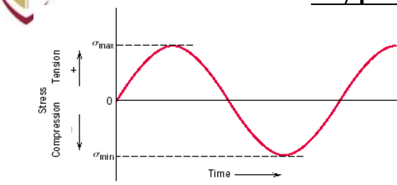
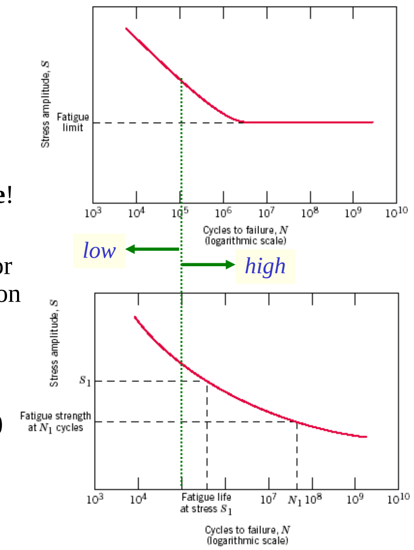
Outline

- Fatigue - *Review*
- Fatigue crack initiation and propagation
- Fatigue fracture mechanics
- Fatigue fractography
- Crack propagation rate
- Example
- Factors affecting fatigue
  - *- Design factors*
  - *- Surface effects*
  - *- Environmental effects*

Types of Fatigue



- Occurs under *dynamic* stresses
- **90% of metal failures occur in fatigue**!
- Occurs in all kinds of materials
- Usually breaks **…………………**; no, or very little, observable plastic deformation (*some micro-deformation*).



low cycle fatigue

- high loads → short N_f (10^4-10^5 cycles)

high cycle fatigue

– low loads → long N_f (>10^5)

Variability in Fatigue Data

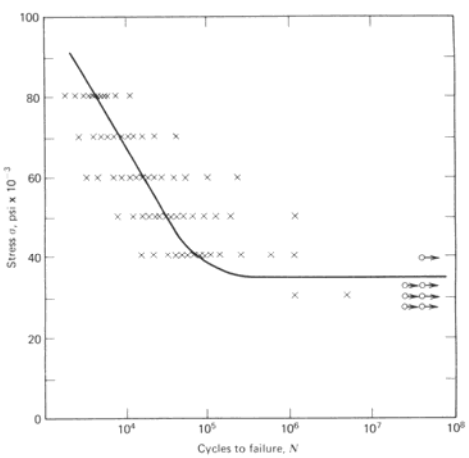


FIGURE 7.13. Plot of stress-cycle (*S-N*) data as it might be collected by laboratory fatigue testing of a new alloy.

- Fatigue data is normally shown as ……….. values.
- It is very useful to evaluate the …………….. of fatigue failure at certain stress level. This is more accurate than "average" values.

Crack Initiation and Propagation

- Three steps:
  – ……………..
  – ……………..
  – final failure (when area decreases sufficiently)
- Fatigue life:

$$N_f = N_i + N_p$$

  – N_i is the number of cycles to initiate fracture
  – N_p is the number of cycles to propagate to failure
- *high cycle fatigue* (…… stress levels)*:*
  – most of the life is spent in **crack initiation** and N_i is *high*
- *low cycle fatigue* (…….. stress levels)*:*
  – propagation step predominates and N_p>N_i

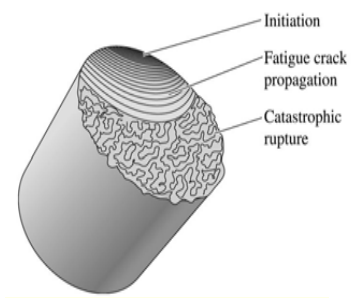


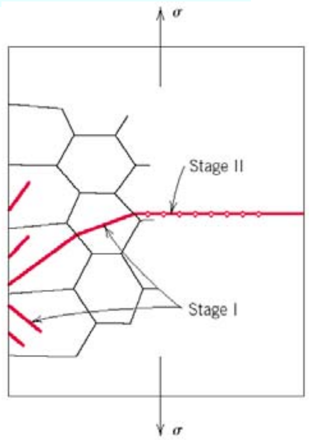
Figure 6.48 Schematic rep. of a fatigue fracture surface in a steel shaft. When the crack length exceeds a critical value at the applied stress, catastrophic rupture occurs. *"The science and Engineering of Materials" 4th edition by D.R. Askeland and P.P. Phule.*

Fracture Mechanisms

Cracks that cause fatigue failure almost always initiate/nucleate at ***component surface*** at some stress concentration: scratches, dents, fillets, keyways, threads, weld beads/spatter, etc

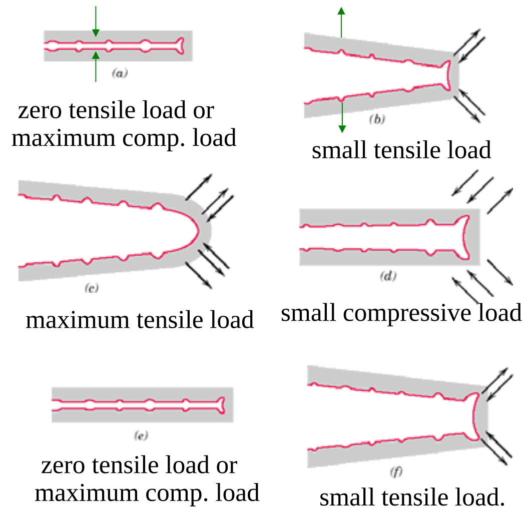
On very smooth surfaces, ***SLIP steps*** can act as stress raisers.

- Cracks propagate in 2 stages
- In ***stage I***, crack tends to grow initially along crystallographic **planes of high shear stress**: *high stresses and notches tend to shorten this stage.*
- It may only propagate over a few grains.
- Length of *stage I* is controlled by presence of stress raisers such as:
  - ……………
  - ……………
  - ……………
- ***stage II*** - crack growth rate increases (*perpendicular to tensile stress direction*)



Fracture Mechanisms

• Fatigue crack propagation mechanism (stage II) by repetitive crack tip plastic blunting and sharpening;



- Double notch at crack tip, extends along …….. planes
- under tensile loading and then blunts due to deformation
- Compression closes crack and shear occurs in opposite sense
- leading to sharp notches again
- And then again and again…

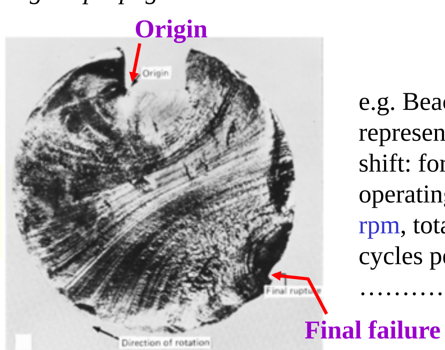
Sometimes this process leaves markings on the fracture surface; …………. and/or …………….
Indicate position of crack tip at some point in time.

Fractography of Fatigue

- *Beachmarks* are *macroscopic* evidence of fatigue and can be observed with the **naked** eye

→ classical fatigue fracture surface (*clam-shell* markings).

- They are always concentric with the fracture origin.
- They are caused by interrupted loading, e.g. machine being switched on and off during *stage II propagation.*



These marks DO NOT indicate the crack growth per stress cycle.

e.g. Beachmarks may represent an 8hr daily shift: for a shaft operating at 3000 rpm, total number of cycles per day is ……………

Fractography of Fatigue

However, *fatigue striations* are microscopic and require a *scanning electron microscope (SEM)* to observe them.

- Each beachmark is composed of thousands of striations.
- Each striation results from incremental advance of the fatigue crack during stage II.
- Propagation region of crack is usually relatively smooth and often discoloured in relation to the *final fracture.*

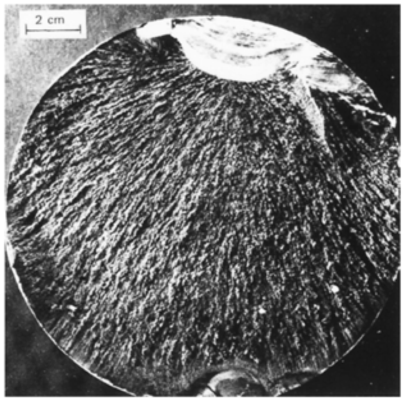
- Each of these microscopic striations is usually caused by one stress cycle.
- If the stress ………., the spacing usually ………….
- Can count striations/mm to get ESTIMATE of crack growth rate.

Fractography of Fatigue

- **Beachmarks** and **striations** will <u>not</u> appear on that region over which the **rapid failure** occurs.
- Rather, the rapid failure may be either <u>ductile</u> or <u>brittle</u>;

- evidence of plastic deformation will be present for ductile failure and absent for brittle failure.

- This region of failure may be noted in this figure.



Fractography of Fatigue

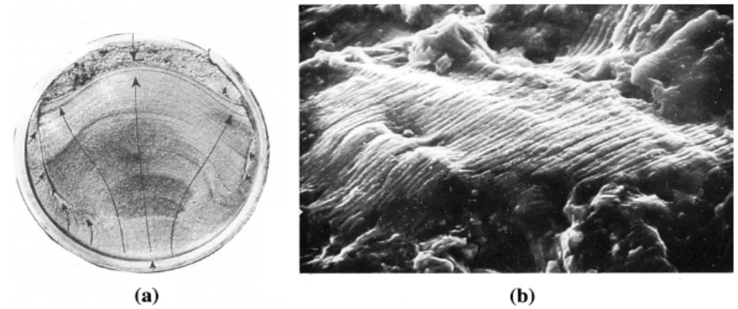


Figure 6.47 Fatigue fracture surface. (a) At low magnifications, the beach mark pattern indicates fatigue as the fracture mechanism. The arrows show the direction of growth of the crack front, whose origin is at the bottom of the photograph. (b) At very high magnifications, closely spaced striations formed during fatigue are observed (x 1000).

From *"The science and Engineering of Materials" 4th edition by D.R. Askeland and P.P. Phule.*

Fatigue Crack Propagation Rate

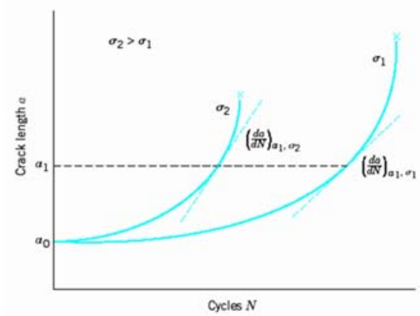
- Results of fatigue studies have shown that the life of a structural component may be related to the rate of crack growth.
- During stage II propagation, cracks may grow from a barely perceivable size to some critical length.
- There are experimental techniques that can be employed to monitor crack length during the cyclic stressing.
- Data are recorded and then plotted as crack length *a* versus the number of cycles *N*.

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

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

From fracture mechanics:

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



(1) initially, growth rate is small, but increases with increasing ………………..

(2) growth rate increases with increasing applied stress level and for a specific crack length.

$\Delta K = K_{max}$-K_{min} (stress intensity not K_{Ic}). If σ_{min} is compressive, it closes the crack so σ_{min} and K_{min} are taken as being zero.

Fatigue Crack Propagation rate

rapid crack growth just prior to final fast fracture

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

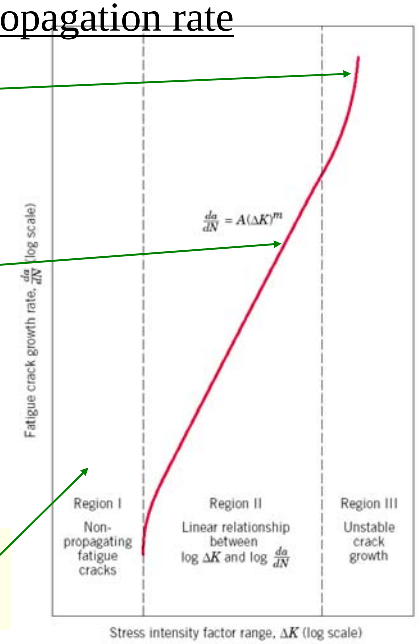
and then taking logs of both sides:

$$\log\left(\frac{da}{dN}\right) = m\log\Delta K + \log A$$

gives straight line of slope m and intercept, log$A$

- crack grew even though $K_{max} < K_c$
- m is typically from 1 to 6
- crack grows faster if
  - $\Delta\sigma$ increases
  - crack gets longer
  - loading freq. increases.

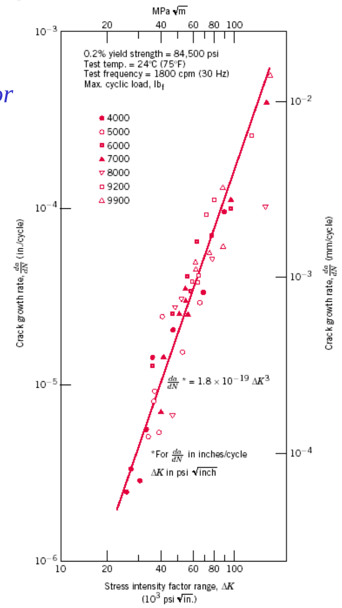
At low stress levels and/or small crack sizes, pre-existing cracks will not grow with cyclic loading.



Fatigue Crack Propagation Rate

Logarithm crack growth rate versus logarithm stress intensity factor range for a Ni–Mo–V *steel.*

- So, a straight-line segment will result when log(*da/dN*) versus log *K* data are plotted.
- The slope and intercept correspond to the values of *m* and log *A*, respectively.
- *A & m are material constants.*



Fatigue Crack Propagation Rate

One goal of failure analysis is to ……… **fatigue life** of a component, given its service conditions.

We are able now to develop analytical expression for Failure by integrating in the linear region:

$$dN = \frac{da}{A(\Delta K)^m} \quad \text{which when integrated gives:}$$

$$N_f = \int_0^{N_f} dN = \int_{a_0}^{a_c} \frac{da}{A(\Delta K)^m}$$

Limits are initial flaw length, a_o which can be determined by NDT, *and critical crack length a_c, which can be determined from fracture mechanics*

$$\text{Substitution for } \Delta K \text{ gives: } N_f = \int_{a_0}^{a_c} \frac{da}{A(Y\Delta\sigma\sqrt{\pi a})^m} = \frac{1}{A\pi^{m/2}(\Delta\sigma)^m}\int_{a_0}^{a_c}\frac{da}{Y^m a^{m/2}}$$

- *This results when assuming that* Δσ is ……….. (which often is not).
- Also it ignores the time needed to initiate the crack.

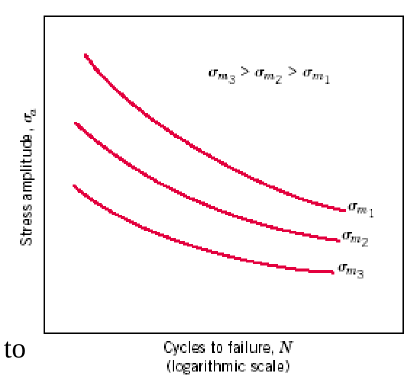
⇒ This analysis is only an **estimate**.

Example

A relatively large sheet of steel is to be exposed to cyclic tensile and compressive stresses of magnitudes 100 MPa and 50 MPa, respectively. Prior to testing, it has been determined that the length of the largest surface crack is 2.0 mm. Estimate the fatigue life of this sheet if its plane strain fracture toughness is 25 MPa√m and the values of *m* and *A* are 3.0 and 1.0 x 10^{-12}, respectively, for Δσ in MPa and *a* in m. Assume that the parameter Y is independent of crack length and has a value of 1.0.

Factors Affecting Fatigue Life

- Important factors are:
  - mean stress level
  - geometrical design
  - surface condition
  - metallurgical structure
  - environment



Mean Stress (σ_m)

- in *stress reversal*, $\sigma_m = 0$
- $\sigma_m > 0$, then S-N curve moves to lower values
- *fatigue life* ……………

Effect of Mean Stress

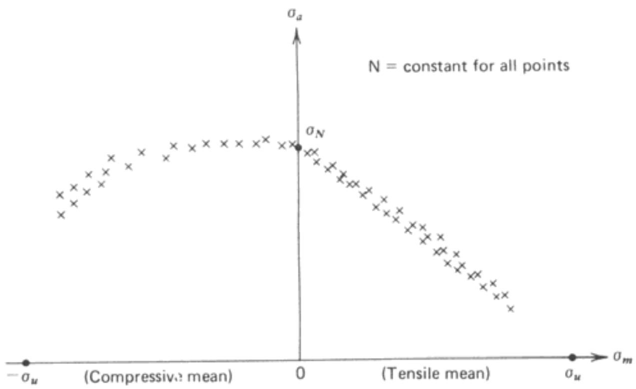
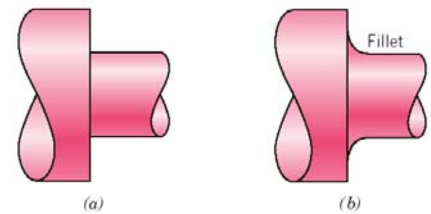


FIGURE 7.59. Simulated high-cycle fatigue failure data showing the influence of mean stress.

Geometrical Effects

Design Factors

- Component design is important.
- Notches or stress raisers act as crack initiation sites for fatigue:
  - *grooves, scratches, keyways, threads, corrosion pits etc.*
- Sharp corners and radii, or any discontinuity
  - *all increase the stress concentration.*
- Rounded fillets where gradual changes of diameter occur in shafts.



- Scratches and machining marks reduce the fatigue life.
- Surface polishing improves the fatigue properties.

Geometrical Effects

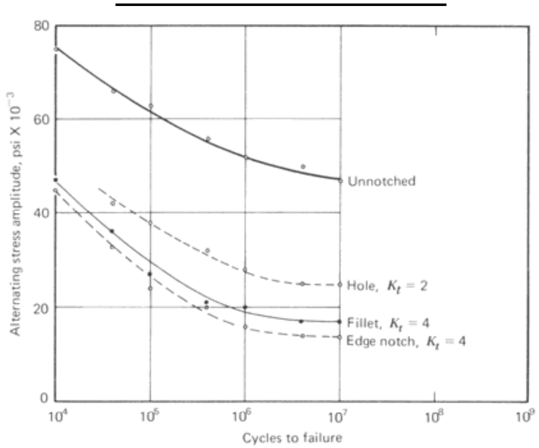


FIGURE 7.29. Effects of geometrical discontinuities on the *S-N* curve of SAE 4130 steel sheet, normalized, tested in completely reversed axial fatigue test. Specimen dimensions (t = thickness, w = width, r = notch radius): Unnotched: $t = 0.075$ inch, $w = 1.5$ inches. Hole: $t = 0.075$ inch, $w = 4.5$ inches, $r = 1.5$ inches. Fillet: $t = 0.075$ inch, $w_{net} = 1.5$ inches, $w_{gross} = 2.25$ inches, $r = 0.0195$ inch. Edge notch: $t = 0.075$ inch, $w_{net} = 1.5$ inches, $w_{gross} = 2.25$ inches, $r = 0.057$ inch. (Data from ref. 6)

Geometrical Effects

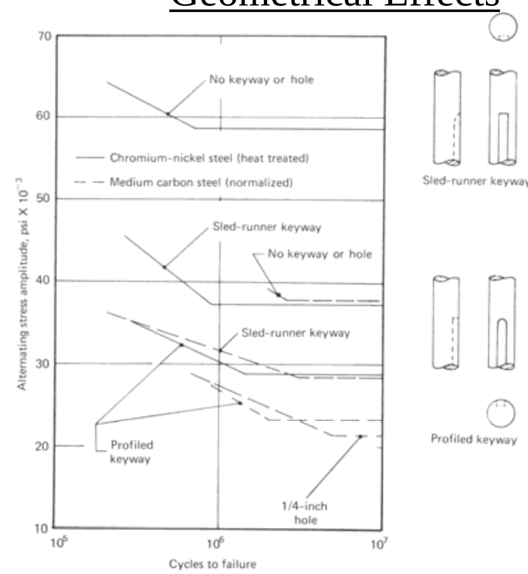


FIGURE 7.30. Effects of keyways and holes on the *S-N* curves of two types of steel. (Data from ref. 26), copyright ASTM; adapted with permission.)

Effect of Surface Conditions

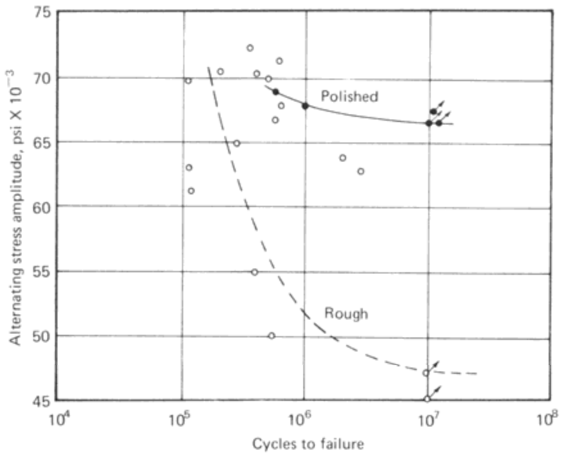


FIGURE 7.35. Effects of polishing die marks from the surface on the *S-N* curve of heat-treated chromium-molybdenum aircraft tubing. Tube dimensions: 0.5-inch O.D. with 0.065-inch wall. Heat treatment: oil quench 1625°F, draw 650°F.

Effect of Welding

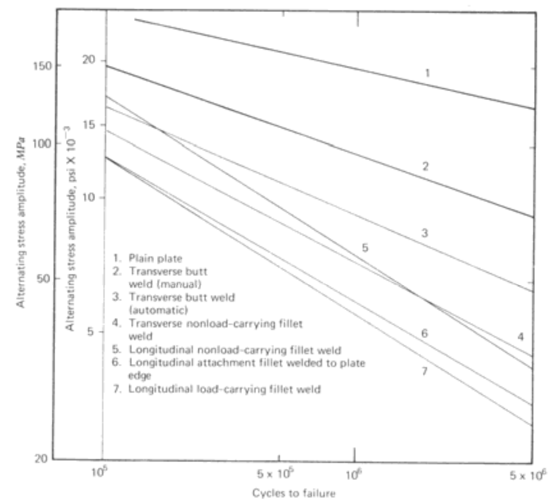
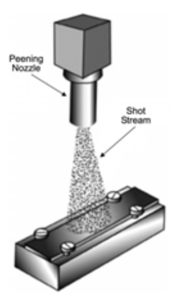
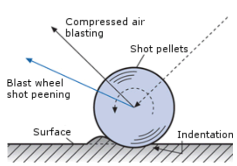
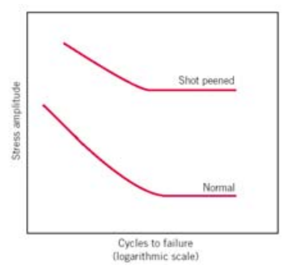


FIGURE 7.26. Effects of welding detail on the *S-N* curve of structural steel, with yield strength in the range 30–52,000 psi. Tests were released tension ($\sigma_{min} = 0$). (Data from ref. 24)

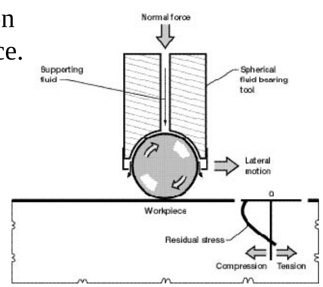
Surface Treatments







- ***Shot peening*** localized micro-plastic deformation using small steel balls (shot) impacting on surface.
- It increases the fatigue properties significantly (aircraft components etc) also increases yield strength, hardness and fatigue life.
- ***Work hardening*** occurs in the surface
  - …………… surface hardness
  - introduces a *residual* ………..…….. *stress*



Surface burnishing

Effect of Welding and Shot Peening

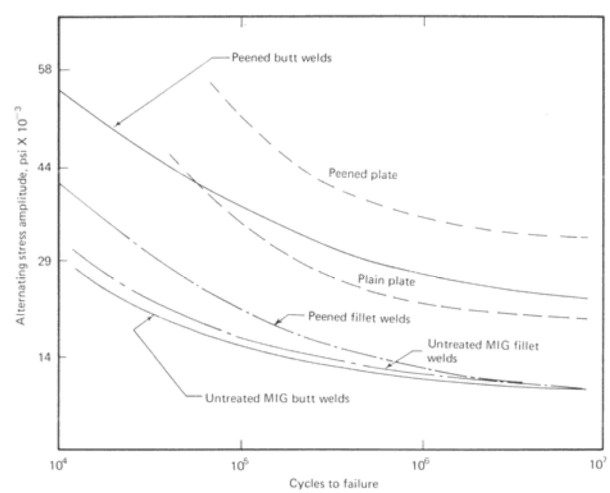


FIGURE 7.39. Effect of shot peening on the *S-N* curves for welded and unwelded steel plate. (Data from ref. 24)

Effect Shot Peening on Mean Stress

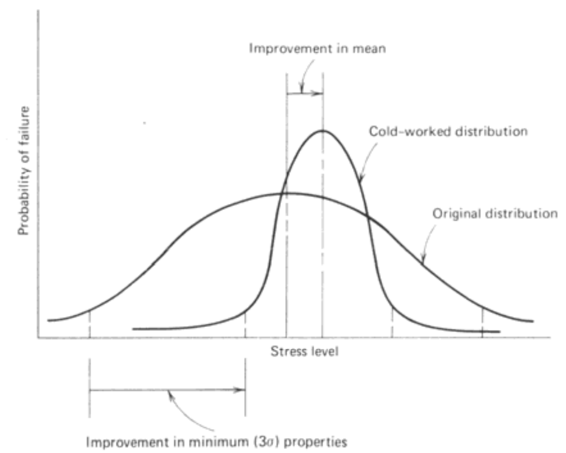
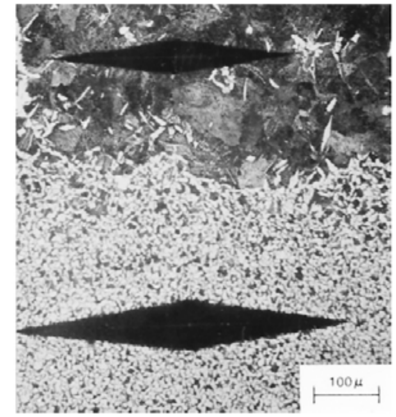


FIGURE 7.45. Illustration of improvement in minimum fatigue properties brought about by reduction in scatter through shot-peening or cold-rolling.

Surface Treatments

Case Hardening:

- Surface hardening through *carburizing or nitriding* increases surface strength and hardness.
- Iron carbide or nitrides (hard) form in the surface layer to ~1mm depth or greater.
- Increase in hardness ……….. the resistance to fatigue.
- Compressive stress in *case hardening* is also generated due to difference in volume of case layer.



Effect of Materials Composition

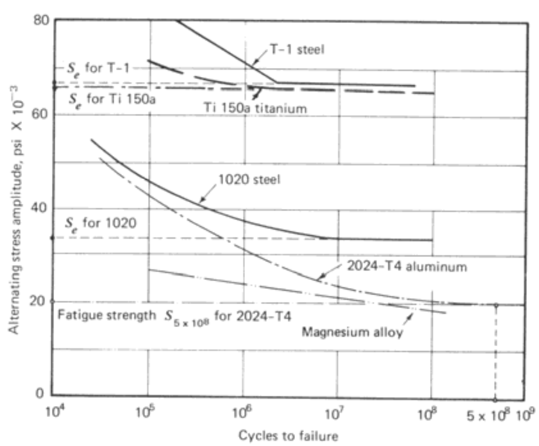


FIGURE 7.17. Effect of material composition on the S-N curve. Note that ferrous and titanium alloys exhibit a well-defined fatigue limit, whereas other alloy compositions do not. (Data from refs. 6 and 21)

Effect of Grain Size

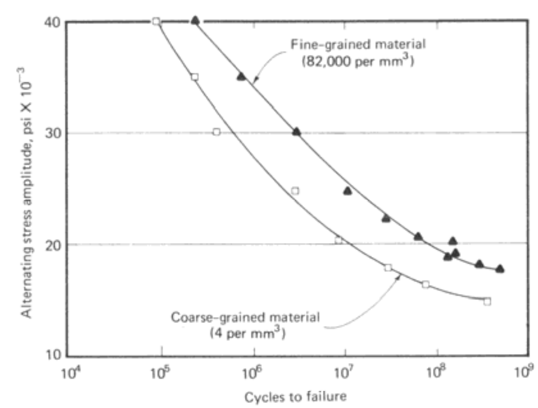


FIGURE 7.18. Effect of grain size on the *S-N* curve for 18S aluminum alloy. Average diameter ratio of coarse to fine grains is approximately 27 to 1. Nominal composition: 4.0 percent copper, 2.0 percent nickel, 0.6 percent magnesium. Note that at a life of 10^8 cycles the mean fatigue strength of the coarse-grained material is about 3000 psi lower than for fine-grained material. (Data from ref. 3; adapted from *Fatigue and Fracture of Metals*, by W. M. Murray, by permission of The MIT Press, Cambridge, Massachusetts, copyright 1952)

Environmental Effects

Thermal Fatigue

- It is created at high temperature by fluctuating *thermal* ……….. (σ_t).
- Restraint in thermal expansion/contraction during uneven heating/cooling

$$\sigma_t = E\ \alpha_l\ \Delta T$$

- α_l is the linear *thermal expansion coefficient*
- E is the *modulus of elasticity*
- ΔT is the temperature difference, $\alpha_l\ \Delta T$ is the *thermal strain* ε_t

• It can be minimized by careful design
  - **elimination of restraint** and temperature gradients (*use expansion gaps)*
  - consideration of **physical properties**, (materials CTE, k)

Environmental Effects

Corrosion Fatigue

- is simultaneous effect of cyclic stress and *chemical attack*
- involves formation of ***pits*** leading to stress concentration on surface and nucleation of fatigue cracks
- the corrosion enhances crack growth rate.

• **Prevention** is by:
  - protective coatings (painting, galvanizing)
  - selection of more corrosion resistant material
  - reducing the corrosive environment
  - ………………………………………..
  - ………………………………………..

Next time:

Creep