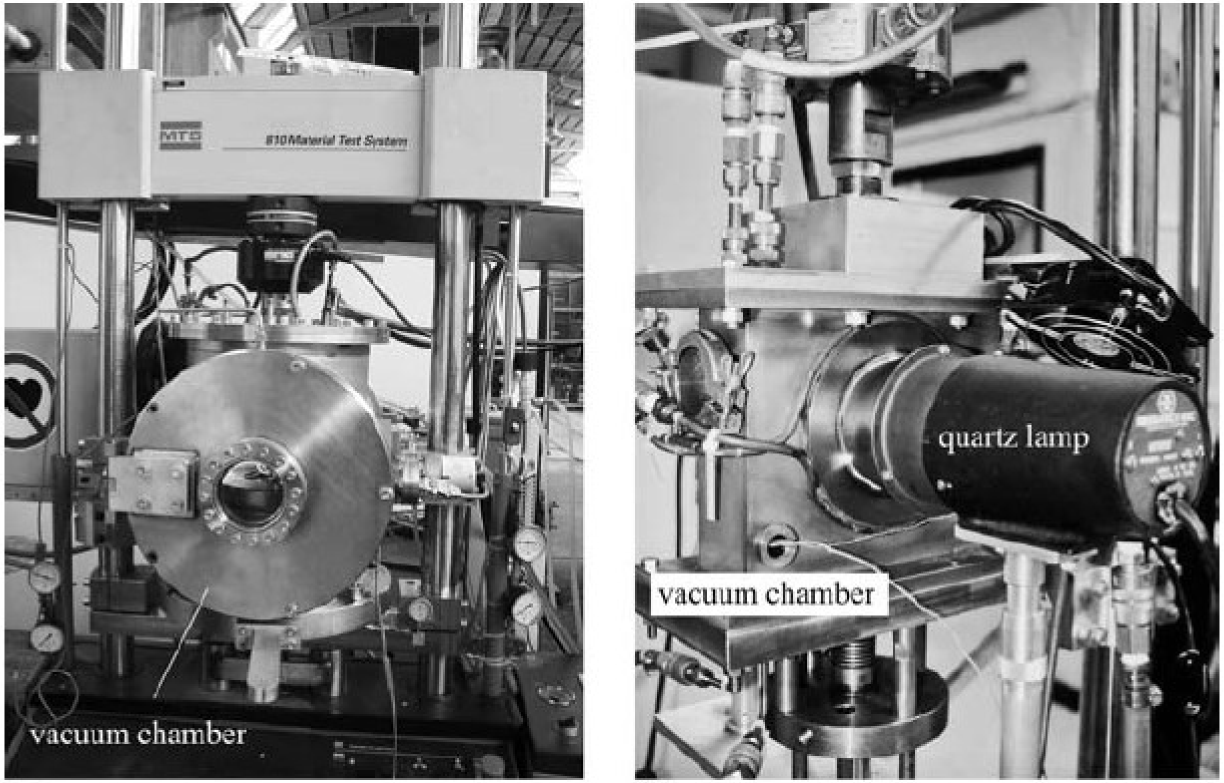
Modern servo-hydraulic push–pull testing system

Servo-hydraulic materials test



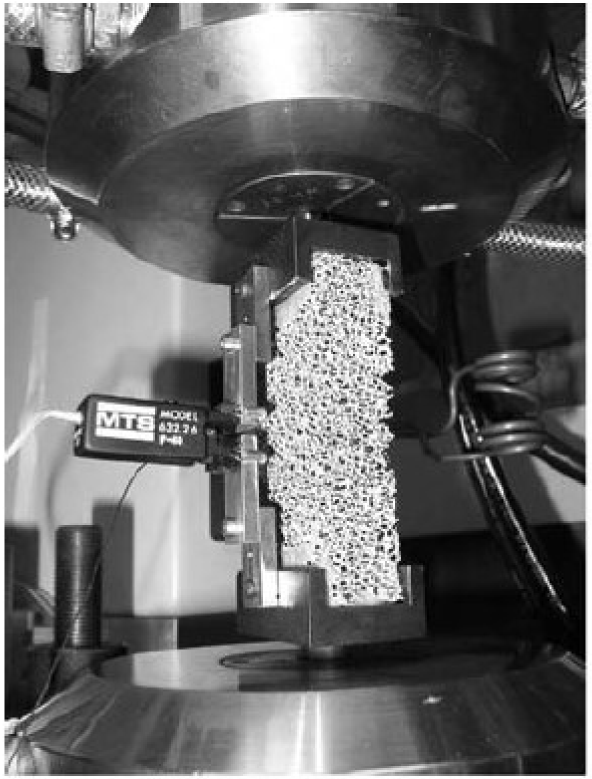
Schematic representation of the working principle of servo-hydraulic materials testing systems.

High-temperature fatigue test



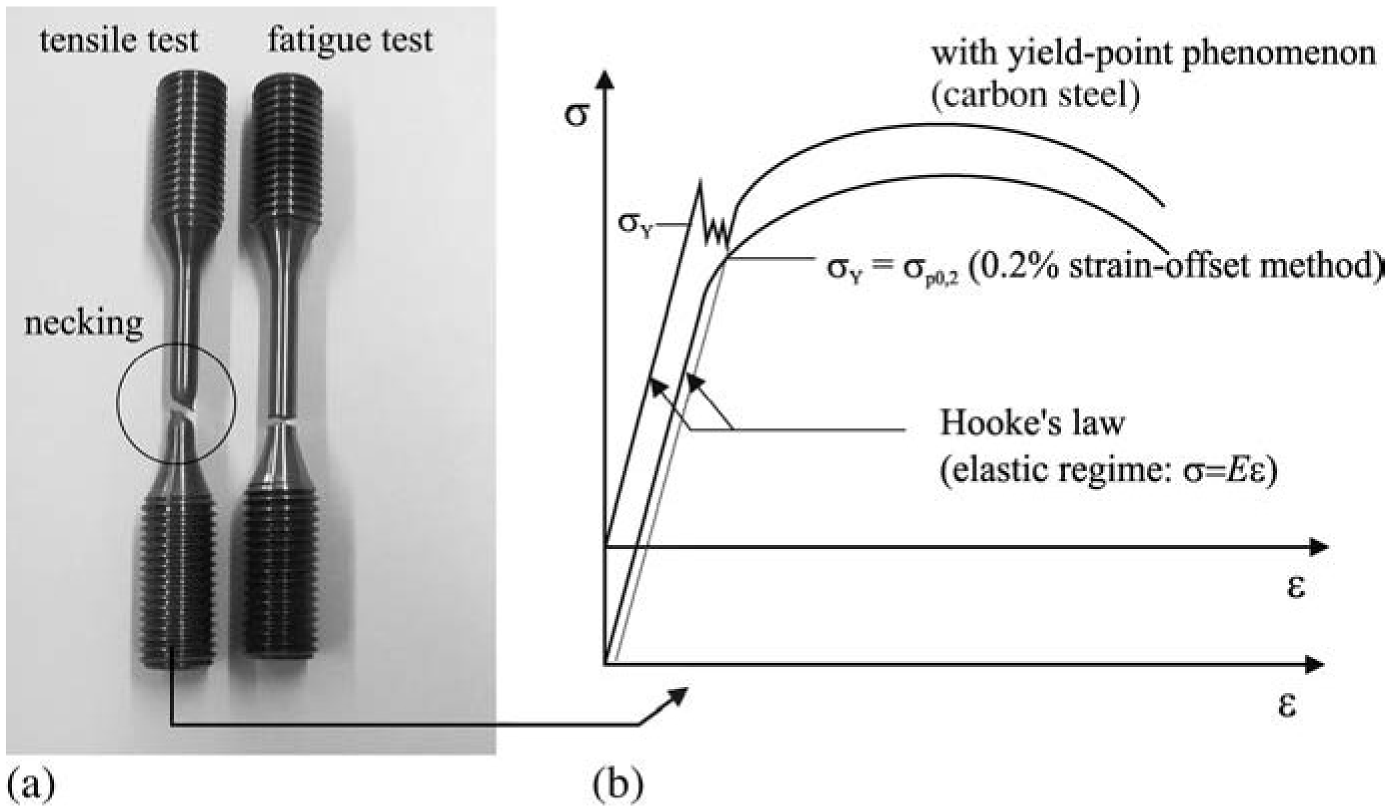
Experimental setup for high-temperature fatigue testing under vacuum or defined-atmosphere

Fatigue test of Al sponge



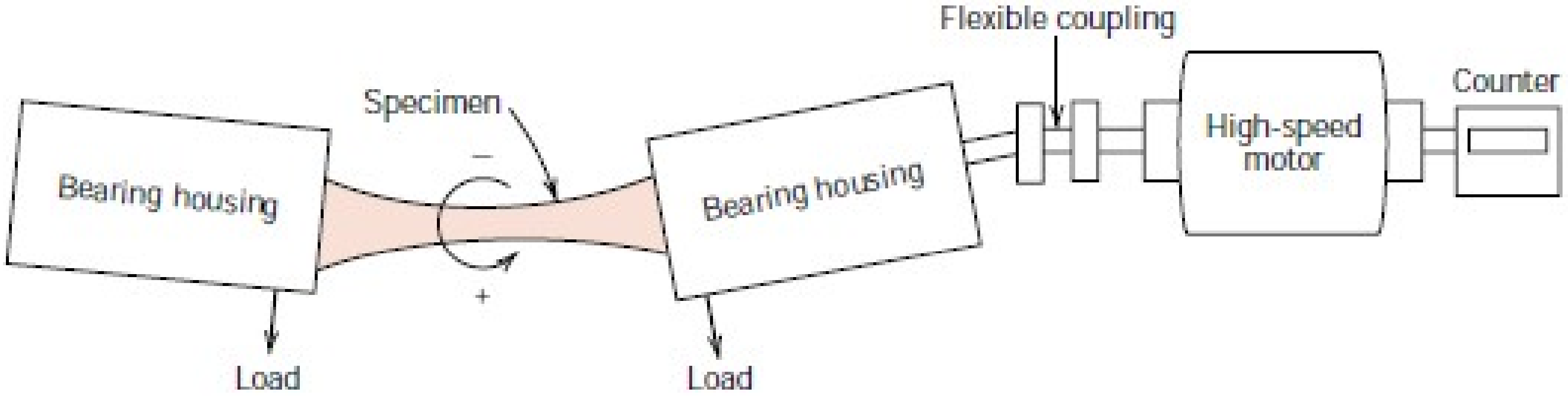
Experimental setup for fully reversed fatigue testing of open-cell Al sponge

Comparison of tensile and fatigue test



(a) Comparison of two cylindrical specimens broken during a monotonic tensile test and broken during fatigue. (b) Stress vs. strain diagram for monotonic tensile tests.

S-N Curve



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

S-N Curve

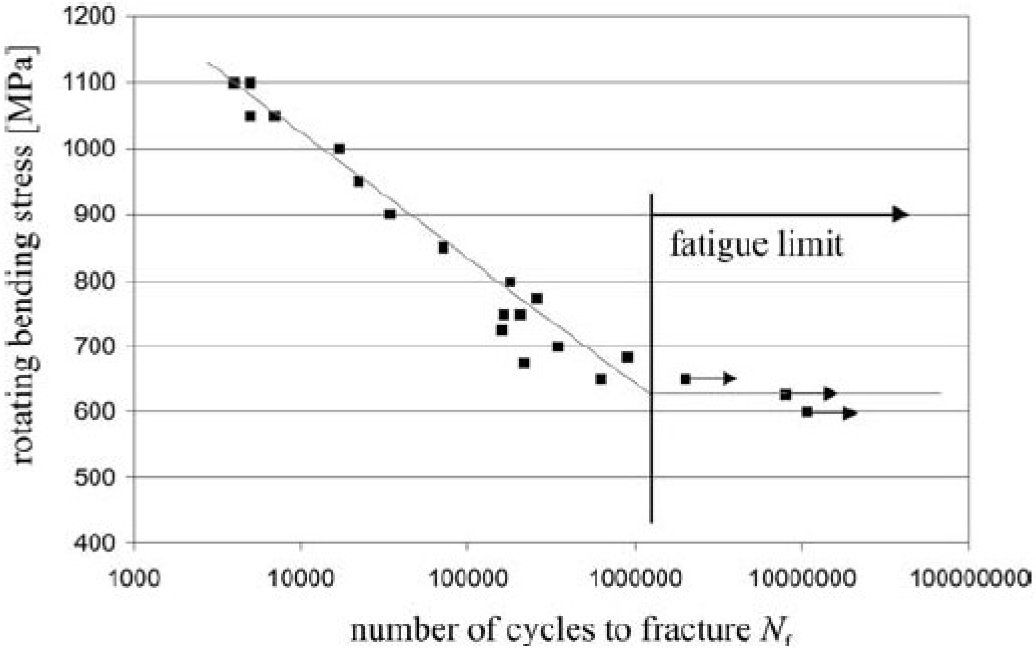
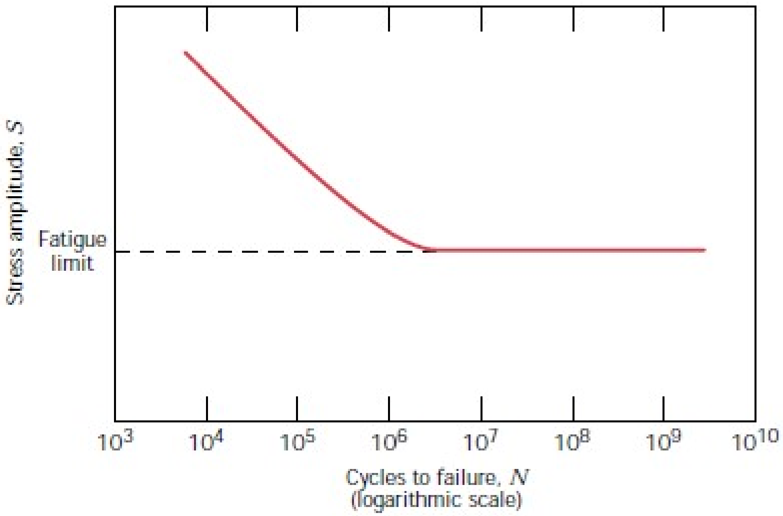


Fig. 2.2 Wöhler diagram of PH 15-5 precipitation-hardened steel (X3CrNiCuNb 15 5 4) showing rotating bending stress vs. number of cycles to fracture.

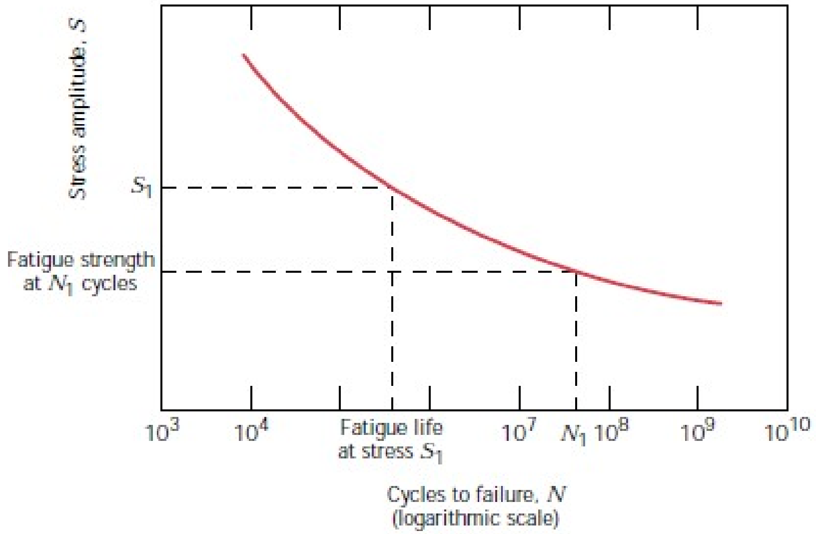
Fatigue / *endurance limit* : *The stress value below* which fatigue failure will not occur.

fatigue limit



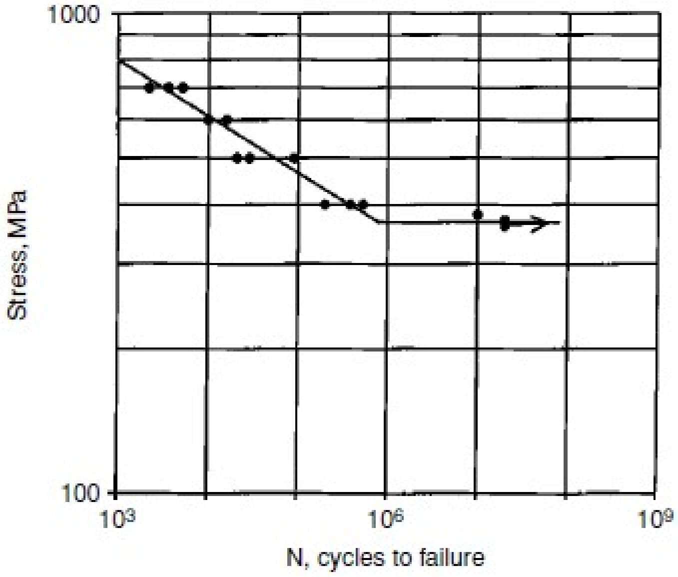
Fatigue life N_f:. *It is the number of cycles to cause failure at a specified stress* level, as taken from the *S–N plot*

fatigue strength

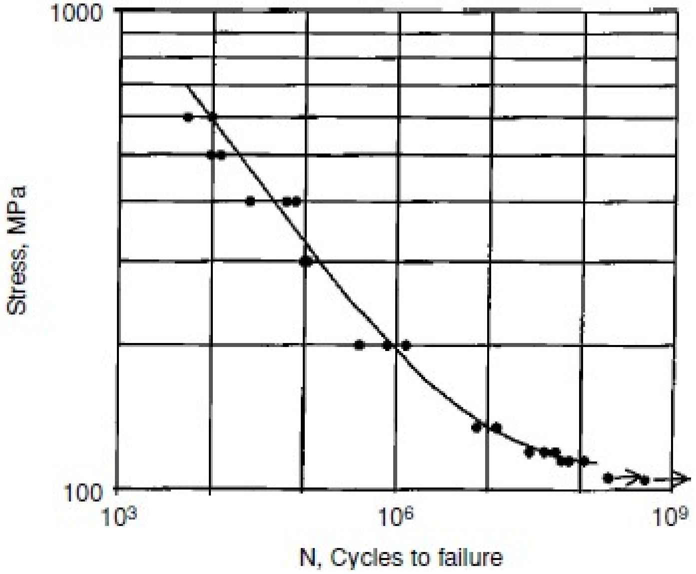


Fatigue Strength: The stress level at which failure will occur for some specified number of cycles (e.g., 5x10^7 cycles).

The *S–N curve for annealed* 4340 steel. Typically the break in the curve for a material with fatigue limit occurs at about 106 cycles.



The *S–N curve for an aluminum* alloy, 7075 T-6. Note that there is no true fatigue limit.



The fatigue life N_f , the total number of cycles to failure is sum of the number of cycles for crack initiation and crack propagation

$$N_f = N_i + N_p$$

The contribution of the final failure step to the total fatigue life is insignificant since it occurs rapidly.

Relative proportions to the total life of N_i and N_p depend on the particular material and test conditions.

Types of Fatigue

- High Cycle Fatigue (HCF)
- Low Cycle Fatigue (LCF)

In High Cycle Fatigue a large fraction of the fatigue life is utilized in crack initiations (N_i). ($N_f > 10^5$)

In Low Cycle Fatigue, the propagation step predominates (N_p). ($N_f < 10^5$)

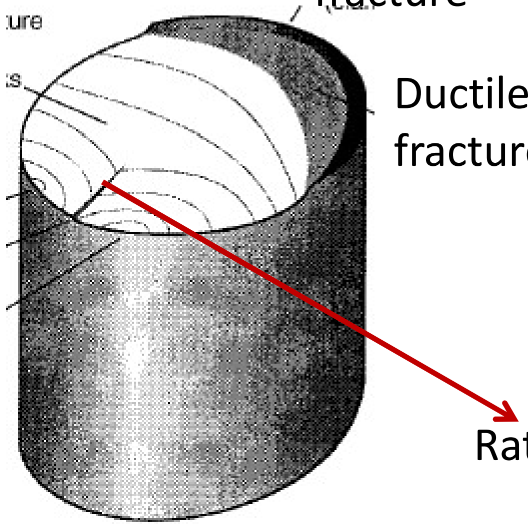
Differentiate LCF and HCF

Low Cycle Fatigue (LCF)	***High Cycle Fatigue (HCF)***
Fatigue failure occurs in low number of cycle	*Fatigue failure occurs in high number of cycle*
Occurs by high stress &/ fluctuation	*Occurs by low stress &/ fluctuation*
Larger proportions of the total cycles to failure are involved in crack propagation.	*Larger proportions of the total cycles to failure are involved in crack initiation.*
Undergoes only elastic deformation before failure	*Undergoes elastic and small amount of plastic deformation before failure*

Macro-fractography of Fatigue Failure

Clamshell or Beach marking:

- Visual examination
- Each marking corresponds to change in stress amplitude



Brittle fracture

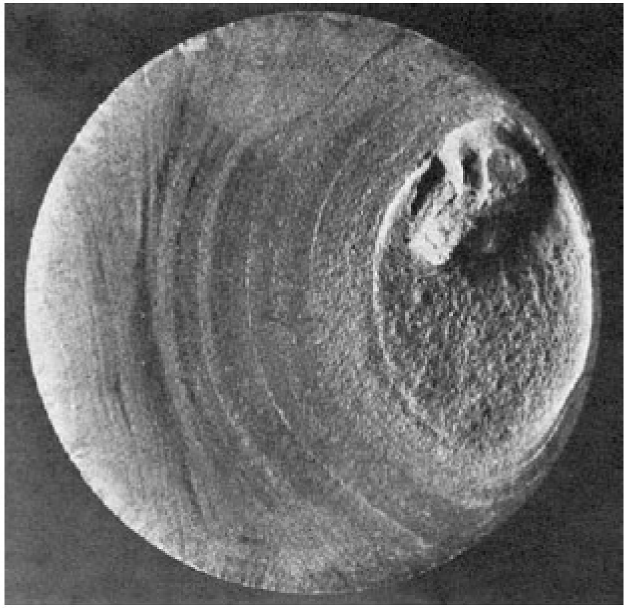
Beach marks

Ductile fracture

Origin

Origin

Ratchet Lines



Ratchet lines represent the junction surfaces between the adjacent cracks

When individual fatigue cracks join together, a ridge is formed between them.

Short ridges along a free edge between relatively flat fracture surfaces are called ratchet marks which are indicative of multiple initiation sites.

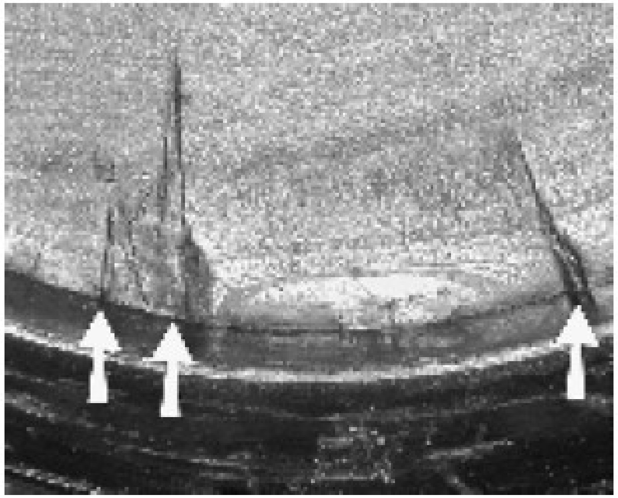


Fig.: Observation of ratchet marks between distinct surface origin sites in low alloy steel shaft.

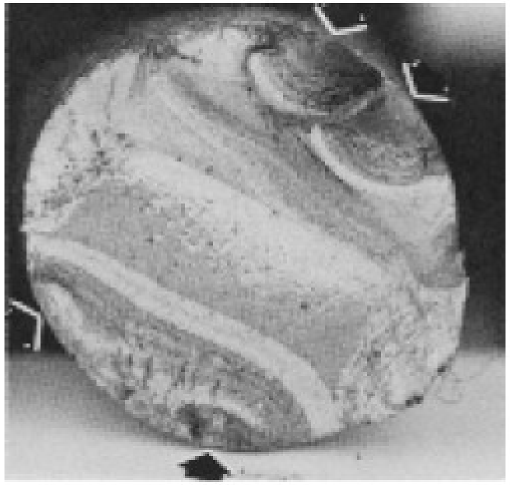


Fig.: Beach marks on quenched and tempered alloy steel pin fractured in low-cycle fatigue

Surface effects on fatigue life

Three catagories

- Surface roughness or stress raiser at the surface
- Changes in the surface properties
- Changes in the residual stress condition of surface

In addition Oxidation and corrosion also plays a role.

Surface Roughness

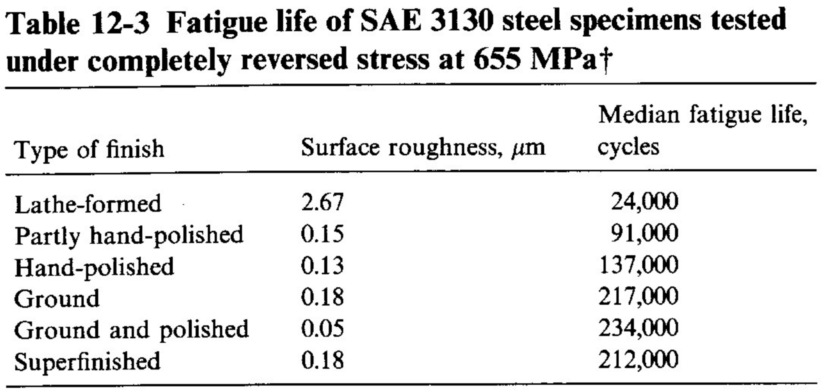
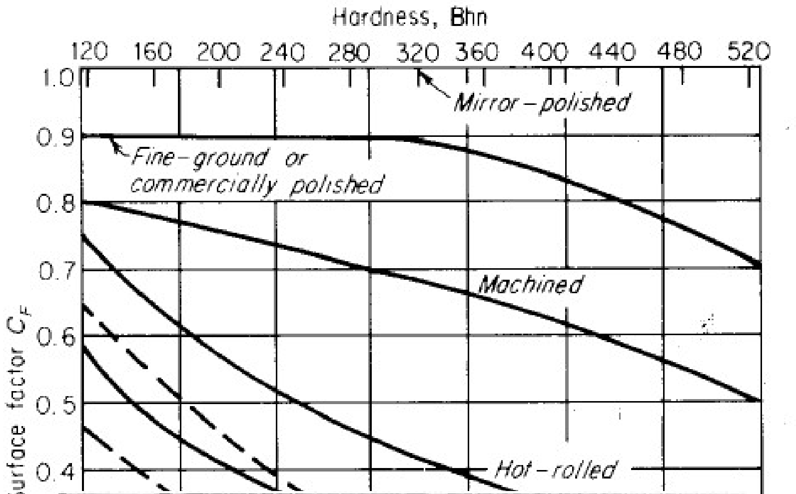
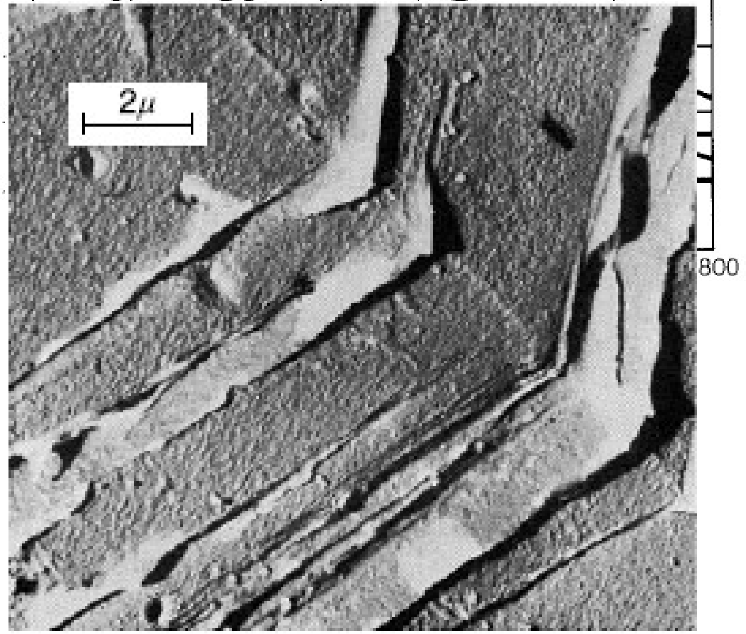


Table 12-3 Fatigue life of SAE 3130 steel specimens tested under completely reversed stress at 655 MPa†

Type of finish	Surface roughness, μm	Median fatigue life, cycles
Lathe-formed	2.67	24,000
Partly hand-polished	0.15	91,000
Hand-polished	0.13	137,000
Ground	0.18	217,000
Ground and polished	0.05	234,000
Superfinished	0.18	212,000





- Surface scratches, dents machining marks or fillets act as stress raiser.
- Corrosion attack the roughness of the surface.
- Extrusion and intrusion makes surface discontinuities which are precursors for fatigue crack formation.

Remedy: Surface should be fine polished.

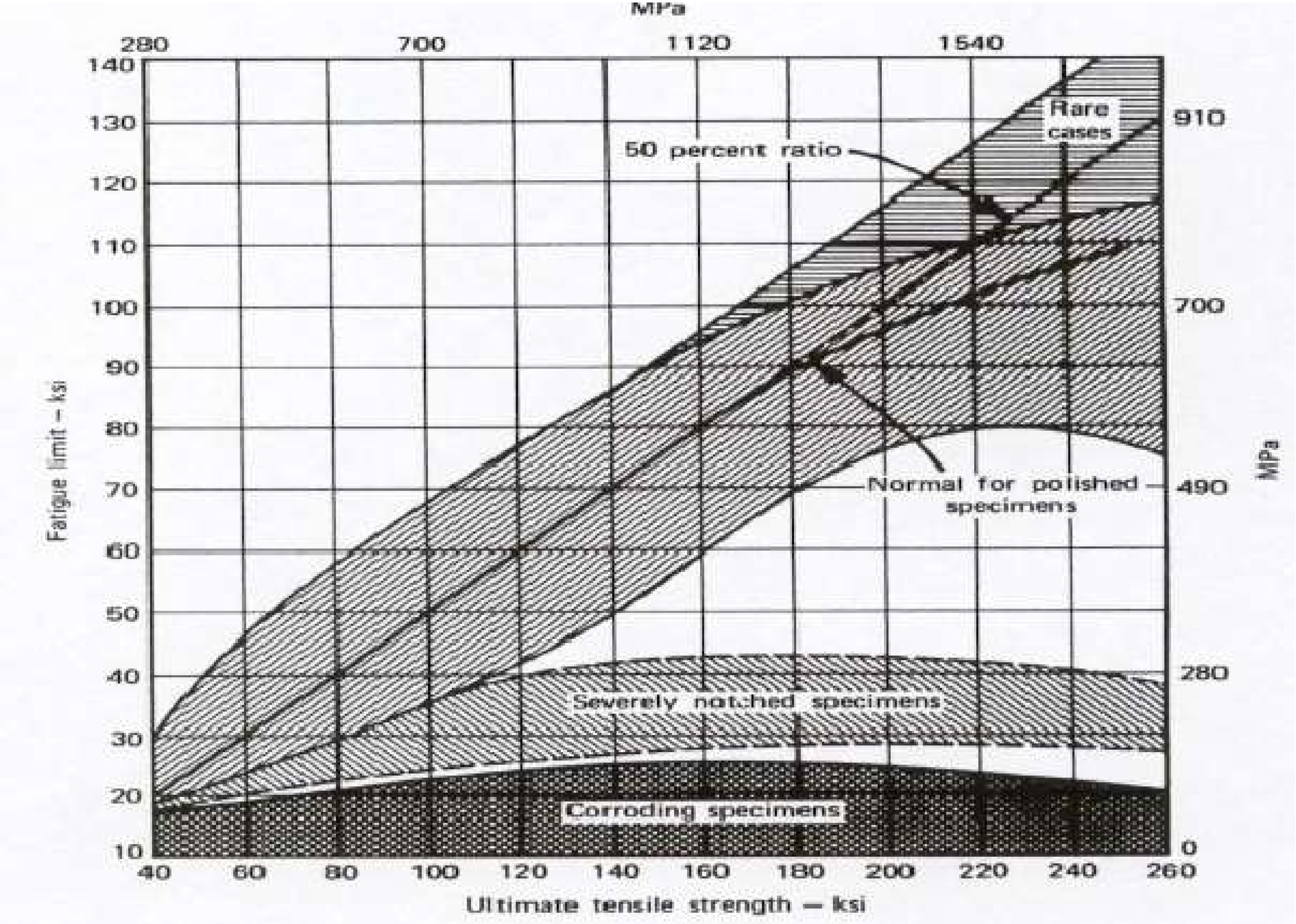
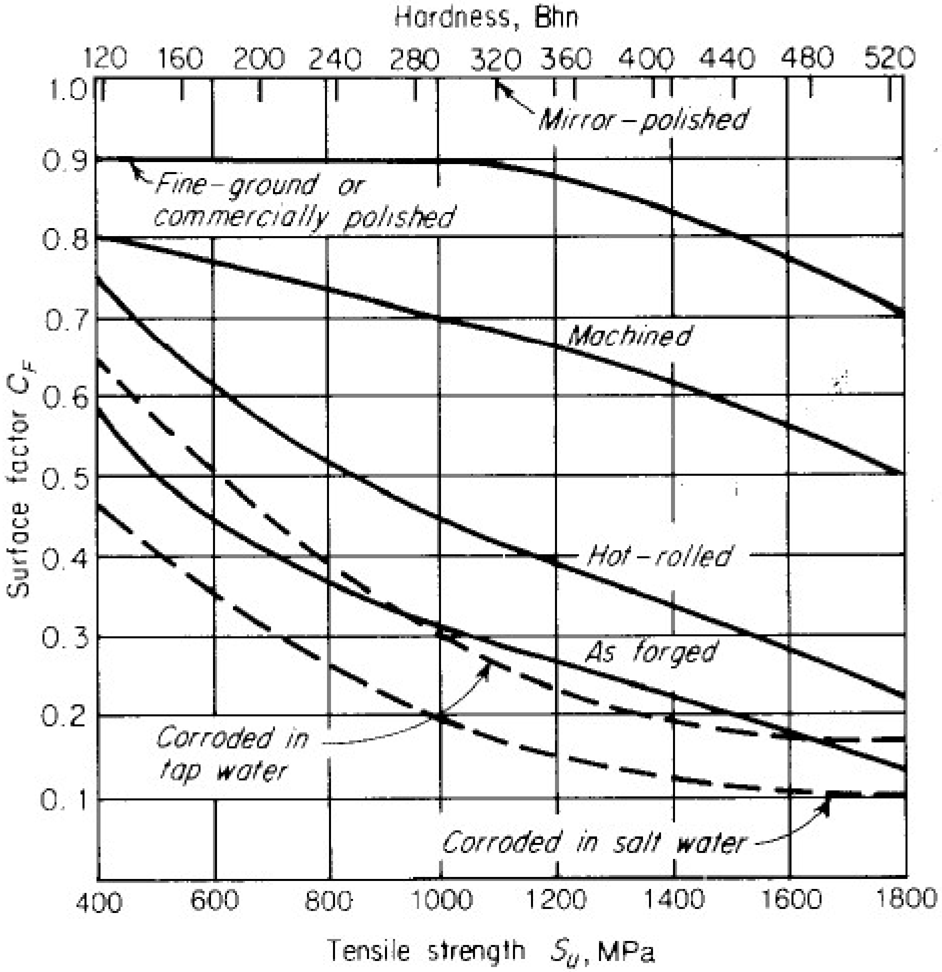

MPa
280
700
1120
1540
Fatigue limit – ksi
140
130
120
110
100
90
80
70
60
50
40
30
20
10
910
700
490
280
0
MPa
Rare cases
50 percent ratio
Normal for polished specimens
Severely notched specimens
Corroding specimens
40
60
80
100
120
140
160
180
200
220
240
260
Ultimate tensile strength – ksi

Figure : Reduction factor for fatigue limit of steel due to various surface treatments



Changes in Surface Properties

- Decarburization
- Soft Al coating over age-hardenable al alloy sheet
- Generally electroplating decreases the fatigue life of the component. Since coating can induce large residual stress, porosity, adhesion and hardness on the surface

Surface Treatments:

- Mechanical Treatments
    - Shot peening, cold rolling, grinding and polishing
- Thermal Treatments
    - Flame and induction hardening
- Surface coatings
    - Case hardening, nitriding and plating
- Nitriding
    - For notch specimen nitriding improve the fatigue properties

Surface Residual Stress

- Compressive residual stress on the surface improve the fatigue properties.

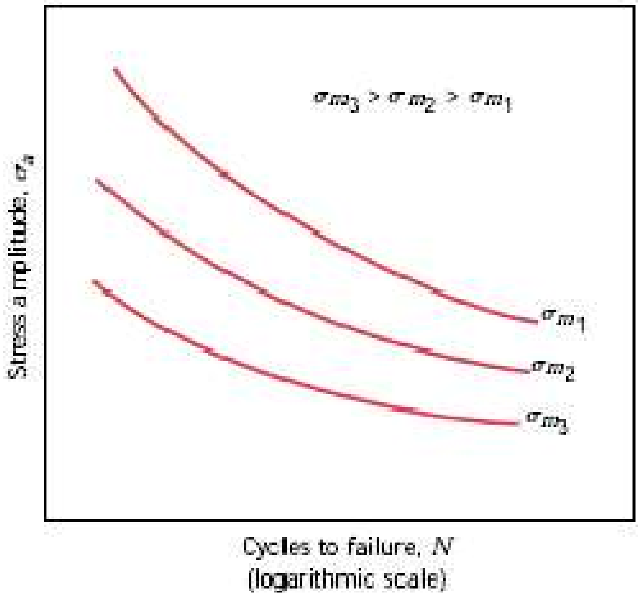
Shot peening:

- small and hard particles (shot)about 0.8 to 0.8mm diameter are blasted onto the surface
- Thin layer of compressive residual stress developed
- Benefit is more for higher strength alloys
- More effective for components have stress concentration or stress gradient.

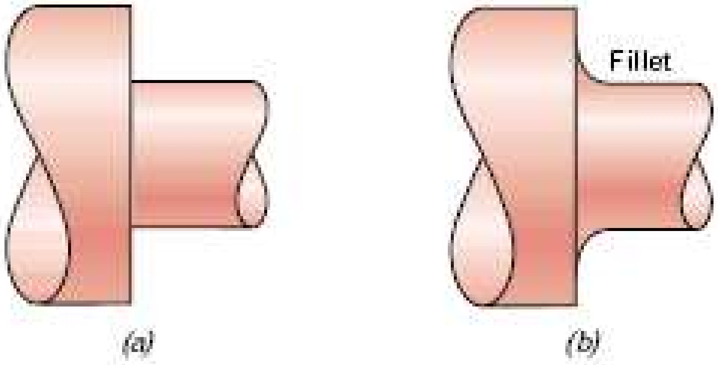
Factors affecting fatigue life

- **Mean stress**

  Fatigue life decreases with increasing mean stress



- **Design factors:** Any notch or geometrical discontinuity can act as a stress raiser and fatigue crack initiation site
  - The structural irregularities or sudden contour changes leading to sharp corners have to be eliminated



- **Surface effects:**

  Most of cracks leading to fatigue failure originate at surface positions

  - Surface treatments:
    - residual compressive stress within a thin outer surface layer. Ex.:shot peening
    - Case hardening
    - Carburizing, nitriding

- Metallurgical variables
  - If the tensile strength increases, fatigue limit also increases.
  - Fatigue ratio = fatigue limit/tensile strength
  - fatigue ratio = 0.5, 0.35 and 0.2 to 0.3 for ferrous, nonferrous and notched components
  - Fatigue life α (grain diameter)$^{-1/2}$

- Metallurgical variables
  - Fatigue is structure sensitive than tensile strength.

  Comparing plain carbon eutectoid steel (which has pearlite) and spheroidite, shows that pearlitic structure have lower fatigue limit than spherodite structure.

  - Stacking fault energy.

  High SFE→ cross slip is easier → dislocation move easily→ large plastic deformation zones → promotes fatigue initiation and propagation

  Low SFE → cross slip is difficult → dislocation move on the same plan→ limit the plastic deformation → limits the fatigue damage

Corrosion Fatigue

- The simultaneous action of cyclic stress and chemical attack is known as corrosion fatigue.
- Corrosive environments have a deleterious influence and produce shorter fatigue life.
- Small pits may form as a result chemical reaction between the environment and material, which serve as points of stress concentration and acts as crack nucleation sites.
- In addition, crack propagation rate is also enhanced.

Remedy:

- Use the materials should have high corrosion resistant properties like stainless steel, bronze or beryllium copper.
- Protection of metal from the corrosive environment by metallic or nonmetallic coatings is successful. Zinc and cadmium coatings on steel and aluminum alloy coating are an example.
- The formation of the surface compressive residual stresses reduces corrosion fatigue. Shot peening and nitriding effective in corrosion fatigue.
- The elimination of stress concentration design is very important for corrosion fatigue

Thermal Fatigue

- Fatigue failure produced by fluctuating thermal stresses under conditions where mechanical stress is absent.
- Change in dimensions of the component due the result of a temperature change induces thermal stresses.
- The thermal stress developed by a temperature change ΔT is

$$\sigma = \alpha E \Delta T$$

  Where α – linear thermal expansion coefficient & E- elastic modulus

- Failure due to cyclic thermal stress of a lower magnitude is called as **thermal fatigue**.
- Thermal fatigue failures are frequently present in high temp. equipment.
- Austenitic stainless steel is particularly sensitive to thermal fatigue due low thermal conductivity and high thermal expansion.

Structural Features of Fatigue

- Crack initiation – where a small crack forms at some point of high stress concentration
- Crack Propagation or growth – increment in crack length with each cycle
- Ultimate final failure – crack length reaches critical size and failure occurs rapidly

$$N_f = N_i + N_p$$

Fatigue Crack Initiation Mechanism

- Fatigue cracks are initiated at heterogeneous nucleation sites
  - preexistent (such as inclusions, gas pores or local soft sports) or generated during the cyclic straining process.
- Extrusions and intrusions or notches acts as nucleation site
- Persistent slip bands (PSB) soften the surface below the extrusions and intrusions relative to the matrix.
- During cyclic loading, the work hardening near the surface is higher than the interior.
- The design features includes grooves, holes, keyways, threads, and so on can act a crack nucleation site.

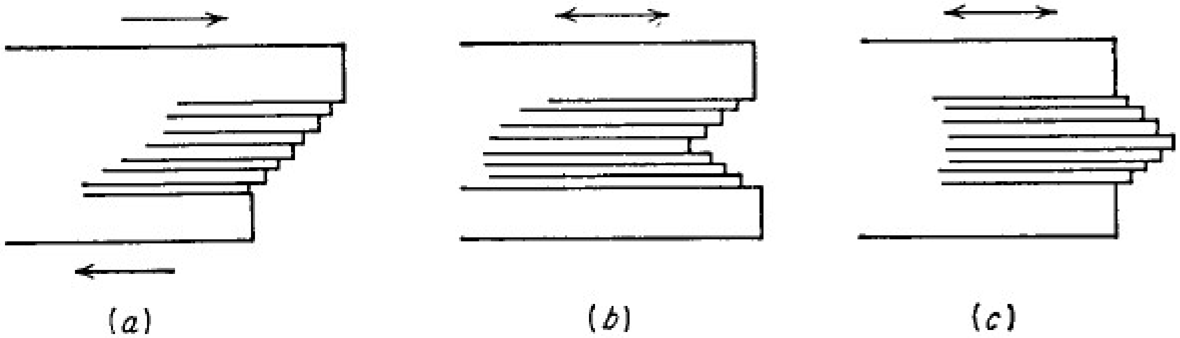
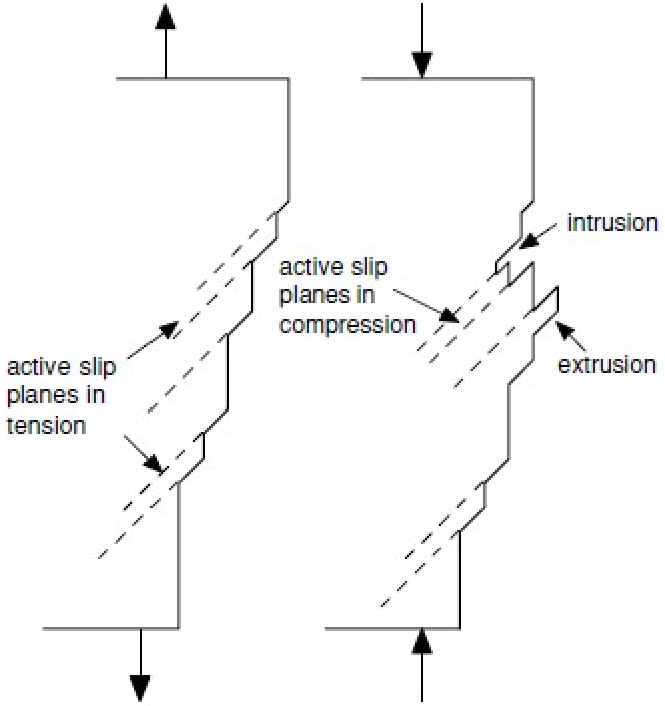


Figure 12-15 W. A. Wood's concept of microdeformation leading to formation of fatigue crack. (*a*) Static deformation; (*b*) fatigue deformation leading to surface notch (intrusion); (*c*) fatigue deformation leading to slip-band extrusion.

Persistent slip bands:

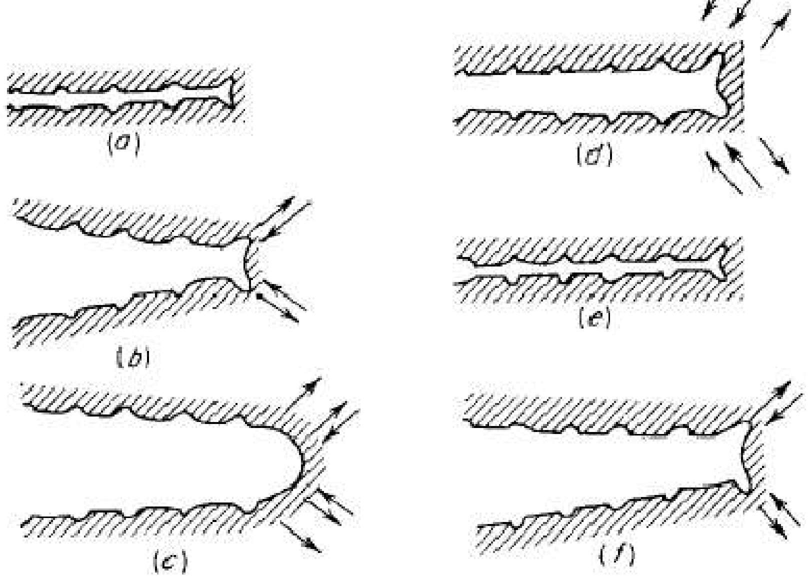
beneath the surface are associated with these intrusions and extrusions

- These intrusions and extrusions are the result of slip on one set of planes during the compression half-cycle and slip on a different set of planes during the tension half-cycle
- Fatigue cracks initiate at the intrusions and grow inward along the persistent slip bands.



Intrusions and extrusions can develop if slip occurs on different planes during the tension and compression portions of loading.

Stage II: Plastic blunting process



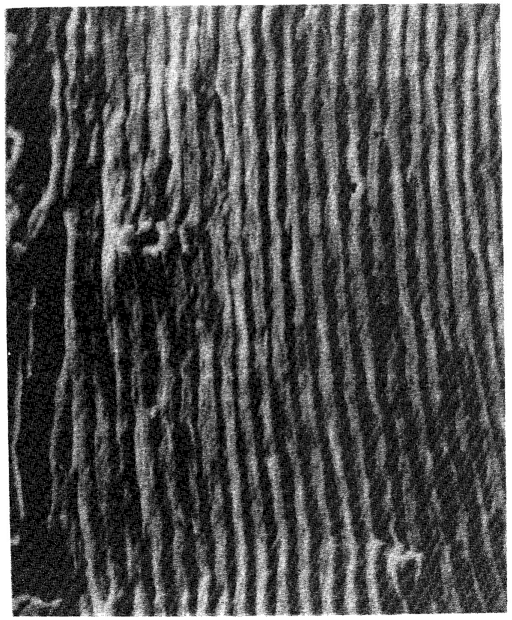


Fig.:Fatigue striation in β-annealed Ti-6Al-4V alloy