Fundamentals of Metal Fatigue:

Stress life method -- plots of alternating stress, S, vs. cycles to failure, N.

- ignores true stress and strain (assumes elastic strains) which may be significant since initiation of fatigue cracks is plastic deformation
- stress life methods should not be used to estimate lives below 1000 cycles

Endurance Limit: stress for which material has "infinite" life (> 1×10^6 cycles)

- existence due to interstitial elements (pin dislocations and prevent slip)
- can disappear due to periodic overloads, corrosive environments or high temperatures
- Most nonferrous alloys do not exhibit endurance limit (some use value at 5×10^8 cycles or some other number much higher than the design life)

Endurance Limit

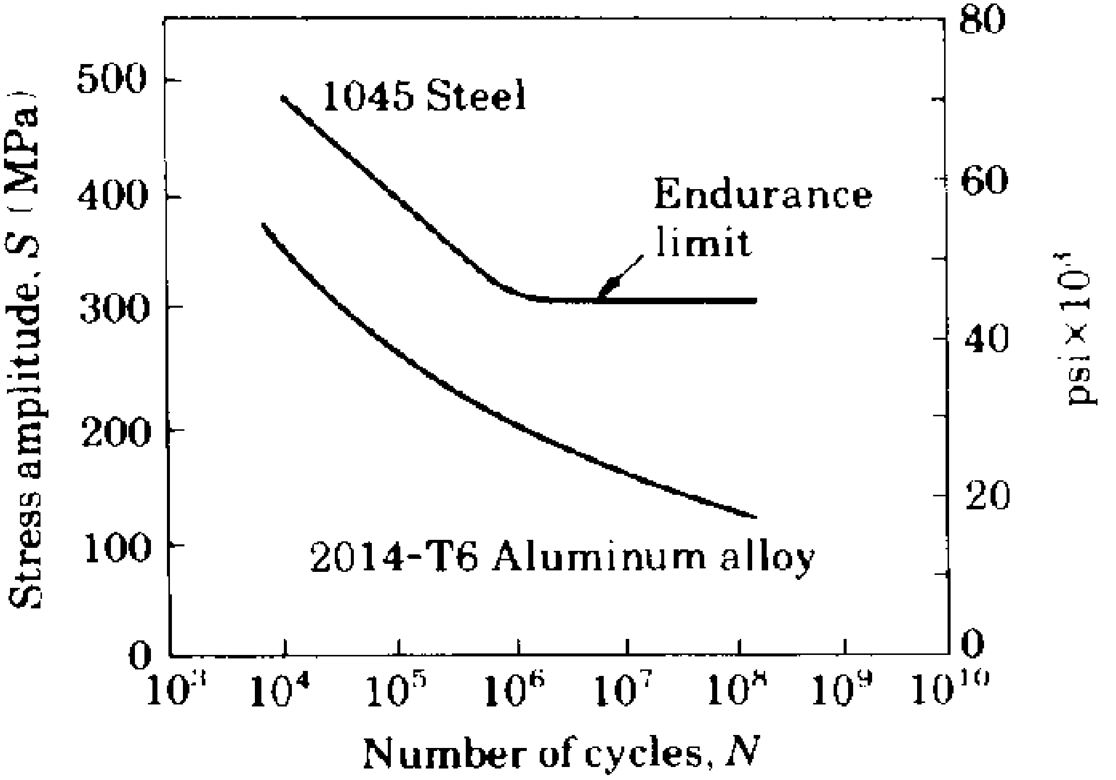


FIGURE 2.17

Typical *S–N* curves for two metals. Note that, unlike steel, aluminum does not have an endurance limit.

Serope Kalpakjian. Manufacturing Engineering and Technology, 3rd Edition. Addison-Wesley Publishing Co. 1995.

Fatigue Failure Examples

Endurance Limits for Common Materials

Turbine Blade Failures

Micromechanics of Failure

Ductile:
High plastic deformation due to exceedance of shear stress allowable
Surface has dimpled appearance due to void coalescence
Inclusions affect void formation
    good bonds with inclusions resist void formation
    hard inclusions promote voids, including mechanical fibering

Transformations between ductile and brittle:
    transition due to BCC, HCP
    transition due to carbon migration pins dislocations (strain aging)

Brittle: glassy appearance at the microscopic level, due to cleavage planes

Fatigue: beach marks

Stress Corrosion Cracking:
    oxidation or other chemical proceses at grain boundaries
    residual stresses

Representative Failure Surfaces

Brittle

Ductile

Fatigue

Stress Corrosion Cracking

Alternating Stress

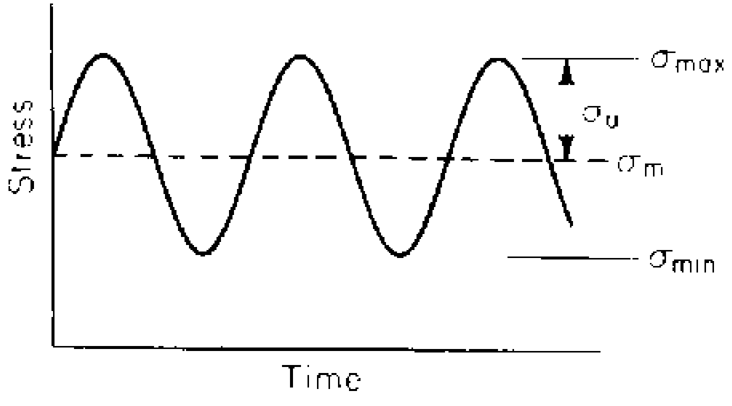


Figure 1.6 Terminology for alternating stress.

$$\Delta\sigma = \sigma_{max} - \sigma_{min} = \text{stress range}$$

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} = \text{stress amplitude}$$

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

$$R = \frac{\sigma_{min}}{\sigma_{max}} = \text{stress ratio} \qquad A = \frac{\sigma_a}{\sigma_m} = \text{amplitude ratio}$$

Stress life curves based on uniform mean and alternating stress

The R and A values corresponding to several common loading situations are:

Fully reversed: $R = -1$ $A = \infty$ $(?_{m} = 0)$

Zero to max: $R = 0$ $A = 1$ $(?_{a} = ?_{m})$

Zero to min: $R = \infty$ $A = -1$ $(?_{a} = |?_{m}|)$

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Mean Stress Effects

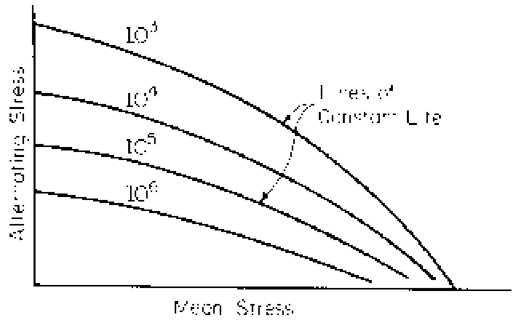


Figure 1.7 Haigh diagram.

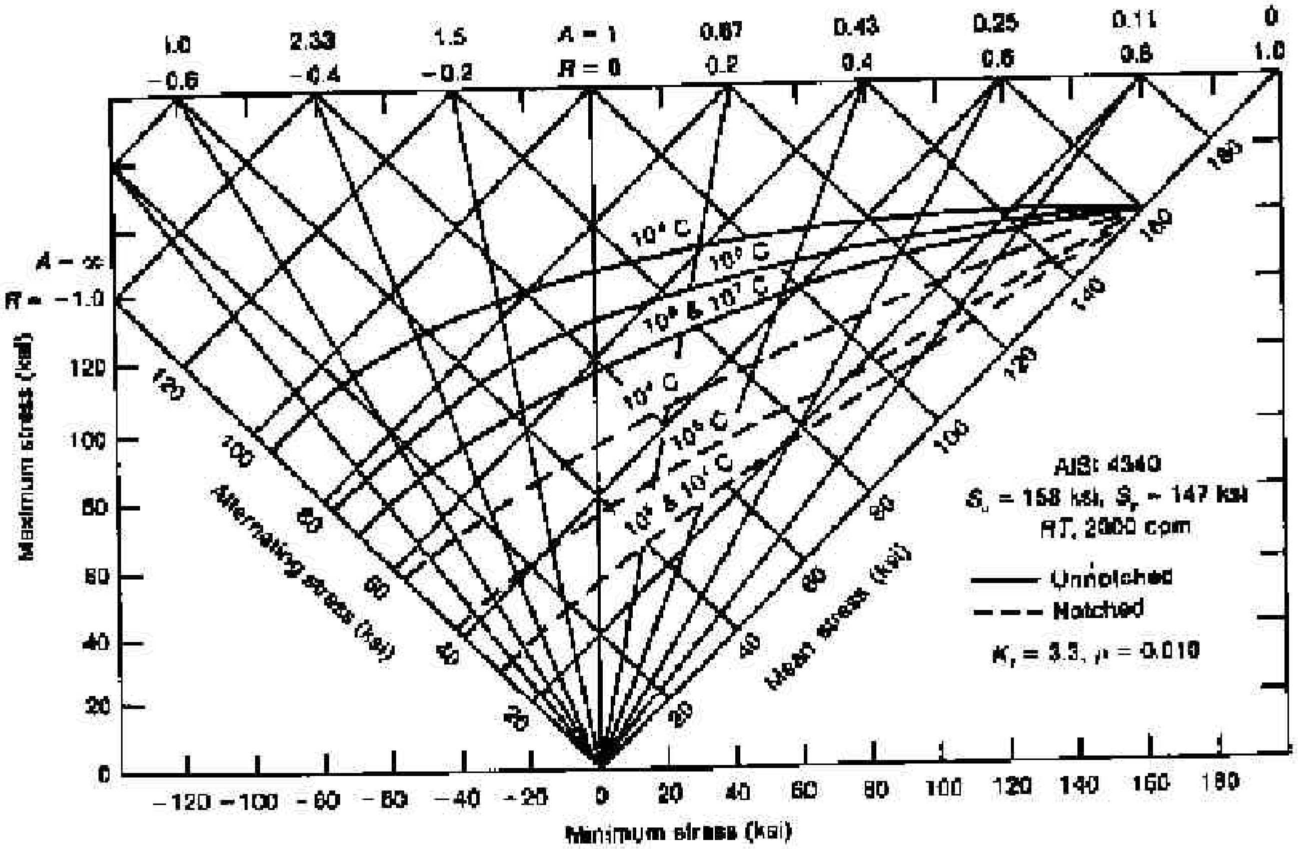


Figure 1.8 Master diagram for AISI 4340 steel. (From Ref. 2.)

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Fatigue S/N Curves

- Life prediction for regular, repeated loading
- S-N curves based on many tests to failure at many stress levels for specific stress ratio and surface finish
- S-N curves can be for mean life or any probability of failure (with a confidence level based on the number of samples taken at each stress level)
- Only good for uniform mean and alternating stress and requires a lot of data to be gathered. It does afford a simple analysis tool.
- MIL-HDBK-5E
    - Data
    - Examples

Fracture Analysis

- Handles irregular, repeated loading
- Covers complex loading, but involves complex analysis
- Basic idea is that cracks undergo predictable growth rate dA/dN for a given stress intensity factor ? K (which is calculated based on stress range and crack geometry such as the sharpness of the crack tip and the shape of the surrounding material)
    - If you know DK, you can find dA/dN
    - For a known DK history, you can estimate total crack growth
    - For a given crack length, the residual strength is often found from test
- MIL-HDBK-5E
    - Data
    - Examples

Miners Rule

A simple cumulative damage rule for irregular, repeated loading

Creep

Intergranular failure

Generally three phases with respect to time

Secondary creep is predicatble

Impact

Good test for toughness

Charpy -- Simply supported beam

Izod -- cantilever beam

Impact Testing Apparatus

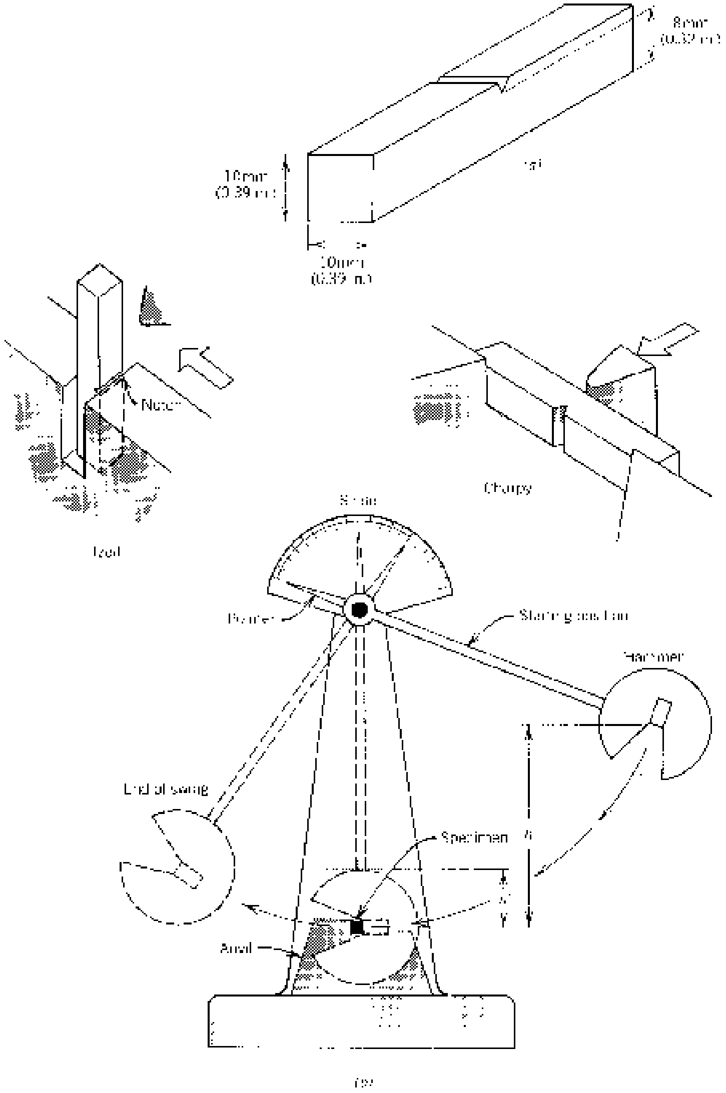


Figure 6.23. (*a*) Specimen used for Charpy and Izod impact tests. (*b*) A schematic drawing of an impact testing apparatus. The hammer is released from fixed height *h* and strikes the specimen; the energy expended in fracture is reflected in the difference between *h* and the swing height *h'*. Specimen placements for both Charpy and Izod tests are also shown. (Figure *b* adapted from Hayden et al., 1965, p. 13.)

William D. Callister, Jr. Materials Science and Engineering, An Introduction. John Wiley & Sons, Inc. 1985

Modifying Factors for Metal Fatigue:

A number of variables can have a significant impact on fatigue, such as:

Size. Larger components are more likely to have fatigue cracks initiate, due to larger volumes of material subject to high stresses, and due to a greater chance of residual stresses (inherent processing difficulty). Effects mainly seen at very long lives.

Type of loading. Endurance limits vary by loading condition (axial, bending, torsion)

Surface finish. Scratches, pits and machining marks add stress concentrations. Fine grained materials (high strength steel) more affected. Large effect, correction factors usually presented graphically

Modifying Factors for Metal Fatigue:

Surface treatments. Fatigue cracks initiate at free surface, treatments can be significant

Plating, thermal or mechanical means to induce residual stress
Compressive residual stresses are beneficial, tension is detrimental
Residual stresses not permanent, can be relaxed (temp., overload)

Temperature. Endurance limits increase at low temperature (but fracture toughness decreases significantly)

Endurance limits disappear at high temperature
Creep is important above 0.5Tm (plastic, stress-life not valid)

Environment. Corrosion has complex interactive effect with fatigue (attacks surface and creates brittle oxide film, which cracks and pits to cause stress concentrations)

Often in practice, there are modifying factors for the above aplied to the equation for the endurance limit.

Surface Finish (Qualitative and quantitative descriptions of surface roughness)

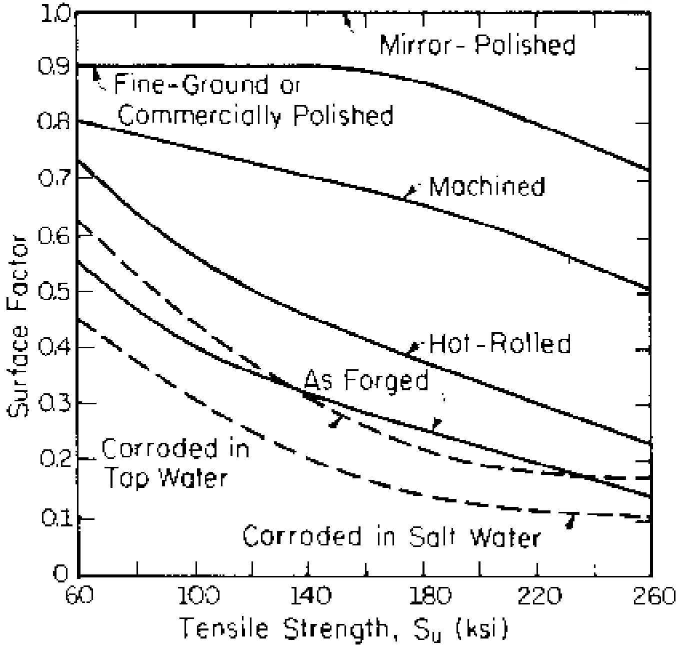


Figure 1.13 Surface finish factor: steel parts. (From Ref. 6.)

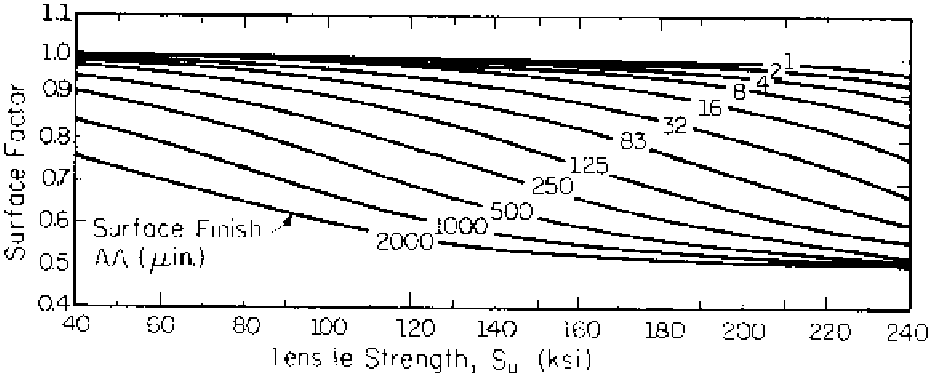


Figure 1.14 Surface finish factor versus surface roughness and strength: steel parts. (From Ref. 7.)

The condition of the surface is more important for high strength materials
Residual surface stresses can be important (e.g. grinding = residual tension)
Condition of surface at shorter lives dominated by crack propagation
(surface condition less of an effect)
Localized surface irregularities (e.g. stamping) can be high stress concentration

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Surface Treatment -- Review of Residual Stresses

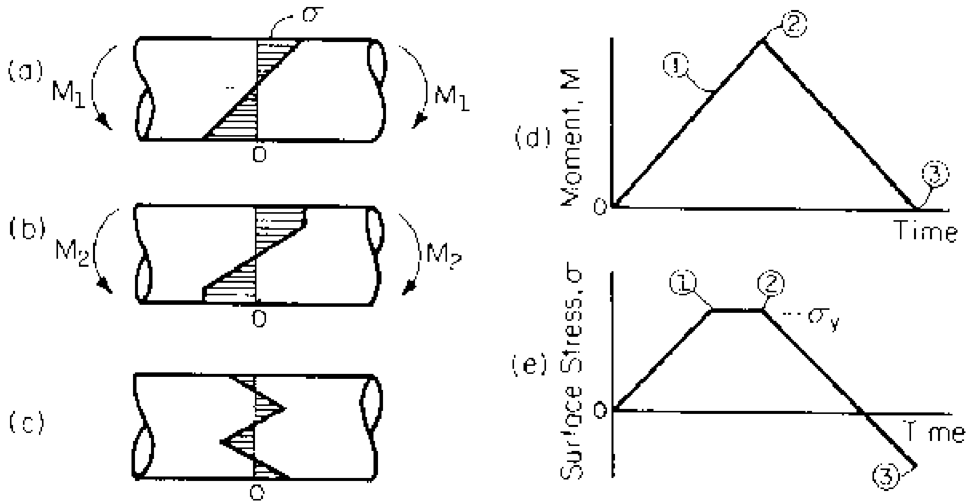


Figure 1.15 Residual stress in unnotched beam in bending.

1. At point 1 the surface of the beam is just at the point of yielding and the stress distribution is linear (Fig. 1.15a).
2. If the moment is increased to point 2, the outer layer of the beam begins to yield (Fig. 1.15b).
3. If the moment is reduced to point 3, the beam will have a residual stress distribution (Fig. 1.15c). When the outer layer of material yielded, it elongated and upon unloading the stresses and strains in the beam must meet compatibility and equilibrium requirements. Although the exact residual stress distribution is difficult to define, the important point is that the outer surface of the beam, which had yielded in tension, is now in residual compression.

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Surface Treatment -- Plating

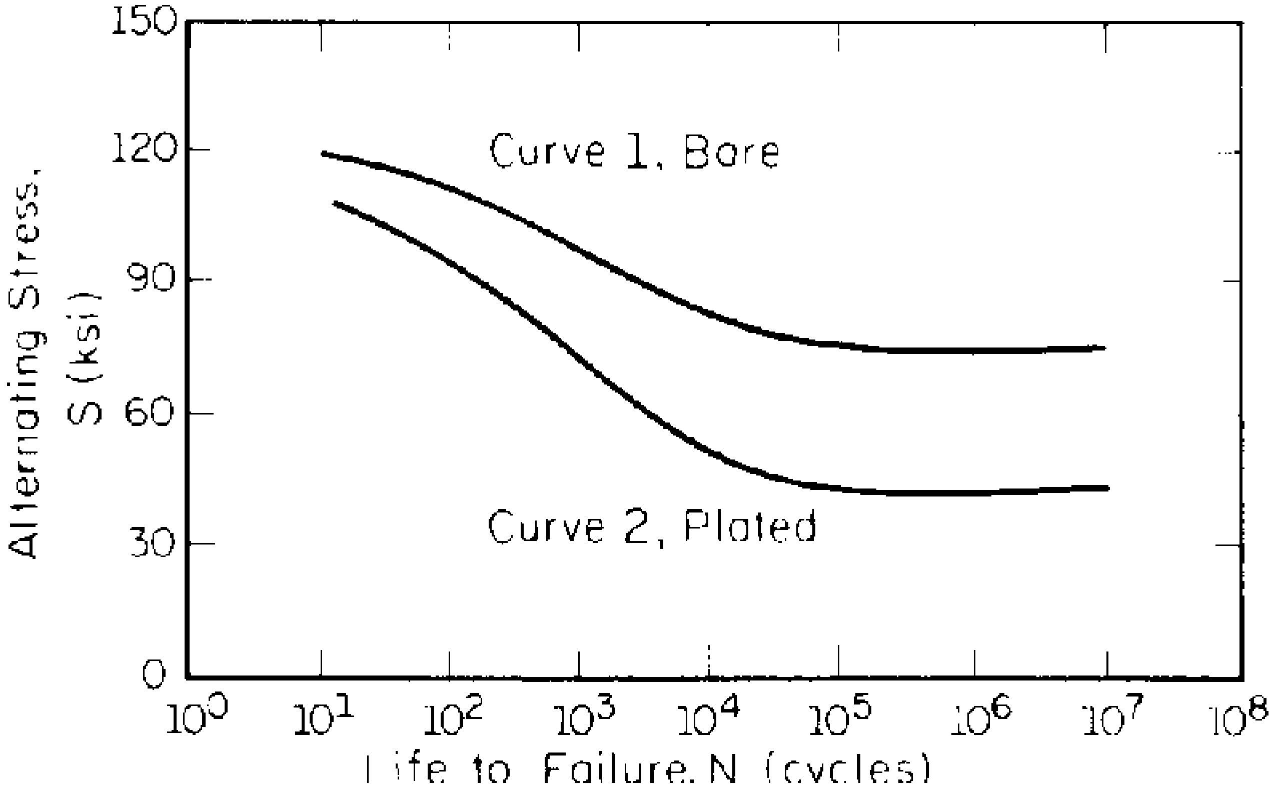


Figure 1.17 Effect of chrome plating on *S–N* curve of 4140 steel. (From Ref. 1.)

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Surface Treatment -- Plating

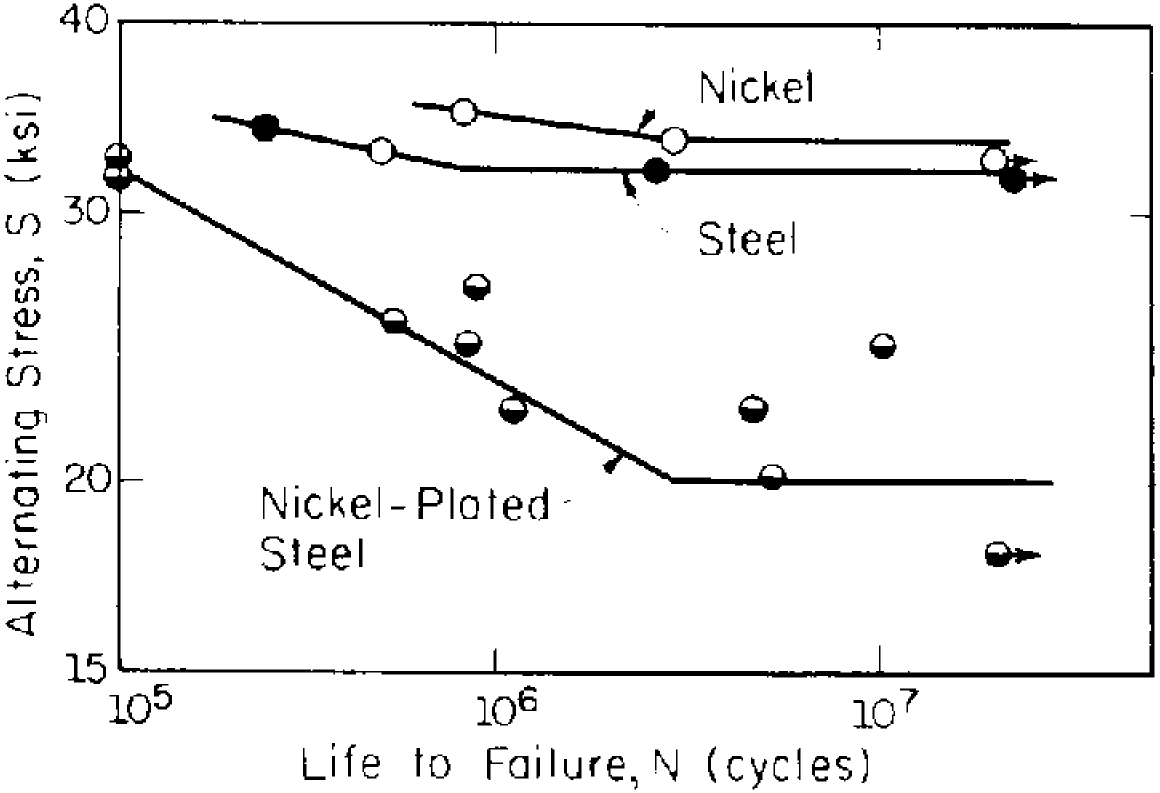


Figure 1.18 Effect of nickel plating on S–N curve of steel (S_u = 63 ksi). (From Ref. 9.)

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

General trends for chrome and nickel plating:

1. There is a greater reduction of fatigue strength as the yield strength of the material being plated increases.
2. The fatigue strength reduction due to plating is greater at longer lives.
3. The fatigue strength reduction is greater as the thickness of the plating increases.
4. It should also be noted that when fatigue occurs in a corrosive environment, the extra corrosion resistance offered by plating can more than offset the reduction in fatigue strength seen in a noncorrosive environment (see Table 1.7).

Plating with cadmium and zinc appear to have no effect on fatigue strength while still offering corrosion resistance. However, plating with these metals does not offer the wear resistance of chromium. It is important to remember that any electroplating operation can cause hydrogen embrittlement if the process is improperly controlled.

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Surface Treatment -- Thermal

Various heat treatment process (e.g. nitriding, carburizing) can produce higher strength materials at the surface which significantly improves fatigue life

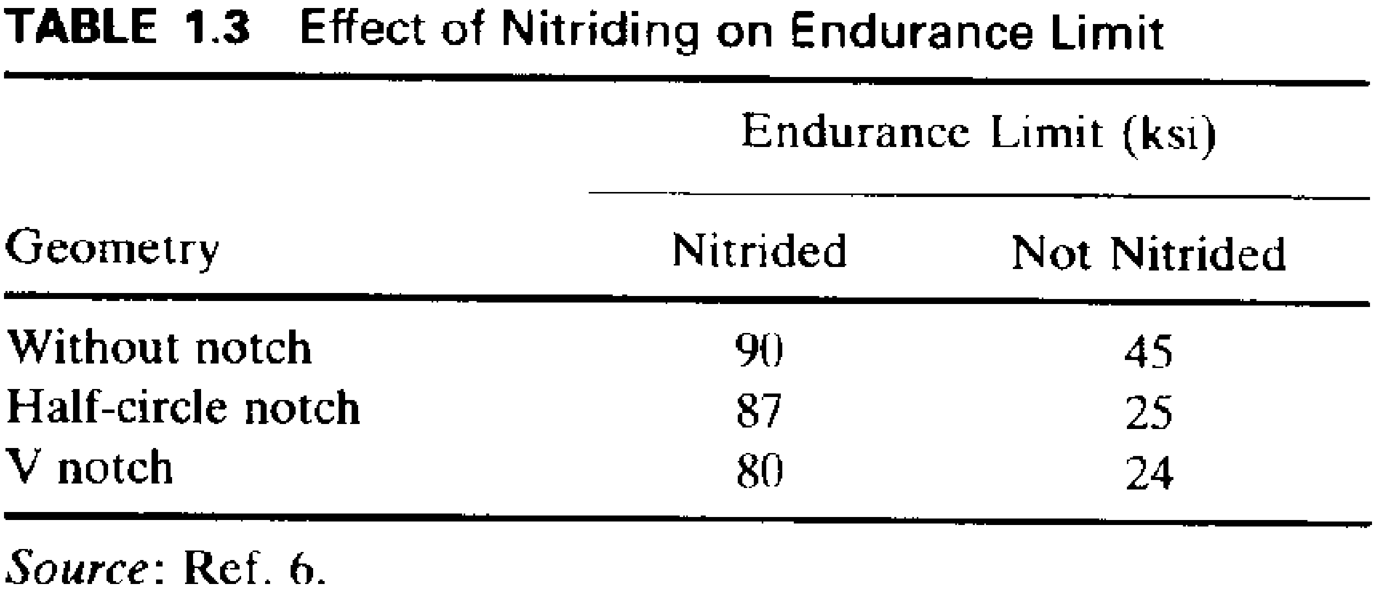


TABLE 1.3 Effect of Nitriding on Endurance Limit

	Endurance Limit (ksi)	
Geometry	Nitrided	Not Nitrided
Without notch	90	45
Half-circle notch	87	25
V notch	80	24

Source: Ref. 6.

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Surface Treatment -- Thermal

Certain processing operations can have reverse effect. For example, hot rolling and forging can cause decarburization (loss of surface carbon atoms), which is very detrimental to fatigue life.

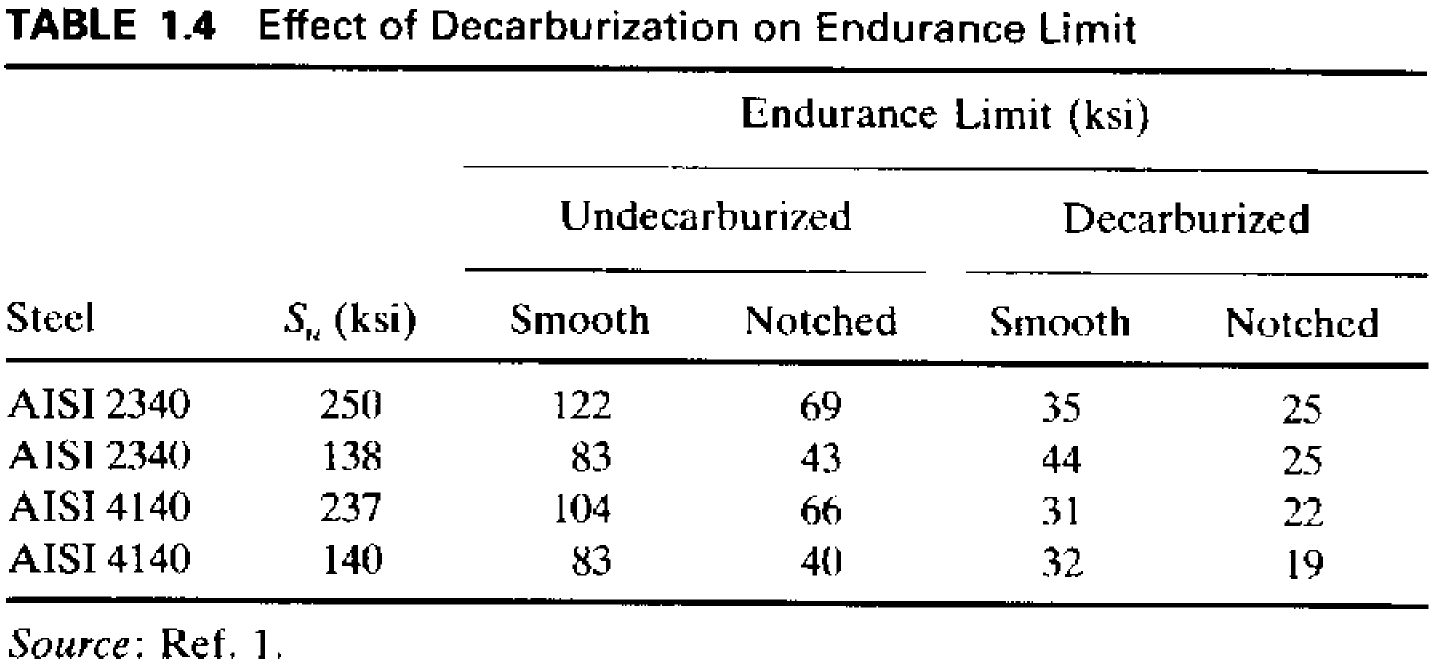


TABLE 1.4 Effect of Decarburization on Endurance Limit

		Endurance Limit (ksi)			
		Undecarburized		Decarburized	
Steel	S_u (ksi)	Smooth	Notched	Smooth	Notched
AISI 2340	250	122	69	35	25
AISI 2340	138	83	43	44	25
AISI 4140	237	104	66	31	22
AISI 4140	140	83	40	32	19

Source: Ref. 1.

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Surface Treatment -- Mechanical

Two most important methods: Cold Rolling and Shot Peening

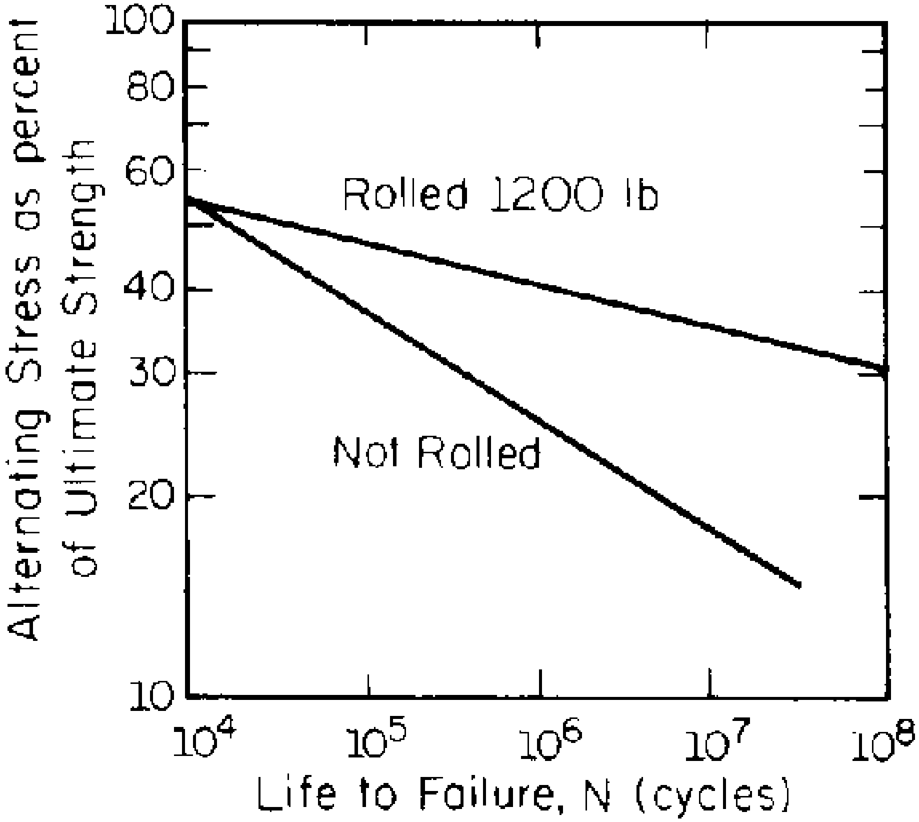


Figure 1.22 Effects of cold rolling on *S*–*N* curve of steel. (From Ref. 9.)

Cold Rolling

- Steel rollers pressed to surface of component as it is rotated in a lathe
- Used on large parts
- Can produce deep residual stress layer

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Surface Treatment -- Mechanical

Two most important methods: Cold Rolling and Shot Peening

Shot Peening

- Surface of component blasted with high velocity steel or glass beads
- Core of material in residual tension, surface in residual compression
- Easily used on odd shaped parts, but leaves surface dimpling

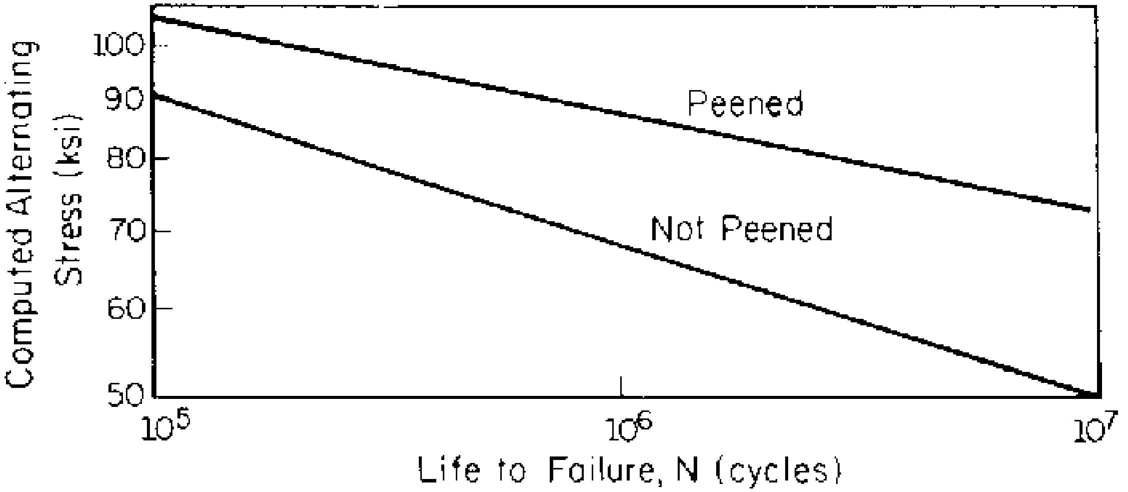


Figure 1.23 S–N curve of carburized gears in peened and unpeened conditions. (From Ref. 12.)

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Shot peening can be used to undo deleterious effects of plating, decarburization, corrosion and grinding

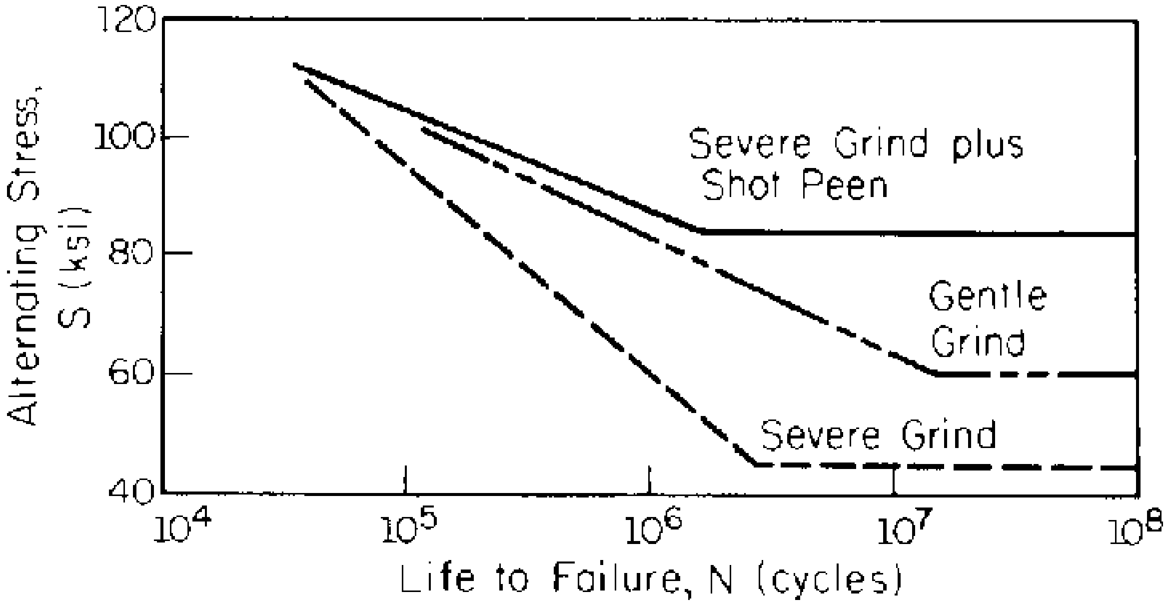


Figure 1.21 Effects of grinding on *S–N* curve of steel. (From Ref. 11.)

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Shot peening can be used to undo deleterious effects of plating, decarburization, corrosion and grinding

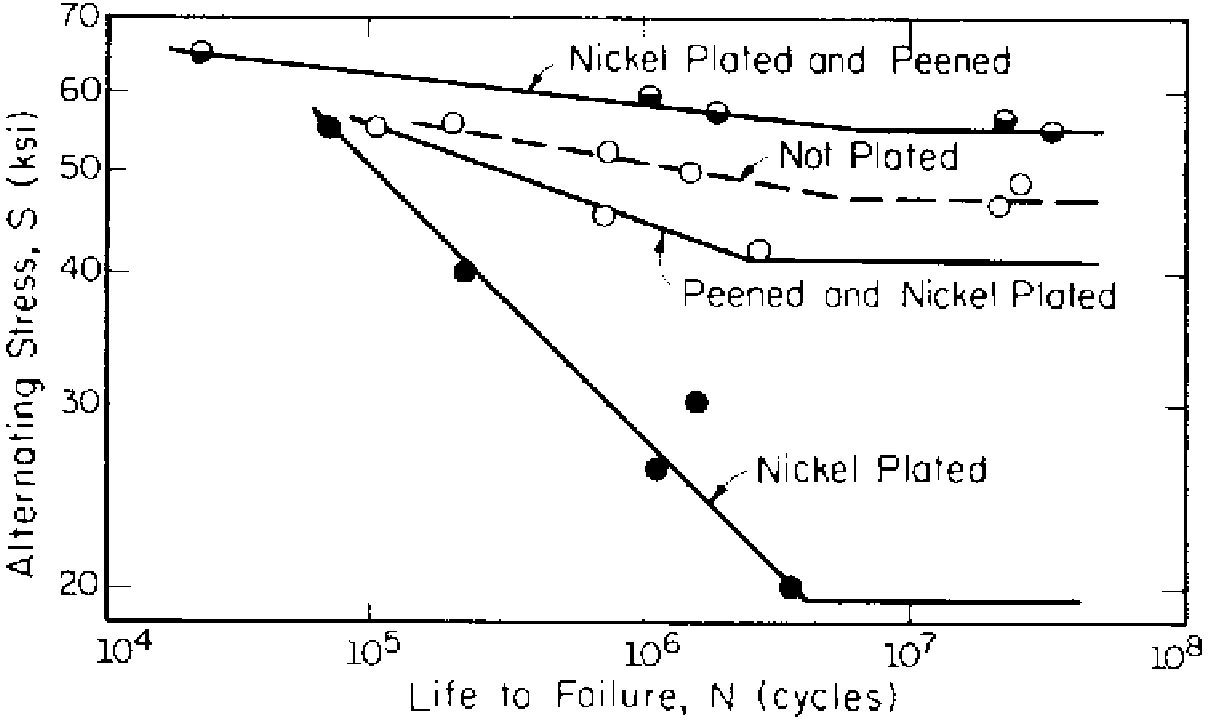


Figure 1.19 Effects of shot peening on $S-N$ curve of nickel plated steel. (From Ref. 9.)

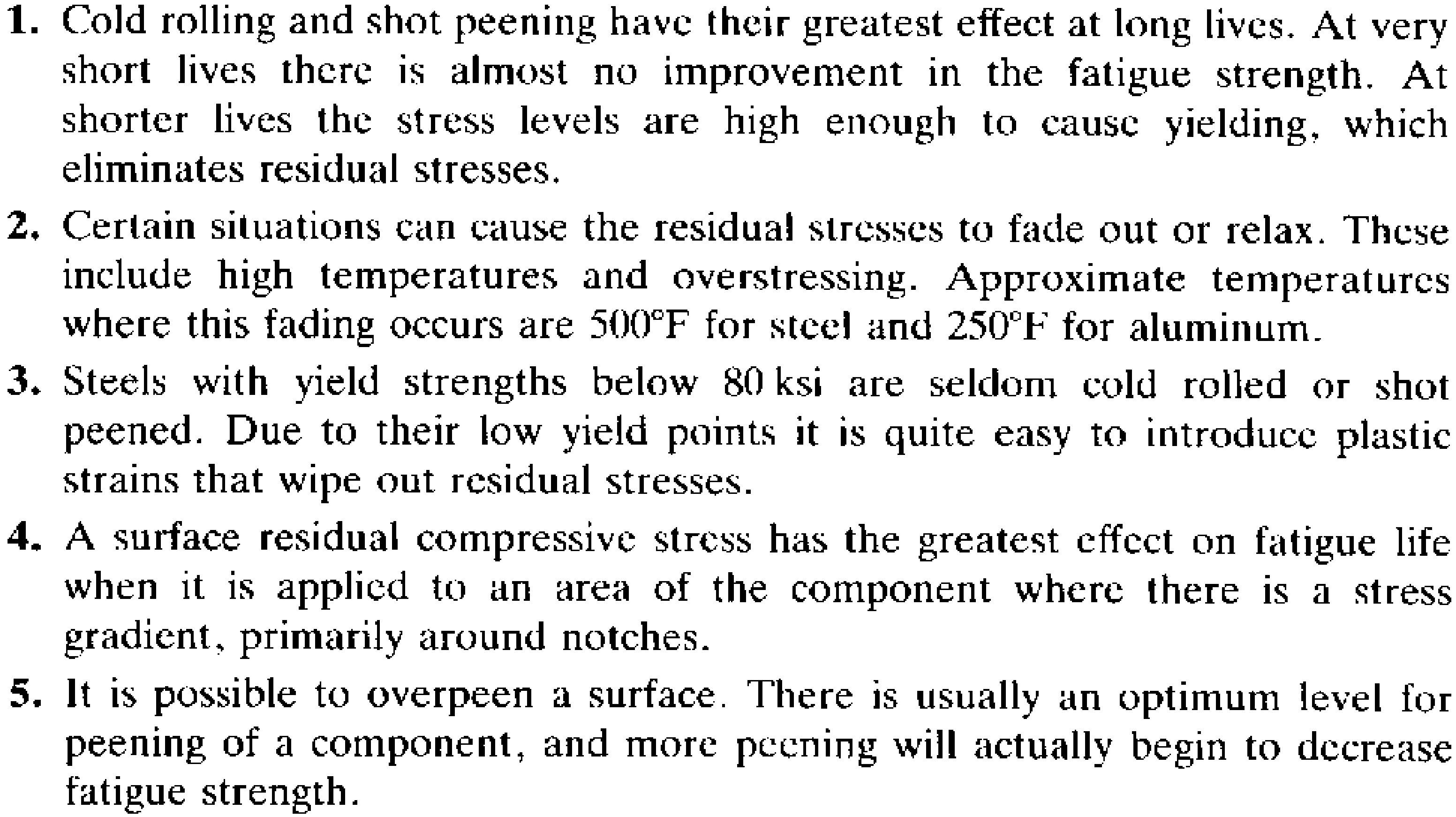
J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Shot Peening

- One of the most economical methods of improving fatigue life of parts subjected to low tension stresses
- Counteracts the surface tension stresses induced by grinding and plating
- Partially offsets the effects of decarburization
- Effect greatly reduced if computed surface stress exceeds ~60% yield stress
- Beneficial effects of peening decrease with temperature (~450°F steel, ~250°F Al)

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Important points about cold-working for residual compressive stress:



1. Cold rolling and shot peening have their greatest effect at long lives. At very short lives there is almost no improvement in the fatigue strength. At shorter lives the stress levels are high enough to cause yielding, which eliminates residual stresses.
2. Certain situations can cause the residual stresses to fade out or relax. These include high temperatures and overstressing. Approximate temperatures where this fading occurs are 500°F for steel and 250°F for aluminum.
3. Steels with yield strengths below 80 ksi are seldom cold rolled or shot peened. Due to their low yield points it is quite easy to introduce plastic strains that wipe out residual stresses.
4. A surface residual compressive stress has the greatest effect on fatigue life when it is applied to an area of the component where there is a stress gradient, primarily around notches.
5. It is possible to overpeen a surface. There is usually an optimum level for peening of a component, and more peening will actually begin to decrease fatigue strength.

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Environmental Effects

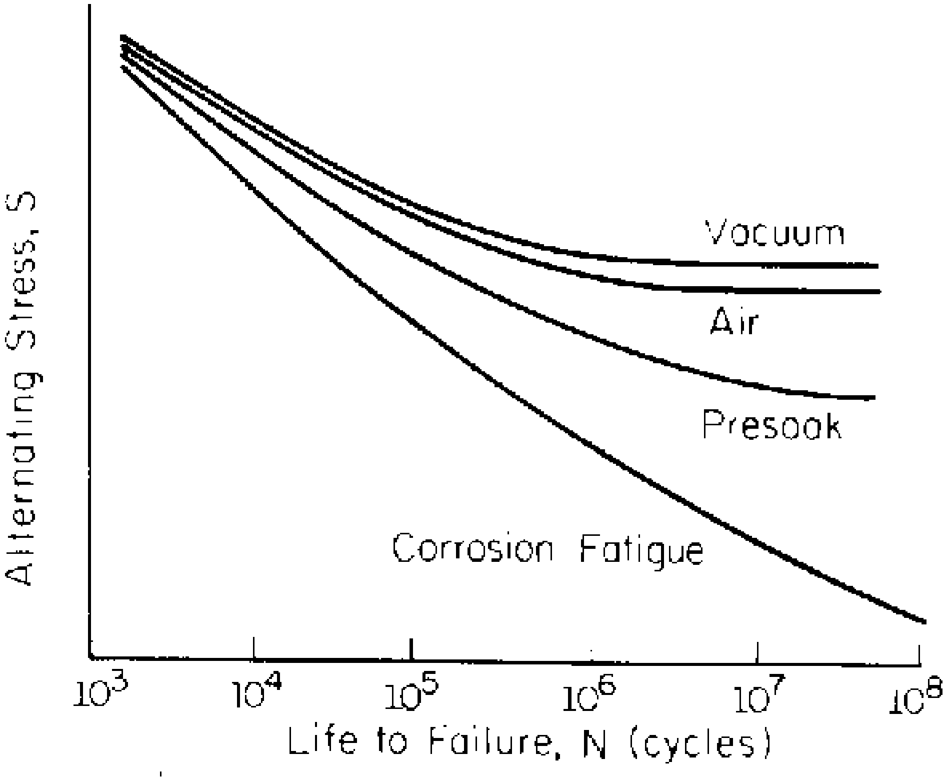


Figure 1.25 Effect of various environments on the S–N curve of steel. (H. O. Fuchs and R. I. Stephens, *Metal Fatigue in Engineering*, John Wiley and Sons, New York, 1980. Reprinted with permission.)

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Environmental Effects

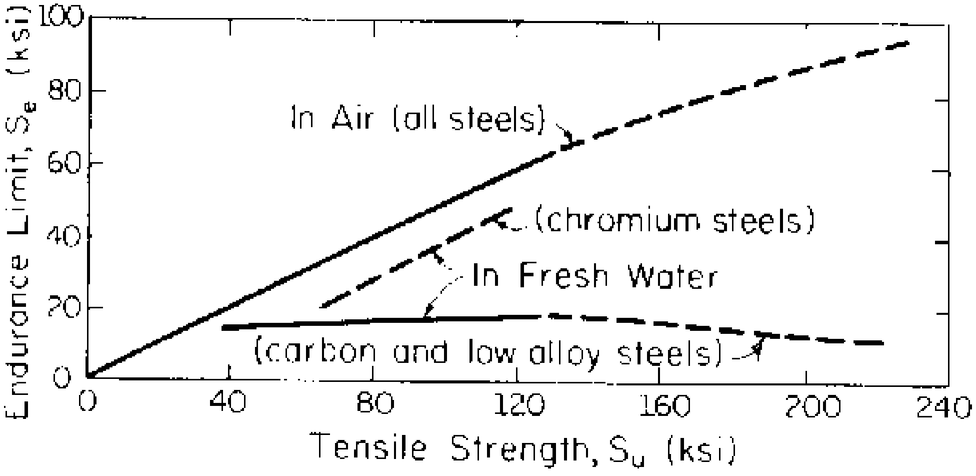


Figure 1.26 Influence of tensile strength and chemical composition on corrosion-fatigue strength of steels. (From Ref. 10.)

J.A. Bannantine, J.J. Comer and J.L. Handrock. Fundamentals of Metal Fatigue Analysis. Prentice-Hall, 1990.

Fatigue Design Guideline (minimize stress concentrations)

1. Consider actual stresses, including stress concentrations, rather than to nominal average stresses.

2. Visualize load transfer from one part or section to another and the distortions that occur during loading to locate points of high stress

3. Avoid adding or attaching secondary brackets, fittings, handles, steps, bosses, grooves, and openings at locations of high stress

4. Use gradual changes in section and symmetry of design to reduce secondary flexure

5. Consider location and types of joints (frequent cause of fatigue problems)

6. Use double shear joints when possible

7. Do noy use rivets for carrying repeated tensile loads (bolts superior)

8. Avoid open and loosely filled holes

Fatigue Design Guideline (minimize stress concentrations)

9. Consider fabrication methods, specify strict requirements when needed

10. Choose proper surface finishes, but not overly severe (rivet holes, welds, openings etc. may be larger drivers)

11. Provide suitable protection against corrosion

12. Avoid metallic plating with widely different properties than underlying material

13. Consider prestressing when feasible, to include shot peening and cold working

14. Consider maintenance, to include inspections, and protection against corrosion, wear, abuse, overheating, and repeated overloading

15. Avoid use of structures at critical or fundamental frequency of individual parts or of the structure as a whole (induces many cycles of relatively high stress)

16. Consider temperature effects