Chapter 9. Fatigue of Materials:

Introduction and Stress-Based Approach

Seoul National University System Health & Risk Management

CHAPTER 9 Objectives

- Explore **the cyclic fatigue behavior** of materials as a process of progressive damage leading to cracking and failure
- Fatigue trends for variables such as **stress level, geometry, surface condition, environment, and microstructure**
- Review laboratory **testing in fatigue**, and **analyze typical test data to obtain stress-life curves** and evaluate **mean stress effects**.
- Apply engineering methods to estimate fatigue life, including the effects of **mean stress**, **multiaxial stress**, and **variable-level cyclic loading**
- Evaluate **safety factors** in stress and in life.

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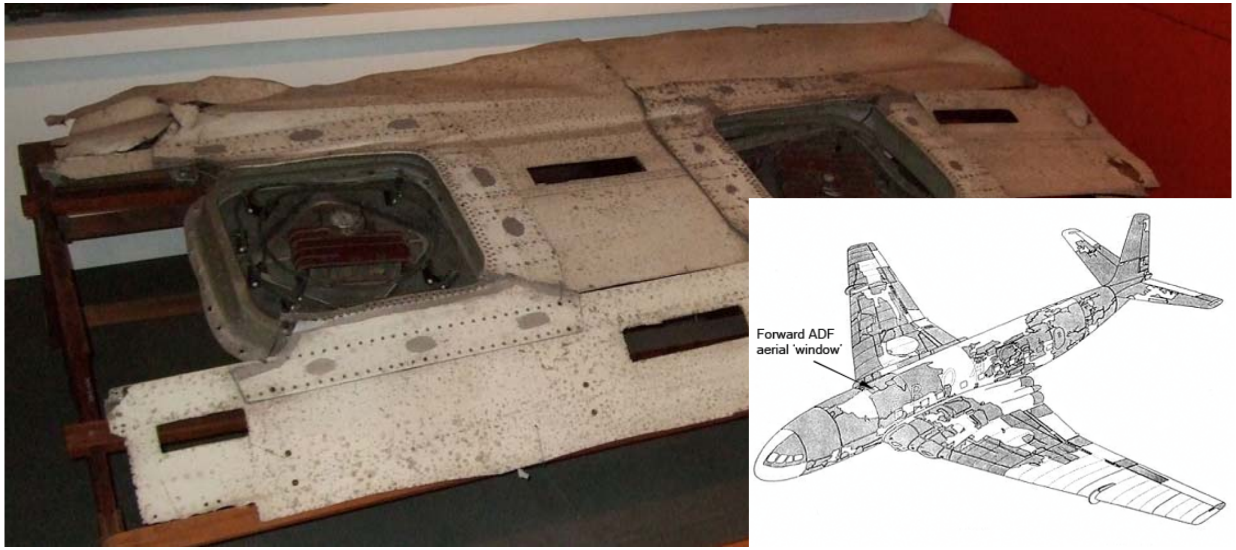
Fatigue Failure: de Havilland Comet disaster

- Three de Havilland Comet passenger jets broke up in mid-flight and **crashed within a few months in 1954.**
- The failure was a result of **metal fatigue in the airframes caused by the repeated pressurisation and de-pressurisation** of the aircraft cabin.
- Unlike drill riveting, the imperfect nature of **the hole created by punch riveting** caused manufacturing defect cracks which may have caused the start of fatigue cracks around the rivet.
- The stresses around pressure cabin apertures were considerably higher than anticipated, especially around sharp-cornered cut-outs, such as windows.
- Systematic tests were conducted on a fuselage immersed and pressurised in a water tank.



*http://en.wikipedia.org/wiki/Fatigue_(material)

9.1 Introduction – What is Fatigue?

- ***Purely static loading*** is rarely observed in modern engineering components or structures. The majority of structures involve parts subjected to ***fluctuating*** or ***cyclic loads***.
- Such loading induces ***fluctuating*** or ***cyclic stresses*** that often lead to ***microscopic damage*** to the materials.
- ***Accumulated microscopic damage*** develops into ***a crack*** or other ***macroscopic damage*** that leads to failure of the structure by ***fatigue***.

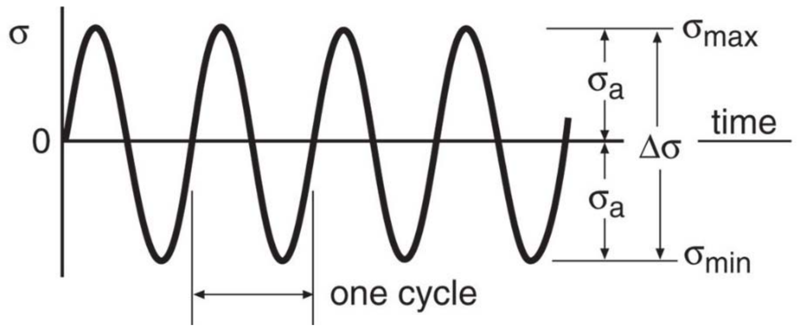


Figure 9.2

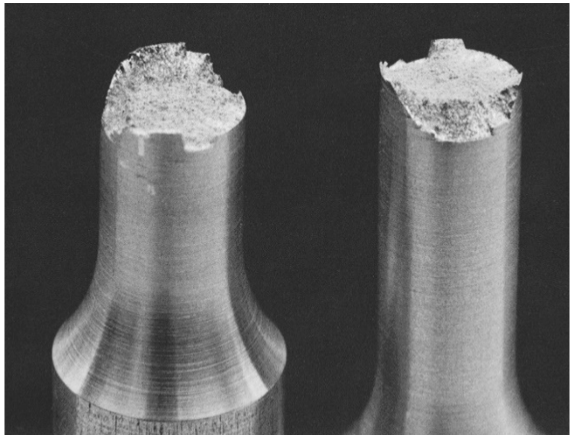
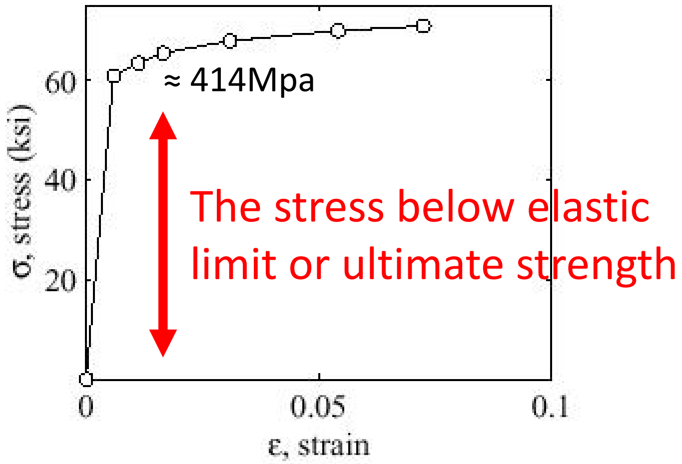


Figure 9.16

9.1 Introduction – What is Fatigue?

- From 80% to 95% of all structural failures occur through a ***fatigue*** mechanism.
- For centuries, it has been known that a piece wood or metal can be made to break by repeatedly bending it back and forth with ***a large amplitude***. However, it came as something of a surprise when it was discovered that repeated loading produced fracture even when ***the stress amplitude*** was apparently well ***below the elastic limit*** of the material (or ***ultimate strength***).

< The Stress-Strain Curve and S-N Curve for 7075-T6 Al>



≈ 414Mpa

The stress below elastic limit or ultimate strength

Figure. Representation of uniaxial stress-strain relationship for 7075-T6 aluminum alloy*

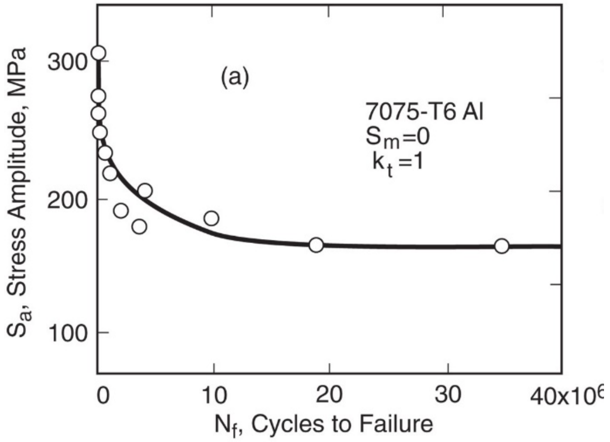


Figure 9.4

* http://www.afgrow.net/applications/DTDHandbook/examples/page1_1.aspx

9.1 Introduction – History of Fatigue

- In 1837, **Wilhelm Albert** published the first article on fatigue, establishing a correlation between applied loads and durability.
- In 1839, **Jean-Victor Poncelet**, designer of cast iron axles for mill wheels, officially used the term "***fatigue***" for the first time in a book on mechanics.
- In the 1850s, **August Wöhler** initiated the development of design strategies for fatigue and identified the importance of cyclic and mean stresses.

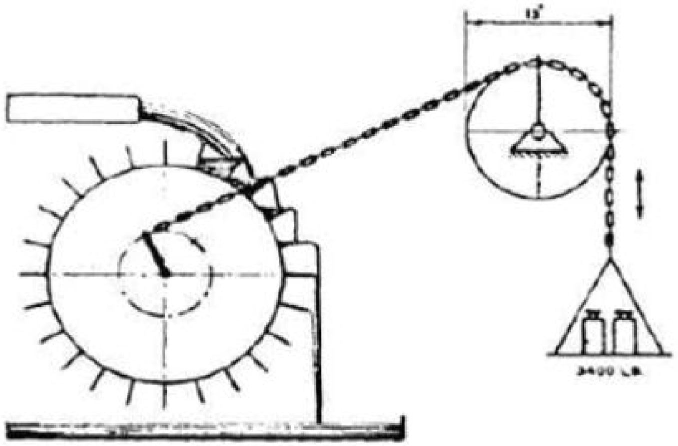


Figure. Albert's fatigue tests of mining chains, sketch

*http://www.atzonline.com/index.php;do=show/site=a4e/sid=GWV/alloc=38/id=61/special=Special+Simulation

9.4 Fatigue Testing

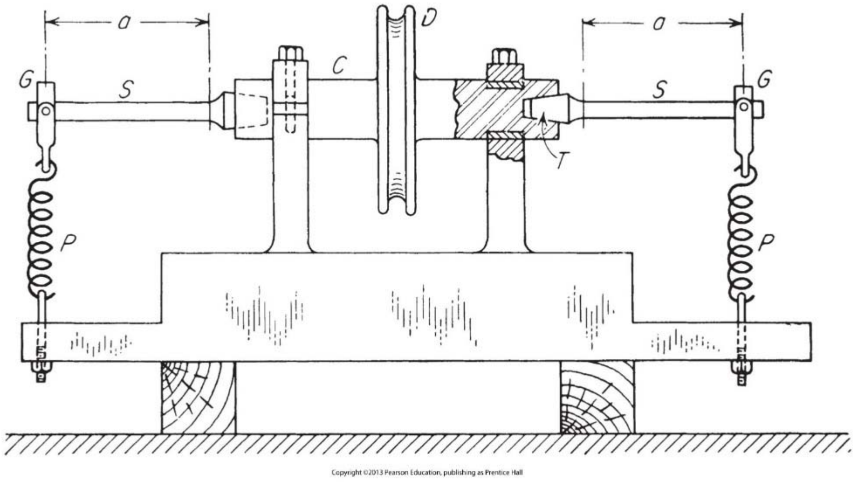


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Figure 9.11 Rotating cantilever beam fatigue testing machine used by **Wöhler.**

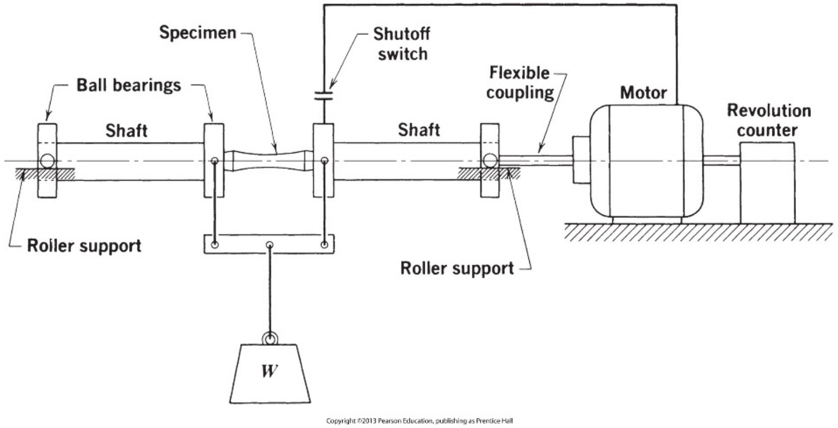

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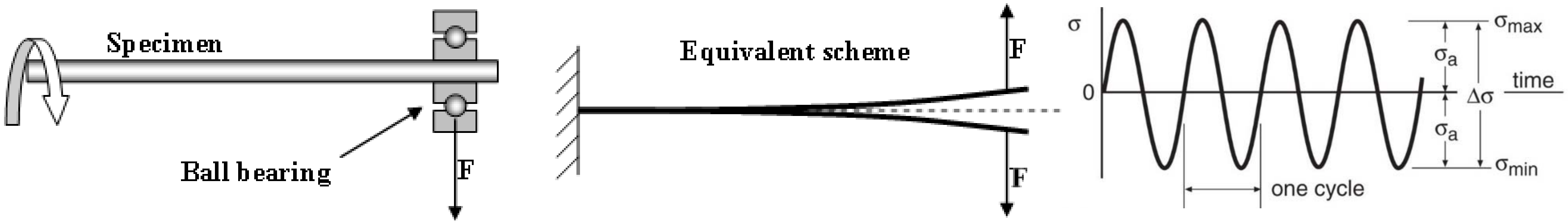
Figure 9.12 The **R. R. Moore** rotating beam fatigue testing machine



< Principle of fatigue testing machine>

9.1 Introduction -
3 major approaches analyzing fatigue failure

- **Stress-based approach (Chapters 9-11)**
  - Analysis based on the nominal (average) stresses in the affected region of the engineering component.
  - The nominal stress that can be resisted under cyclic loading is determined by considering mean stresses and by adjusting for the effects of stress raisers, such as grooves, holes, fillets, and keyways.
- **Strain-based approach (Chapter 14)**
  - More detailed analysis of the localized yielding that may occur at stress raisers during cyclic loading
- **Fracture mechanics approach (Chapter 11)**
  - Specifically treats growing cracks by the methods of fracture mechanics

Stress-based approach

- **The stress-life**, or **S-N method** was the first approach used in an attempt to understand and quantify metal fatigue.
- The basis of the stress-life method is the **Wöhler** or **S-N diagram**, which is a plot of alternating stress, S, versus cycles to failure, N.
- The most common procedure to obtain S-N data is **the rotating bending test (R. R. Moore test).**
- If **S-N test data** are found to approximate a straight line on a log-linear plot (or log-log), those can be fitted to obtain **a mathematical representation of the curve.**

Stress-based approach

- One of the major drawbacks of the stress-life approach is that it ignores true stress-strain behavior and treats **all strains as elastic**.
- The simplifying assumptions of the S-N approach are **valid only if the plastic strains are small.**
- At long lives most steels have only a small component of cyclic strain which is plastic (in some cases it is effectively too small to measure) and the S-N approach is valid.
- The stress-life method does not work well in low-cycle applications, where the applied strains have a significant plastic component. In this range a strain-based approach is more appropriate.

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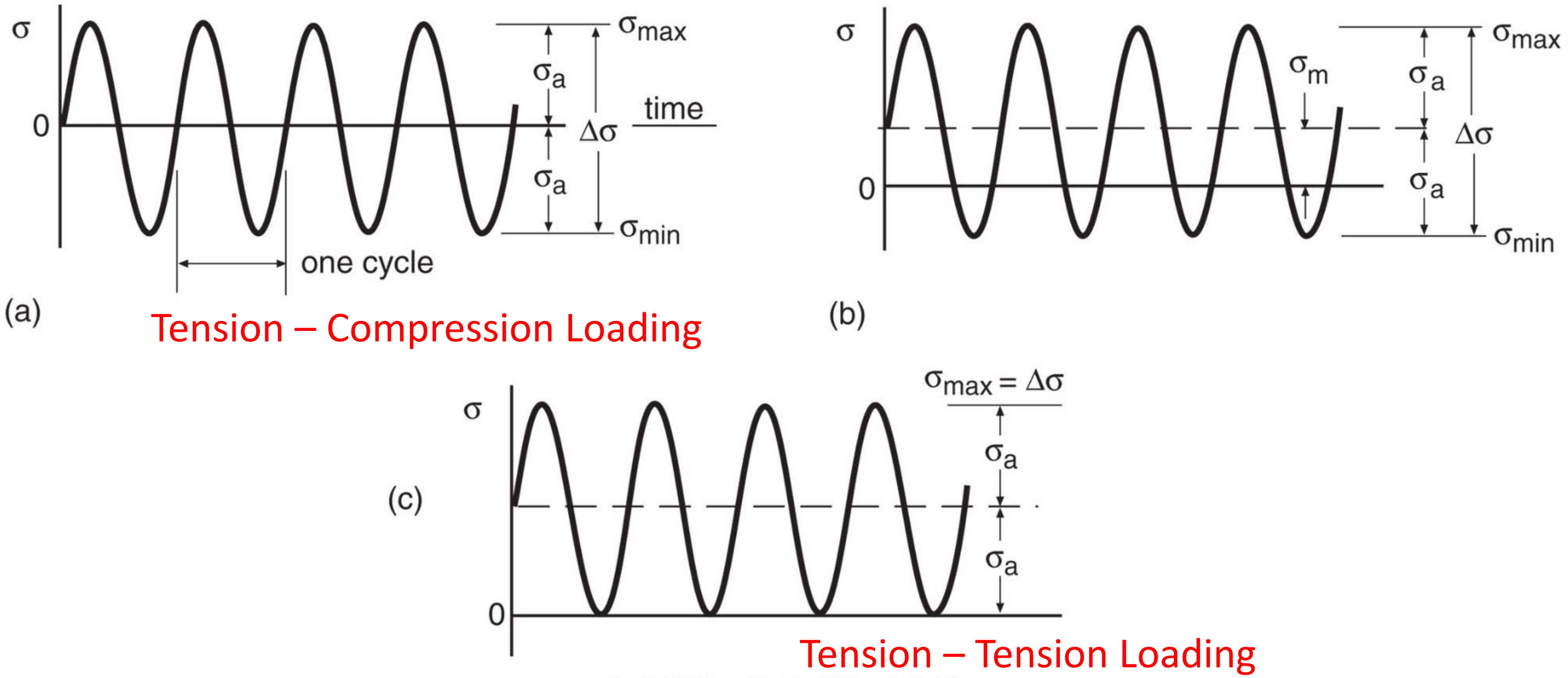
9.2.1 Description of Cyclic Loading



Tension – Compression Loading

Tension – Tension Loading

Figure 9.2 Constant amplitude cycling and the associated nomenclature. Case (a) is completely reversed stressing, $\sigma_m = 0$; (b) has a nonzero mean stress σ_m; and (c) is zero-to-tension stressing, σmin = 0.

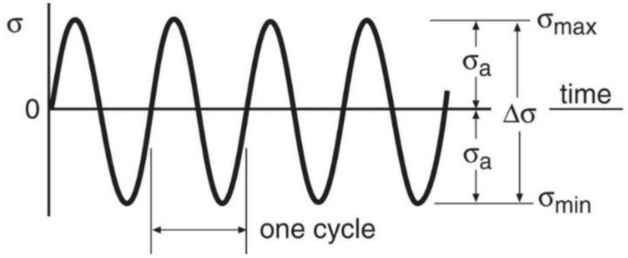
9.2.1 Description of Cyclic Loading

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

(9.2) $$\sigma_{max} = \sigma_m + \sigma_a \qquad \sigma_{min} = \sigma_m - \sigma_a$$

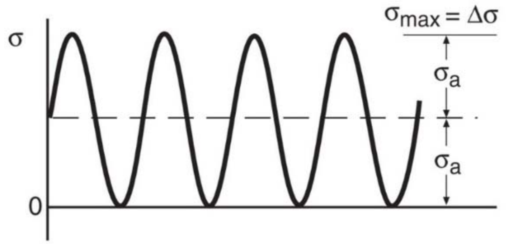
(9.3) Stress Ratio, $R = \frac{\sigma_{min}}{\sigma_{max}}$ Amplitude Ratio, $A = \frac{\sigma_a}{\sigma_m}$ -> Describing Cyclic Loading

(9.4) $$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{max}}{2}(1 - R) \qquad \sigma_m = \frac{\sigma_{max}}{2}(1 + R) \qquad R = \frac{1 - A}{1 + A} \qquad A = \frac{1 - R}{1 + R}$$



$$\sigma_m = 0 \; or \; R = -1$$

< Completely Reversed Cycling>

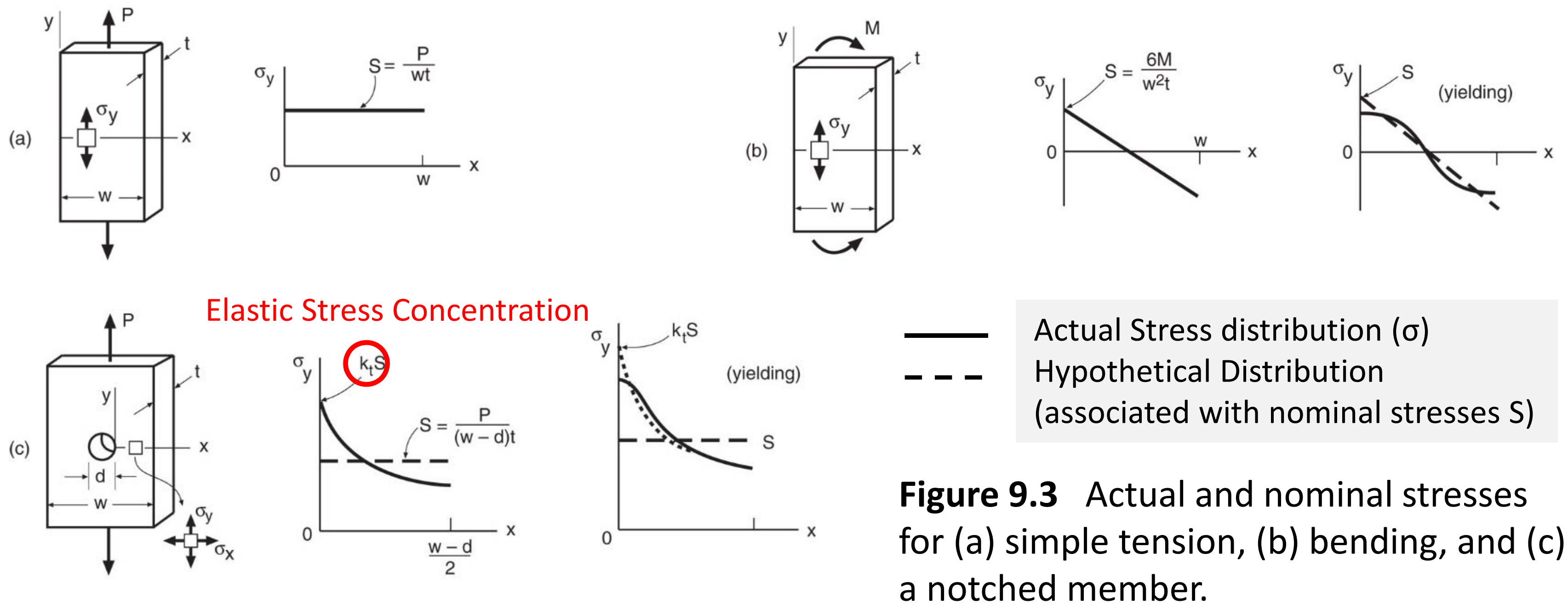


$$\sigma_{min} = 0 \; or \; R = 0$$

< Zero-to-Tension Cycling>

9.2.2 Point Stresses vs. Nominal Stresses

Stress at a point, σ	Nominal or Average stress, S
- Actual stress occurred at a point	- Calculated stress from force or moment or their combination as a matter of convenience and is only equal to σ in certain situations
-> Simple Axial Loading	-> Complicated Bending, notched member (except where it is truly appropriate to use σ)



Elastic Stress Concentration

<Elastic Behavior>

<Plastic Behavior>

—— Actual Stress distribution (σ)

- - - Hypothetical Distribution (associated with nominal stresses S)

Figure 9.3 Actual and nominal stresses for (a) simple tension, (b) bending, and (c) a notched member.

9.2.3 Stress Versus Life (S-N) Curves

- The results of tests from a number of different stress levels may be plotted to obtain a stress-life curve, also called an S-N curve.
- On the linear plot, the cycle numbers for the shorter lives cannot be read accurately.

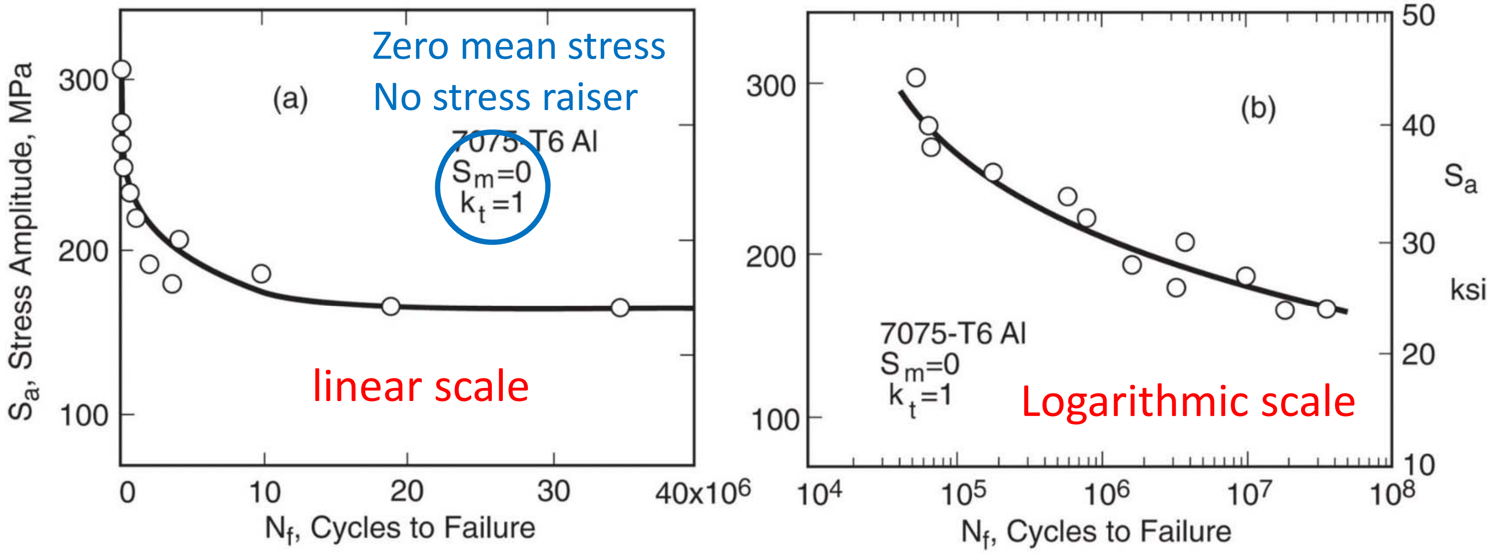


Figure 9.4 Stress versus life (S-N) curves from rotating bending tests of unnotched specimens of an aluminum alloy. Identical linear stress scales are used, but the cycle numbers are plotted on a linear scale in (a), and on a logarithmic one in (b). (Data from [MacGregor 52].)

9.2.3 Stress Versus Life (S-N) Curves

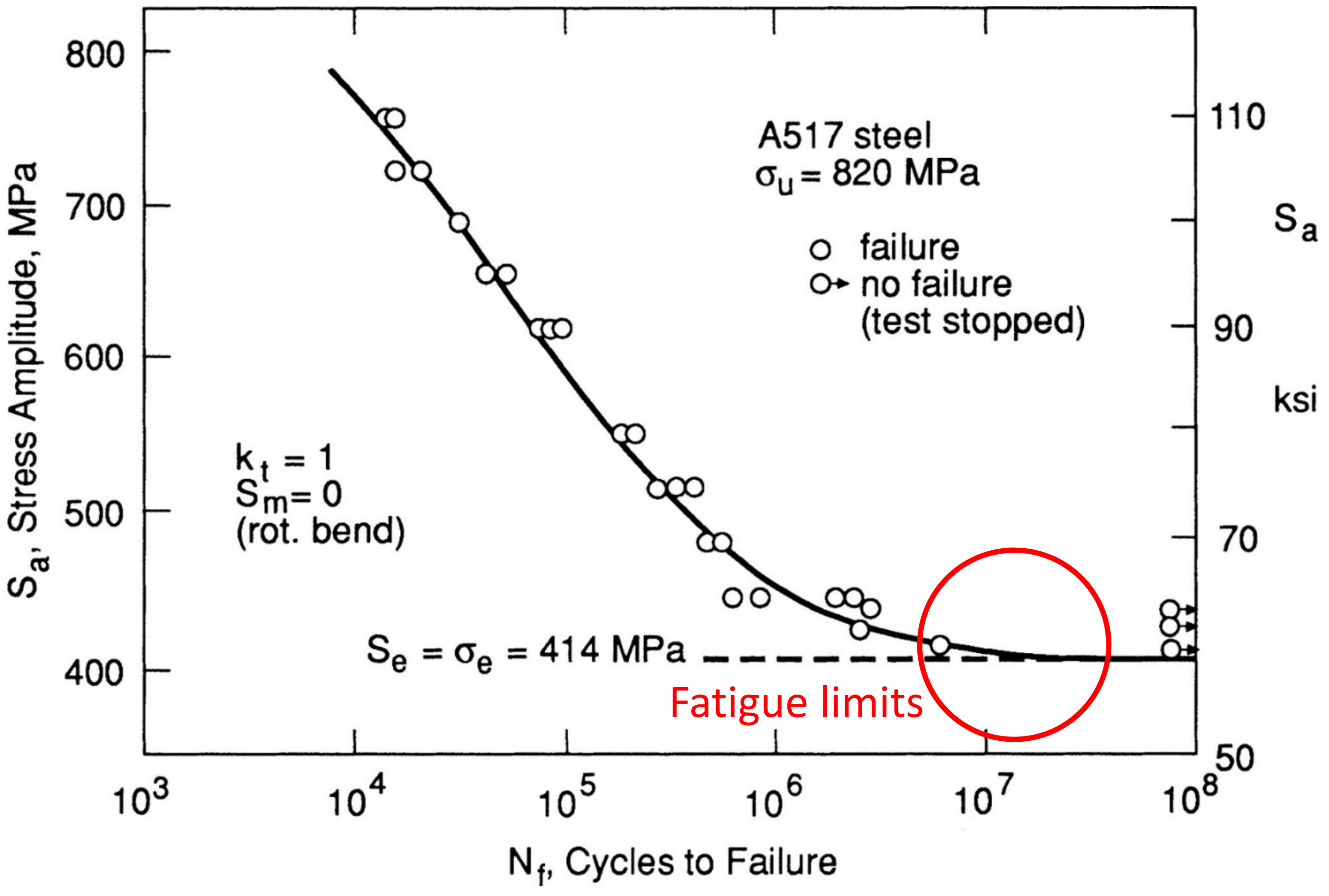


Figure 9.5 Rotating bending S-N curve for unnotched specimens of a steel with a distinct fatigue limit. (Adapted from [Brockenbrough 81]; used with permission.)

9.2.3 Stress Versus Life (S-N) Curves

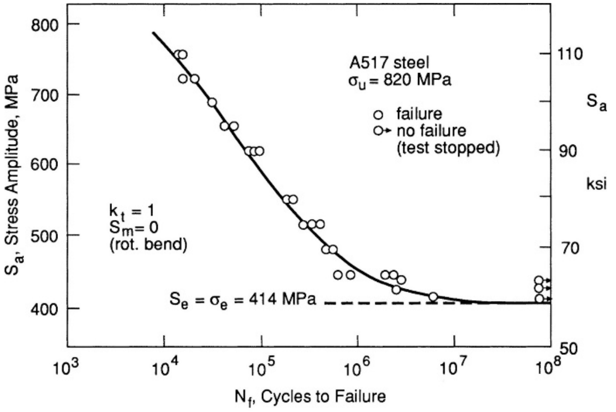


Figure 9.5

(9.5) Log-linear plot, $\sigma_a = C + D \log N_f$

(9.6) Log-log plot, $\sigma_a = AN_f^B$

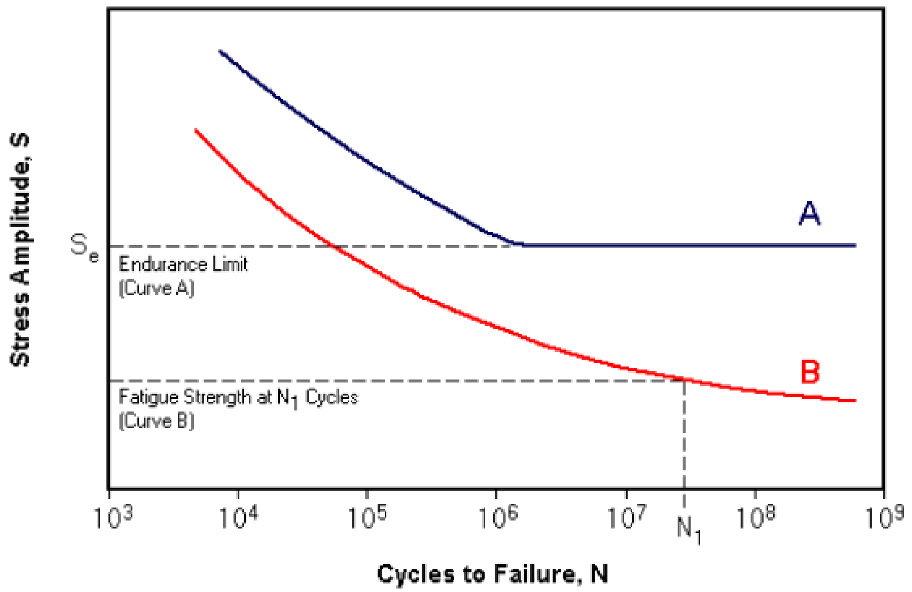
(9.7) Different Log-log plot, $\sigma_a = \sigma_f'(2N_f)^b$

(9.8) $A = 2^b\sigma_f' \quad B = b$

Table 9.1 Constants for stress-life curves for various ductile engineering metals, From tests at zero mean stress on unnotched axial specimens

	$\sigma_a = \sigma_f'(2N_f)^b = AN_f^B$		
Material	σ_f'	A	$b = B$
(a) Steels			
SAE 1015 (normalized)	1020 (148)	927 (134)	−0.138
Man-Ten (hot rolled)	1089 (158)	1006 (146)	−0.115
RQC-100 (roller Q & T)	938 (136)	897 (131)	−0.0648
SAE 4142 (Q & T, 450 HB)	1937 (281)	1837 (266)	−0.0762

9.2.3 Stress Versus Life (S-N) Curves



- **B, Fatigue Strength**
  - A stress amplitude value from an S-N curve at a particular life of interest.
- **A, Endurance Limit, S_e (or σ_{erb}, Fatigue Limit) for most steels**
  - If the applied stress level is below the endurance limit of the material, the structure is said to have an safe and infinite life.
  - The endurance limit is due to interstitial elements, such as carbon or nitrogen in iron, which pin dislocations. This prevents the slip mechanism that leads to the formation of micro cracks.

9.6.1 Trends with Ultimate Strength

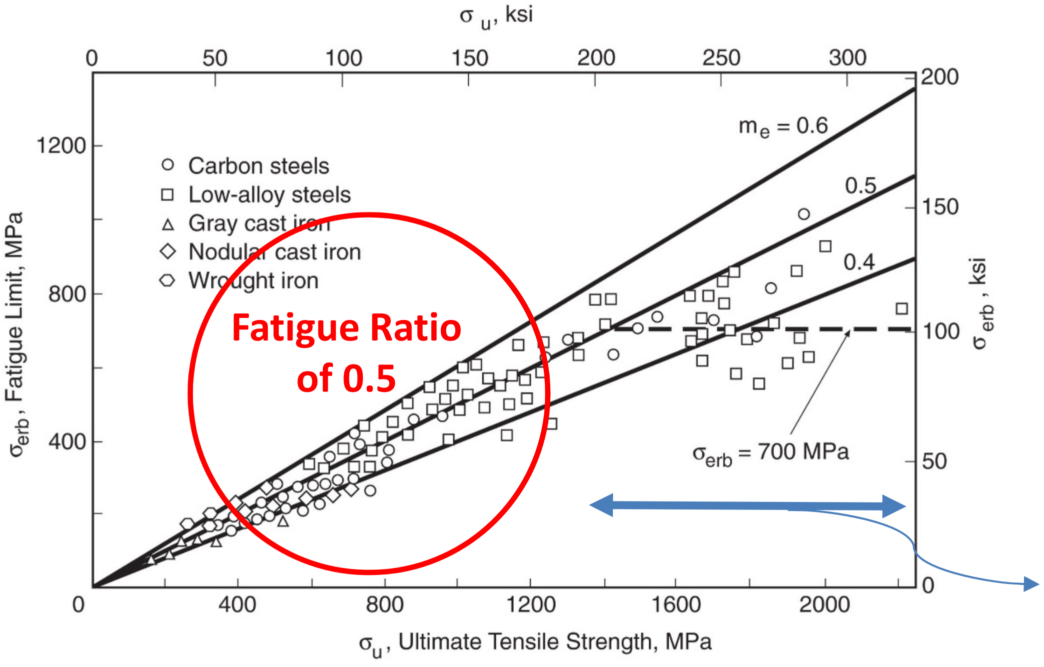


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Figure 9.24 Rotating bending fatigue limits, or failure stresses for 10^7 to 10^8 cycles, from polished specimens of various ferrous metals. The slopes $m_e = \sigma_{erb}/\sigma_u$ indicate the average and approximate extremes of the data for $\sigma_u < 1400$ MPa.

Most steels have limited ductility at high-strength levels

< Endurance Limit Related to Ultimate Strength>

$$S_e \approx 0.5 \times S_u \;\; for \;\; S_u \le 200ksi \qquad = 1379\text{Mpa}$$

$$S_e \approx 100ksi \;\; for \;\; S_u > 200ksi$$

-> A reasonable degree of ductility is helpful in providing resistance to cyclic loading.

-> Too high-strength materials can lead to fatigue failures.

9.2.4 Safety Factors for S-N Curves

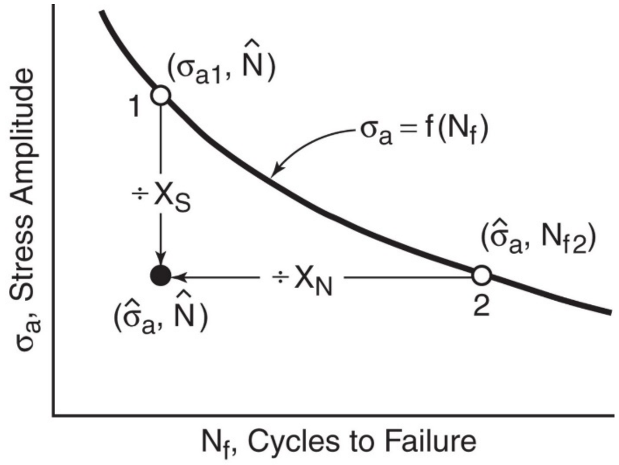

Figure 9.6 Stress–life curve and the stress amplitude and number of cycles expected in actual service, σ_a and N, giving safety factors X_s in stress and X_N in life.

(9.9) The safety factor in stress, $X_S = \frac{\sigma_{a1}}{\hat{\sigma}_a}, (N_f = \hat{N})$

(9.10) The safety factor in life, $X_N = \frac{N_{f2}}{\hat{N}}, (\sigma_a = \hat{\sigma}_a)$

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9.3 Sources of Cyclic Loading

- Some practical applications involve cyclic loading at a constant amplitude, but irregular load versus time histories are more commonly encountered.

Loads	Characteristics
Static loads	Do not vary and continuously present Ex) Highway bridge, The always-present weight of the structure and roadway
Working loads	Change with time and incurred as a result of the function performed by the component Ex) The weight of vehicles, forces due to inertia
Vibratory loads	Relatively high-frequency cyclic loads from environment or as a secondary effect of the function of the component Ex) tires interacting with the roughness of the roadway, bouncing of vehicle, wind turbulance
Accidental loads	Rare events occurring under abnormal circumstances Ex) Vehicle accident, Earthquake

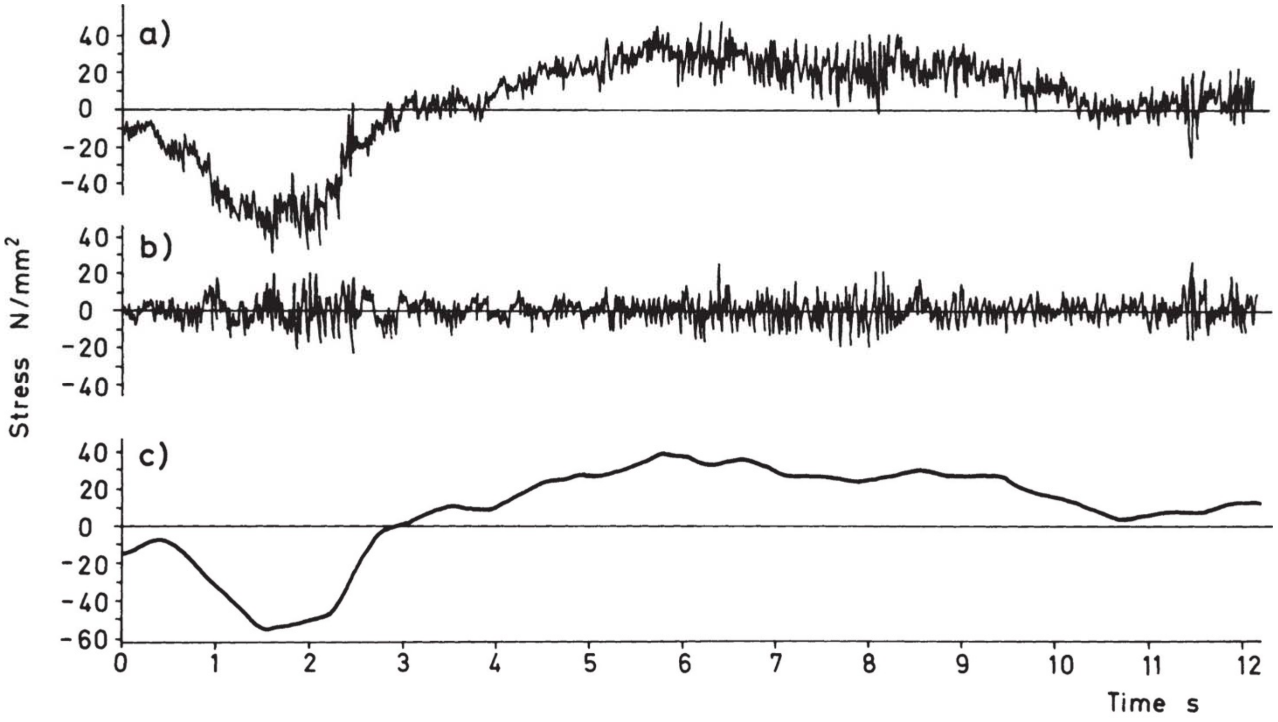
- Working loads and vibratory loads are the cyclic loads causing fatigue failure. However, the damage due to static loads and accidental loads also plays an additional role.

I-5 Skagit River Bridge collapse: Accidental loads

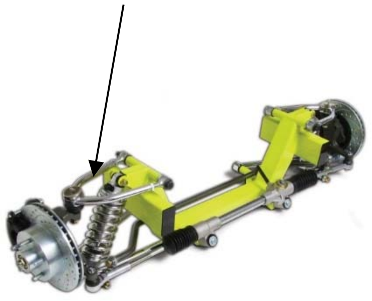
A collapsed section of the Interstate 5 bridge over the Skagit River (north of Seattle) is seen in an aerial view Friday, May 24, 2013.

*http://www.columbian.com/news/2013/may/24/north-wash-i-5-bridge-collapse-caused-oversize-loa/

9.3 Sources of Cyclic Loading



Steering Knuckle arm



Chassis Suspension

Figure 9.7 Sample record of stresses at the steering knuckle arm of a motor vehicle, including the original stress–time history (a), and the separation of this into the vibratory load due to roadway roughness (b) and the working load due to maneuvering the vehicle (c). (From [Buxbaum 73]; used with permission; first published by AGARD/NATO.)

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2. Definitions and Concepts
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    - **Microscopic**
    - **Macroscopic**
6. Trends in S-N Curves
7. Mean Stresses
8. Multiaxial Stresses
9. Variable Amplitude Loading
10. Variable Amplitude Loading

9.5 The (Microscopic) physical Nature of Fatigue Damage

- When viewed at a sufficiently small size scale, all materials are anisotropic and inhomogeneous. (∵ grain, crystal plane, voids, particles)
- As a result of nonuniform microstructure, stresses are distributed in a nonuniform manner when viewed at the micro size.
- Regions where the stresses are severe are usually the points where fatigue damage starts.

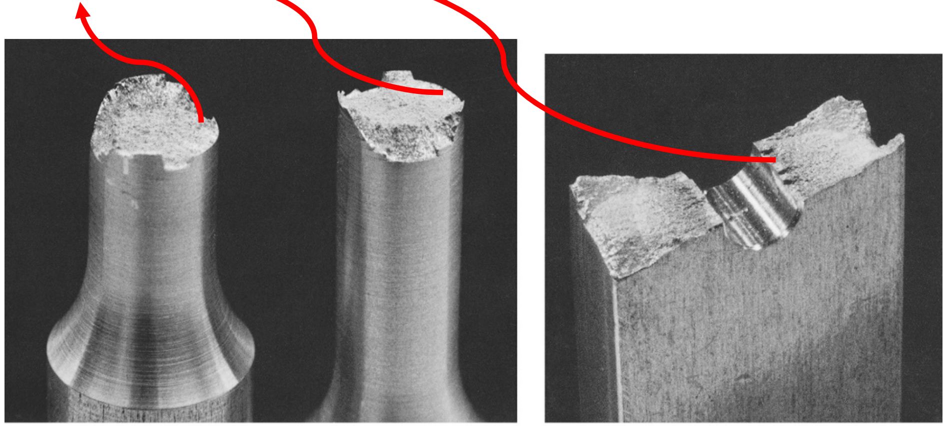


Figure 9.16 Photographs of broken 7075-T6 aluminum fatigue test specimens: unnotched axial specimen, 7.6 mm diameter (left); and plate 19 mm wide with a round hole (right). In the unnotched specimen, the crack started in the flat region with slightly lighter color, and cracks in the notched specimen started on each side of the hole.

9.5 The (Microscopic) physical Nature of Fatigue Damage

- *For ductile engineering metals*, crystal grains that have an unfavorable orientation relative to the applied stress first develop slip bands.
- Additional slip bands form as more cycles are applied until saturation level.
- Individual slip bands become more severe, and some develop into cracks within grains, which then spread into other grains, joining with other similar cracks, and producing a large crack that propagates to failure.

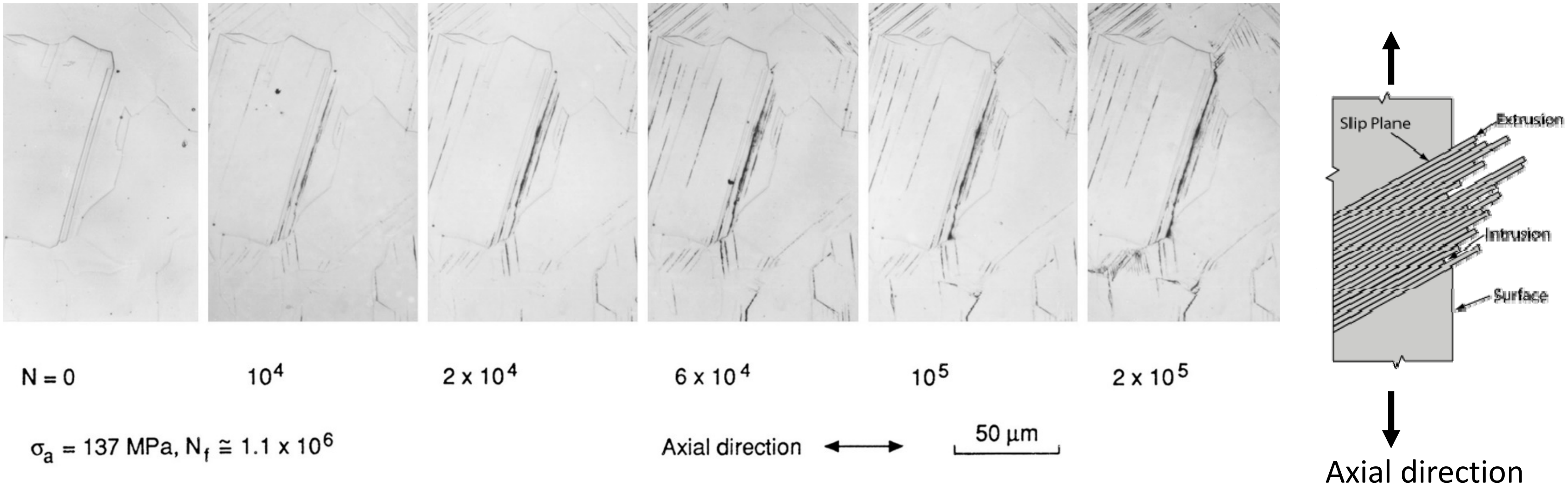
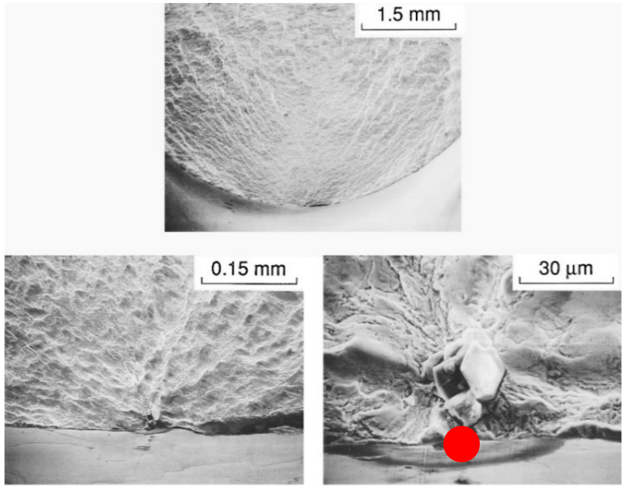


Figure 9.17 The process of slip band damage during cyclic loading developing into a crack in an annealed 70Cu-30Zn brass.

9.5 The (Microscopic) physical Nature of Fatigue Damage

- *For materials of somewhat limited ductility*, such as high-strength metals, the microstructural damage is less widespread and tends to be concentrated at defects in the materials.
- A small crack develops at a void, inclusion, slip band, grain boundary, or surface scratch, or there may be a sharp flaw initially present that is essentially a crack. This crack grows in a plane generally normal to the tensile stress until it causes failure.



Crack Started from the inclusion

Figure 9.18 Fatigue crack origin in an unnotched axial test specimen of AISI 4340 steel

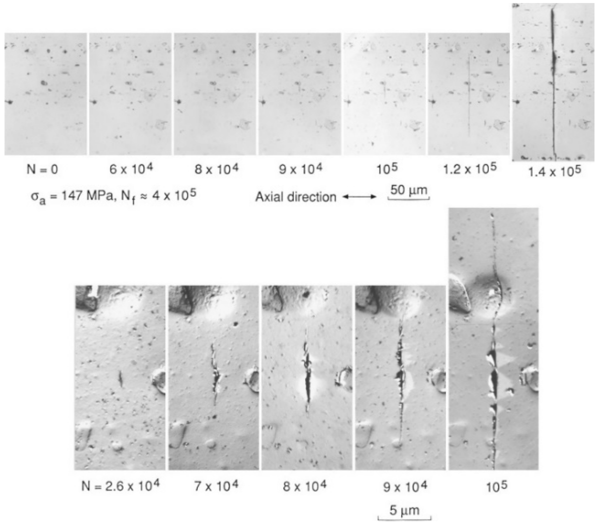
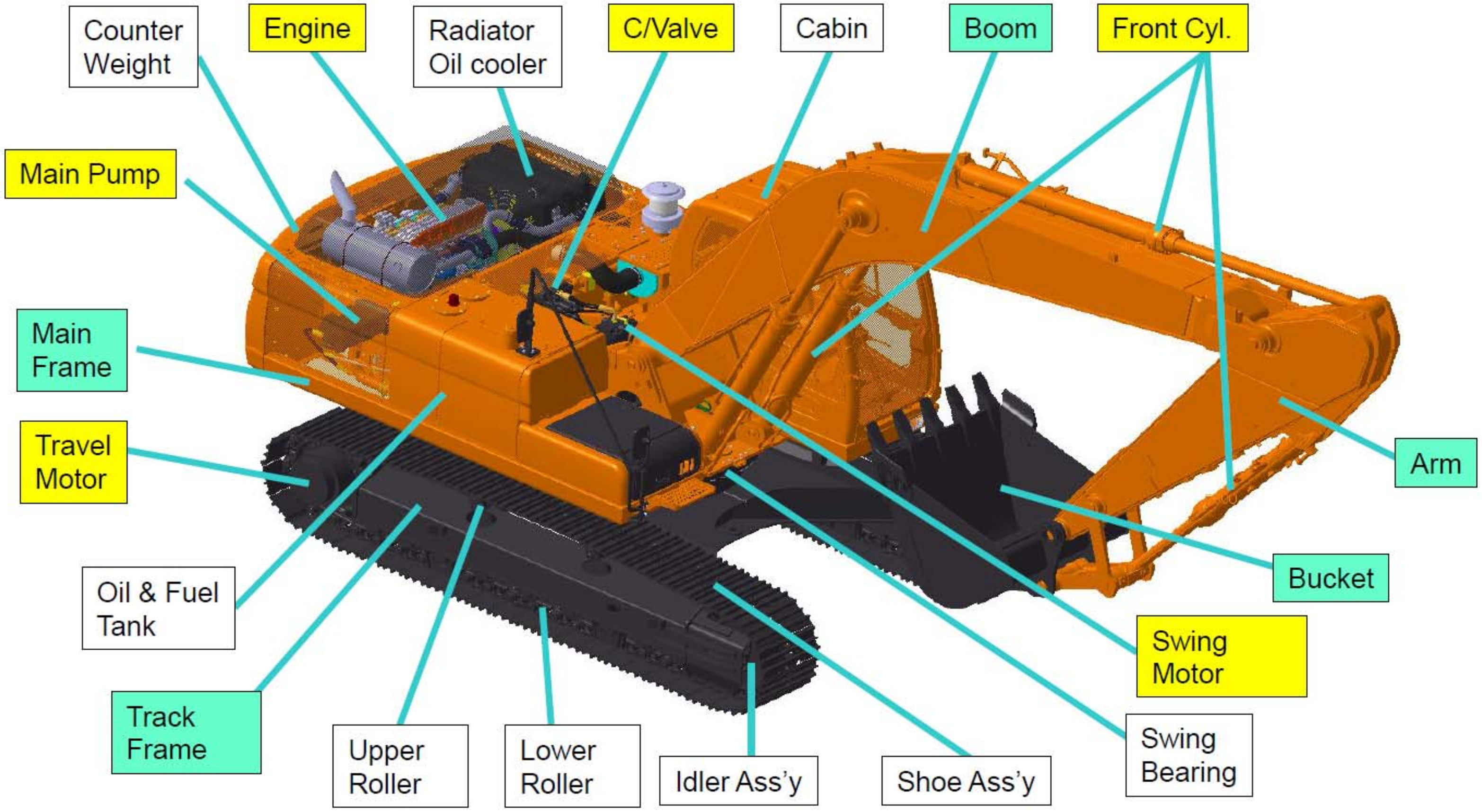


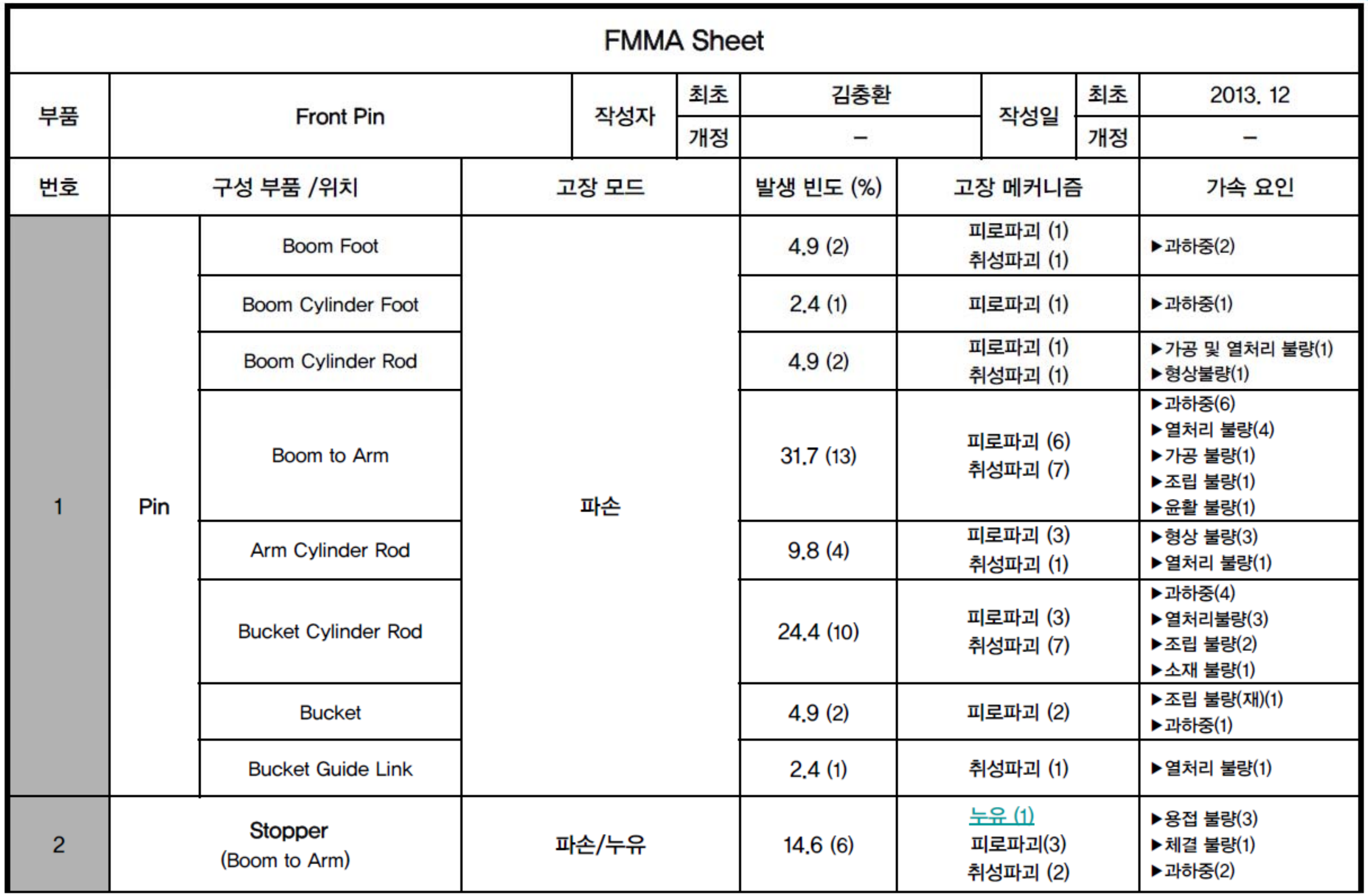
Figure 1.8 Development of a fatigue crack during rotating bending of a precipitation-hardened aluminum alloy.

Excavator and Its Main Components

주요 구성 부품(Crawler)



3. FMMA Sheet



FMMA Sheet

부품	Front Pin	작성자	최초	김충환	작성일	최초	2013. 12
			개정	–		개정	–

번호	구성 부품 /위치		고장 모드	발생 빈도 (%)	고장 메커니즘	가속 요인
1	Pin	Boom Foot	파손	4.9 (2)	피로파괴 (1) 취성파괴 (1)	▶과하중(2)
		Boom Cylinder Foot		2.4 (1)	피로파괴 (1)	▶과하중(1)
		Boom Cylinder Rod		4.9 (2)	피로파괴 (1) 취성파괴 (1)	▶가공 및 열처리 불량(1) ▶형상불량(1)
		Boom to Arm		31.7 (13)	피로파괴 (6) 취성파괴 (7)	▶과하중(6) ▶열처리 불량(4) ▶가공 불량(1) ▶조립 불량(1) ▶윤활 불량(1)
		Arm Cylinder Rod		9.8 (4)	피로파괴 (3) 취성파괴 (1)	▶형상 불량(3) ▶열처리 불량(1)
		Bucket Cylinder Rod		24.4 (10)	피로파괴 (3) 취성파괴 (7)	▶과하중(4) ▶열처리불량(3) ▶조립 불량(2) ▶소재 불량(1)
		Bucket		4.9 (2)	피로파괴 (2)	▶조립 불량(재)(1) ▶과하중(1)
		Bucket Guide Link		2.4 (1)	취성파괴 (1)	▶열처리 불량(1)
2	Stopper (Boom to Arm)		파손/누유	14.6 (6)	누유 (1) 피로파괴(3) 취성파괴 (2)	▶용접 불량(3) ▶체결 불량(1) ▶과하중(2)

4. Failure Analysis Review Sheet

<table>
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<tr><td>제목</td><td colspan="5">S55–V Bucket Pin 절손원인조사</td><td>고장 모드 / 메커니즘</td><td>파손/열처리불량(취성파괴)</td></tr>
<tr><td>보고서 번호</td><td>TE99MX–361</td><td>기종</td><td>S55–V</td><td>작성자</td><td>이영근</td><td>작성일</td><td>1999.06.05</td></tr>
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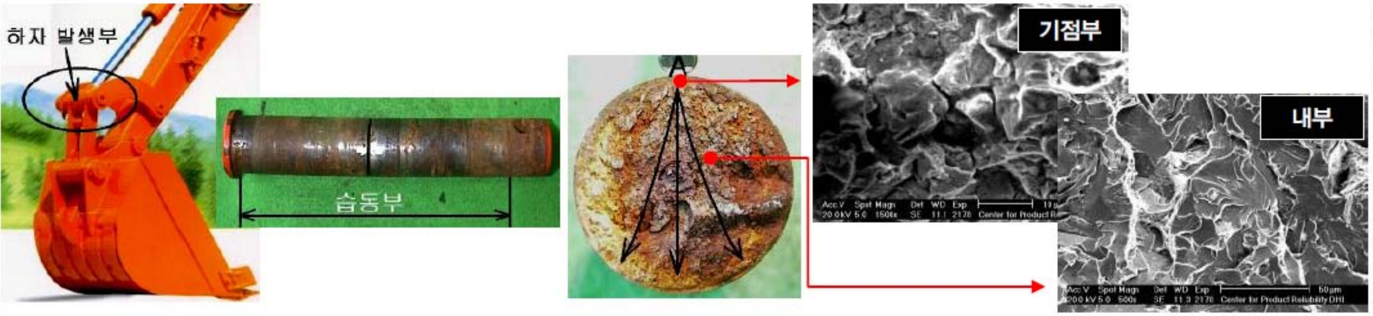
<tr><td>고장 상황</td><td colspan="7">
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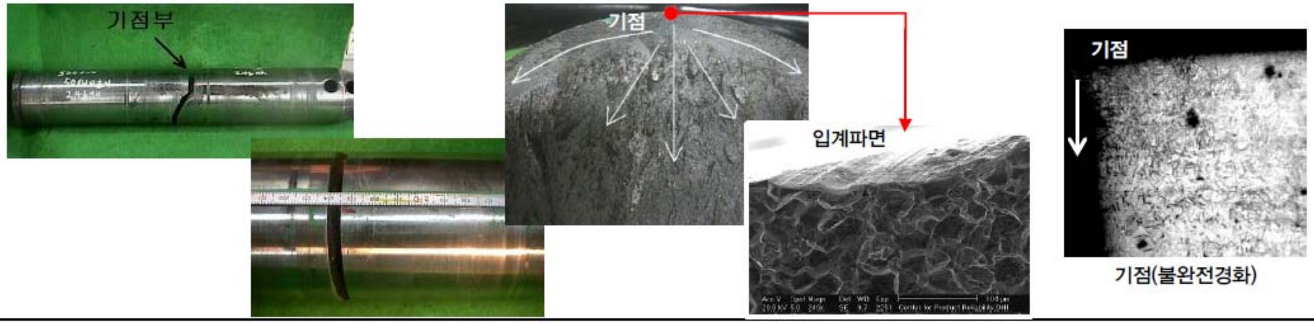
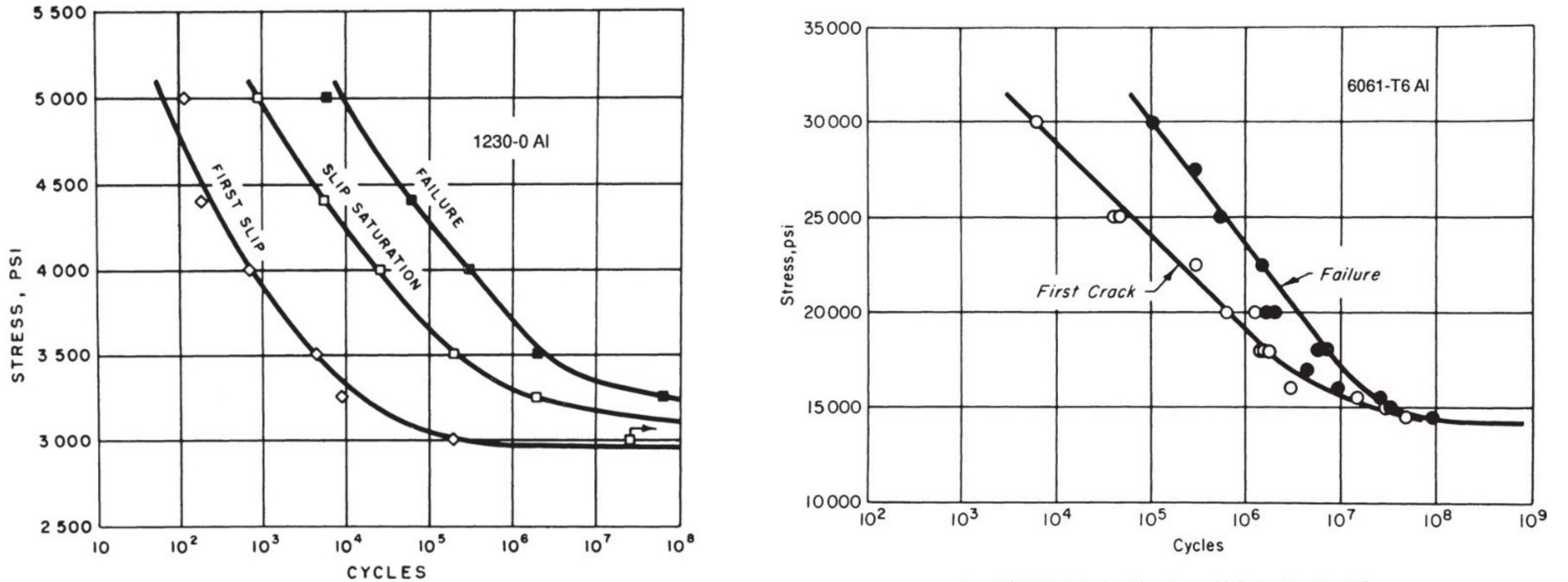
<tr><td>고장 설명</td><td colspan="7">▶Bush(Bucket Cylinder Rod Bush와 Push Link Bush)와 습동되는 길이의 약 1/2 정도에서 절손
▶기점부 근방인 표면 경화부에서는 입계+피로파괴 양상으로 나머지 파면은 취성(벽개)파괴 양상임.</td></tr>
<tr><td>재료</td><td colspan="3">SM45C</td><td>열처리 종류</td><td colspan="3">QT + 고주파</td></tr>
<tr><td>화학 성분</td><td colspan="3">양호
C 0.45 Si 0.22 Mn 0.71 P 0.018 S 0.012</td><td>기계적 성질</td><td colspan="3">열처리 불량
표면(HRC 47.1~61.7) / 내부(HBW 181) / 깊이(0.55 mm)</td></tr>
<tr><td>부하 조건</td><td colspan="3">–</td><td>사용 기간 / 환경 조건</td><td colspan="3">324 시간</td></tr>
<tr><td>고장 원인과 대책</td><td colspan="7">▶열처리품질 불량(조질처리 불량 및 불완전 경화)으로 인한 소재의 인성부족에 의해서 취성파괴됨.
▶열처리품질 확보방안을 강구하기 위한 QT, 고주파열처리 공정에 대한 개선이 필요함.</td></tr>
</table>

4. Failure Analysis Review Sheet

Failure Analysis Sheet							
제목	S220-V Bucket Cylinder Pin 절손 원인조사				**고장 모드 / 메커니즘**	파손/열처리불량(취성파괴)	
보고서 번호	TE99MX-673	**기종**	S220-V	**작성자**	이영근	**작성일**	1999.10.25
부품	Bucket Cyl. Pin						
고장 상황	 기점(불완전경화)						
고장 설명	▶절손은 전체 길이의 약 1/2지점으로 Bucket Cylinder Bush의 한쪽 끝단부 근방에서 절손						
재료	SCM440/KBMA 75			**열처리 종류**	QT + 고주파		
화학 성분	SCM440 (양호) C 0.43 Si 0.24 Mn 0.77 P 0.021 S 0.014 Cr 0.96 Mo 0.17			**기계적 성질**	**열처리 불량** 표면(HRC **51.4~60.6**) / 내부(HBW 254) / 깊이(4.1 mm)		
부하 조건	–			**사용 기간 / 환경 조건**	246 시간		
고장 원인과 대책	▶불완전 경화로 인해 응력 불균일이 발생되고 취성이 증대되어 경계부에서 사용중 일시적으로 집중응력이 인가되면서 조기에 절손이 발생된 것으로 판단. ▶고주파경화 공정개선을 통한 불완전경화발생 방지방안 강구 필요.						

9.5 The (Microscopic) physical Nature of Fatigue Damage



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< Material of Ductility>

< Material of Limited Ductility>

Figure 9.19 Stress–life curves for completely reversed bending of smooth specimens, showing various stages of fatigue damage in an annealed 99% aluminum (1230-0), and in a hardened 6061-T6 aluminum alloy.

9.5 The (Macroscopic) physical Nature of Fatigue Damage

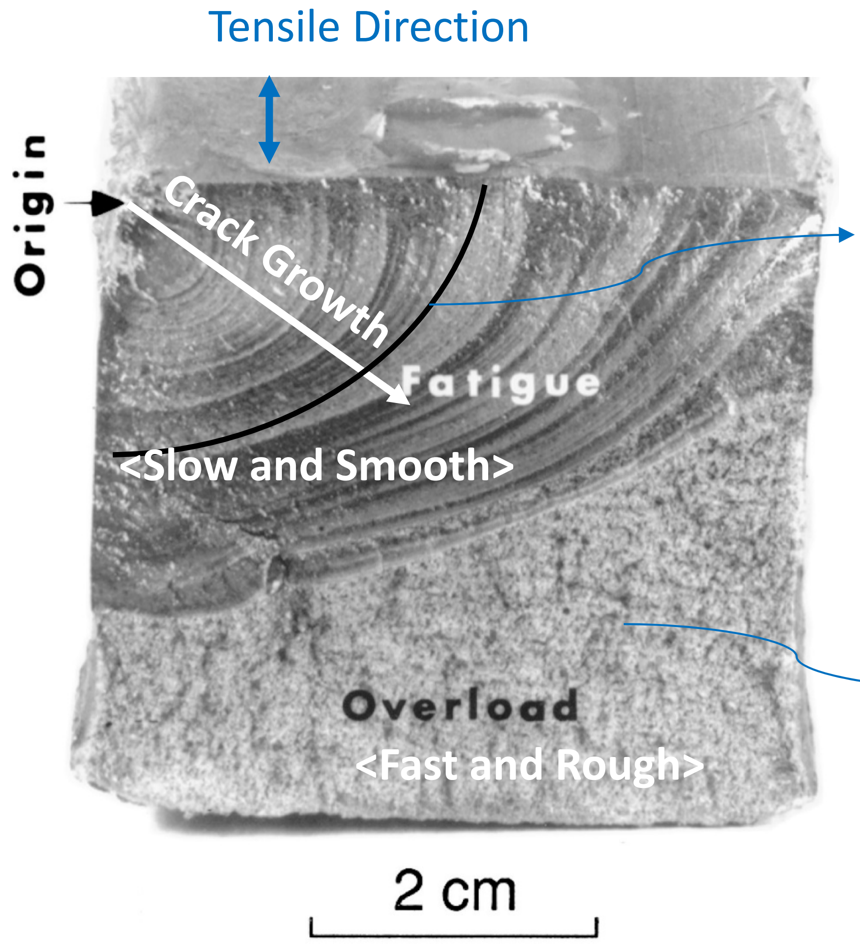
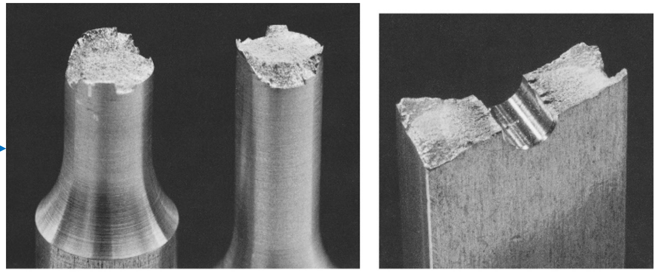


Figure 9.21 Fracture surfaces for fatigue and final brittle fracture in an 18 Mn steel member.

<Beach marks (the process of crack)>

(1) Growth rate change due to altered stress level, temperature, chemical environment

(2) Discoloration due to corrosion



<Shear lip>

- Ductile material forms a shear lip, inclined at approximately 45 degrees to the applied stress

9.5 The (Microscopic) physical Nature of Fatigue Damage

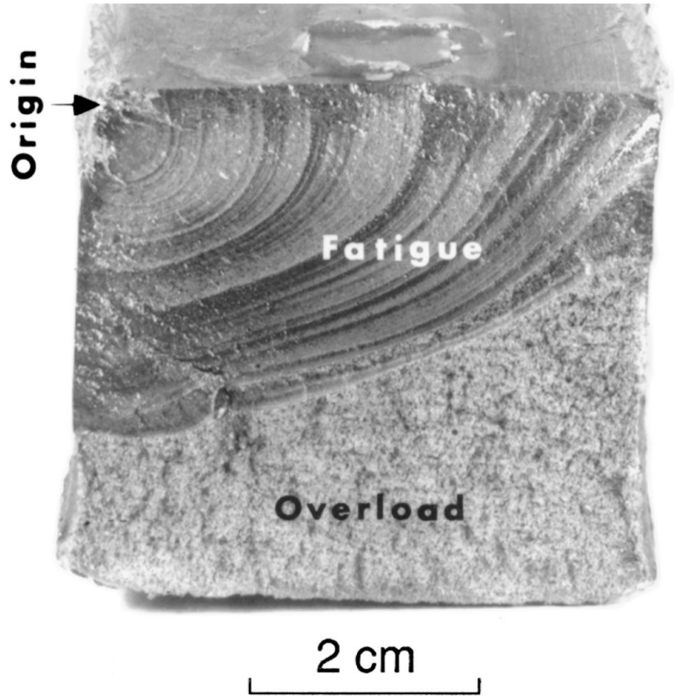
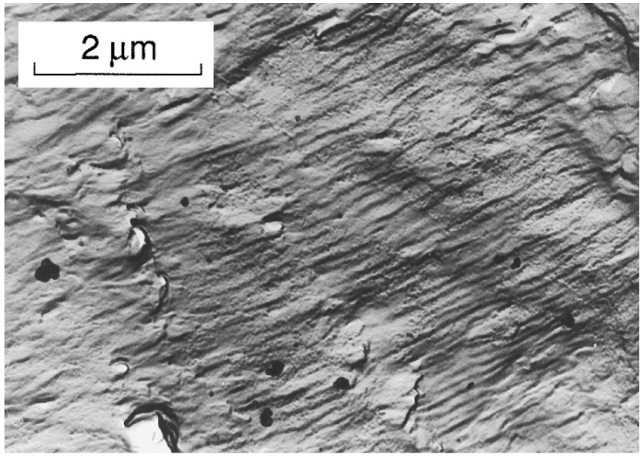


Figure 9.21 Fracture surfaces for fatigue and final brittle fracture in an 18 Mn steel member.



<Striations>

- Ductile material often reveals marks left by the progress of the crack on each cycle.

Figure 9.22 Fatigue striations spaced approximately 0.12 μm apart, from a fracture surface of a Ni-Cr-Mo-V steel.

Contents

9.6 TRENDS IN S-N CURVES

- S-N curves vary widely for different classes of materials.
- The higher the S-N curve -> the more resistant to fatigue

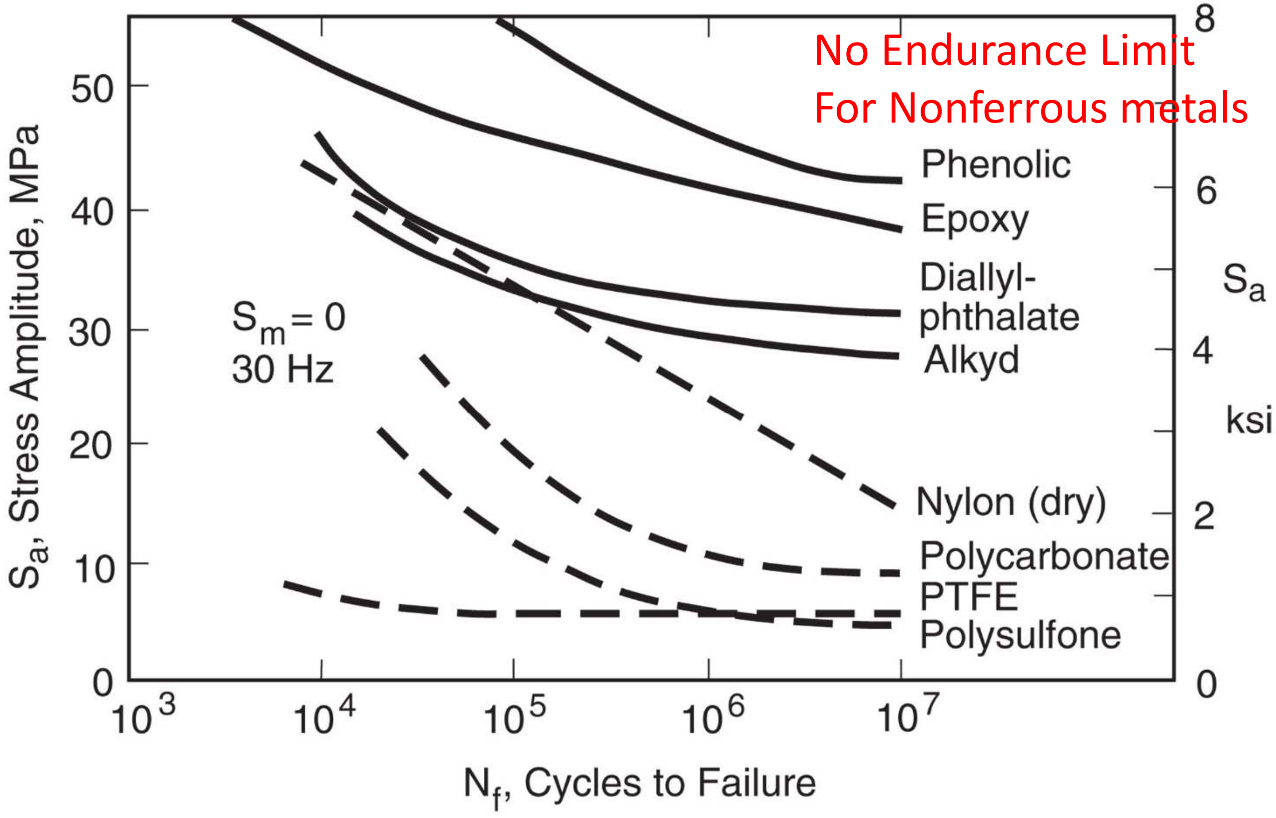


Figure 9.23 Stress–life curves from cantilever bending of mineral and glass-filled thermosets (solid lines) and unfilled thermoplastics (dashed lines).

9.6.1 Trends with Ultimate Strength

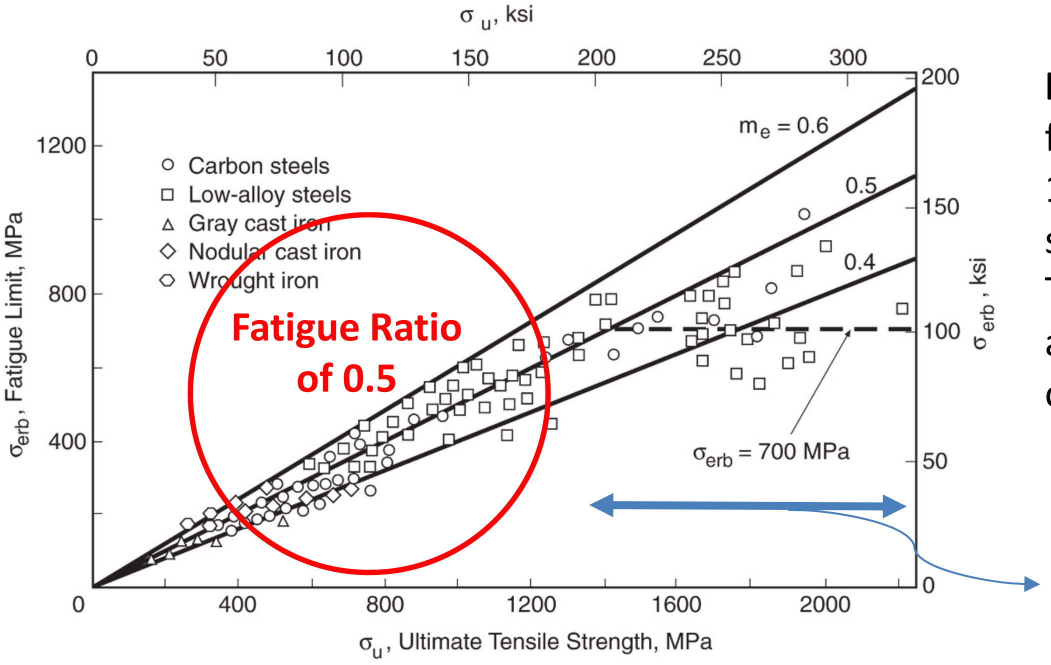


Figure 9.24 Rotating bending fatigue limits, or failure stresses for 10^7 to 10^8 cycles, from polished specimens of various ferrous metals. The slopes $m_e = \sigma_{erb}/\sigma_u$ indicate the average and approximate extremes of the data for σ_u < 1400 MPa.

Most steels have limited ductility at high-strength levels

< Endurance Limit Related to Ultimate Strength>

$$S_e \approx 0.5 \times S_u \;\; for \;\; S_u \leq 200ksi$$ = 1379Mpa

$$S_e \approx 100ksi \;\; for \;\; S_u > 200ksi$$

-> A reasonable degree of ductility is helpful in providing resistance to cyclic loading.

-> Too high-strength materials can lead to fatigue failures.

9.6 TRENDS IN S-N CURVES

Factors lowering the S-N curve	Factors raising the S-N curve
- Reduce the value of endurance limit - Shorten the life - Lowering the fatigue strength	- Increase the value of endurance limit - Extension of the life - Raising the fatigue strength
- High-strength material (limited-ductility material) - Tensile mean stress - Stress raisers (notches, high stress concentration factor k_t) - Harsh environment (high temperature, salt solution, moisture and gases in air) - Micro defects (larger size of inclusions and voids, larger size of grains (annealing))	- High ultimate strength - Compressive mean stress - Dense network of dislocations - Processing without decreasing the ductility (cold rolling, shoot peening, carburization) Chapter Later on $S_e = C_L C_G C_S C_T C_R S_e'$ (Moore endurance limit)

9.6.1 Trends with Mean Stresses

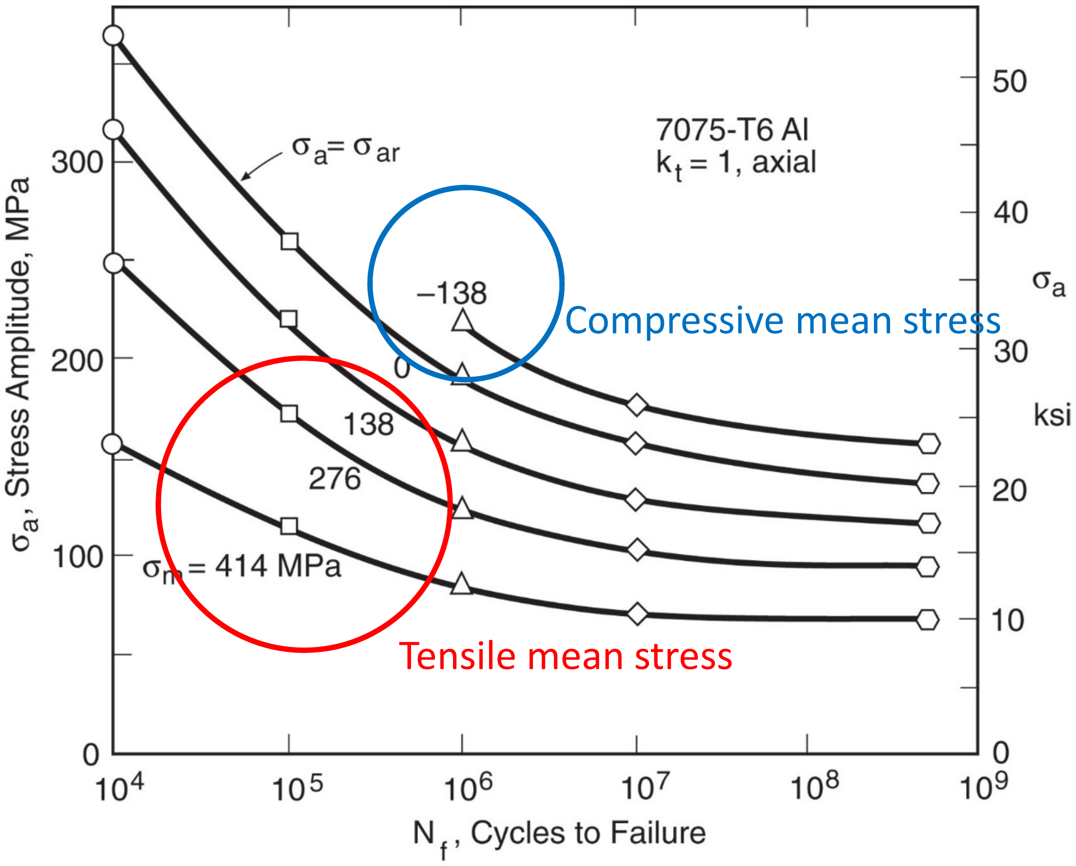


Figure 9.26 Axial loading S-N curves at various mean stresses for unnotched specimens of an aluminum alloy. The curves connect average fatigue strengths for a number of lots of material.

9.6.1 Trends with Member Geometry

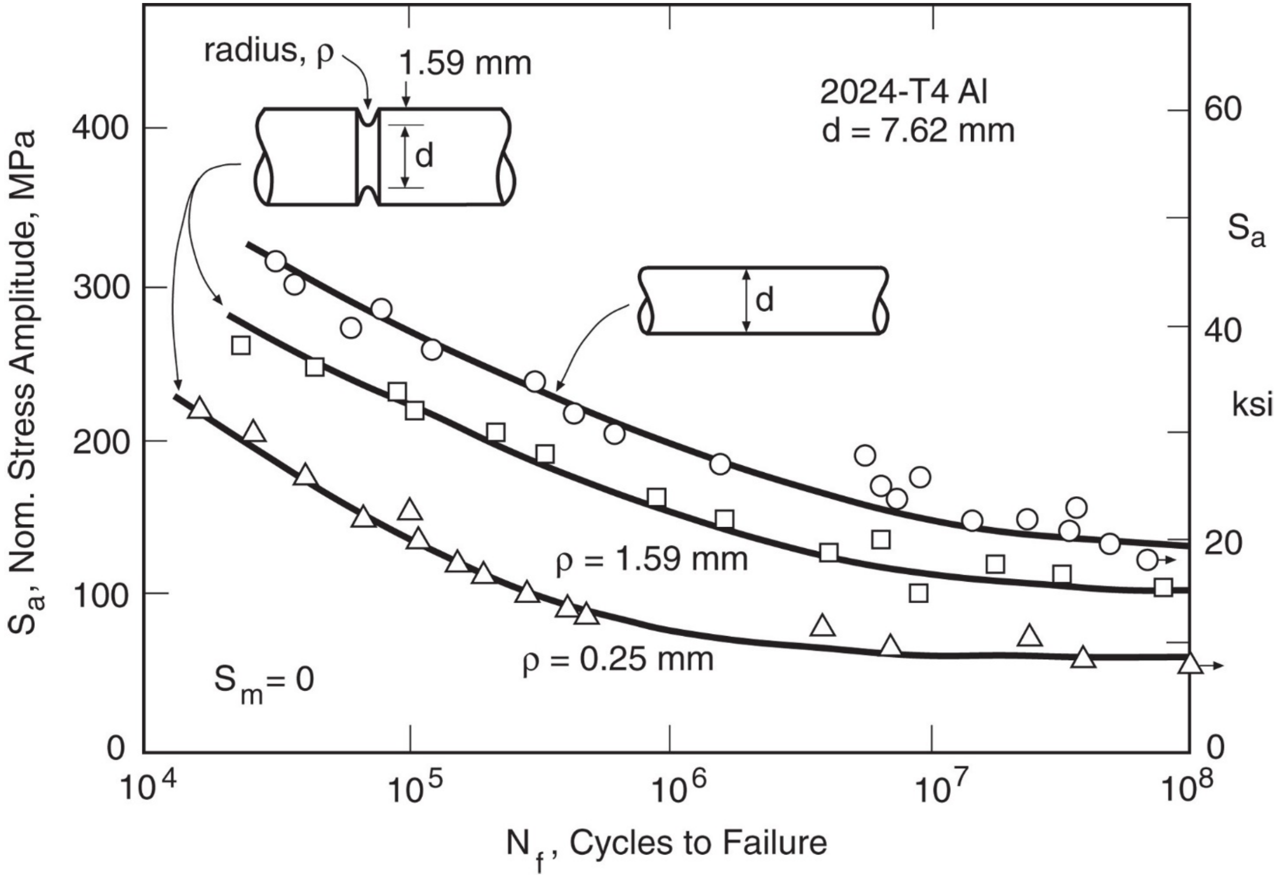


Figure 9.27 Effects of notches having k_t = 1.6 and 3.1 on rotating bending S-N curves of an aluminum alloy. (Adapted from [MacGregor 52].)

9.6.2 Effects of Environment

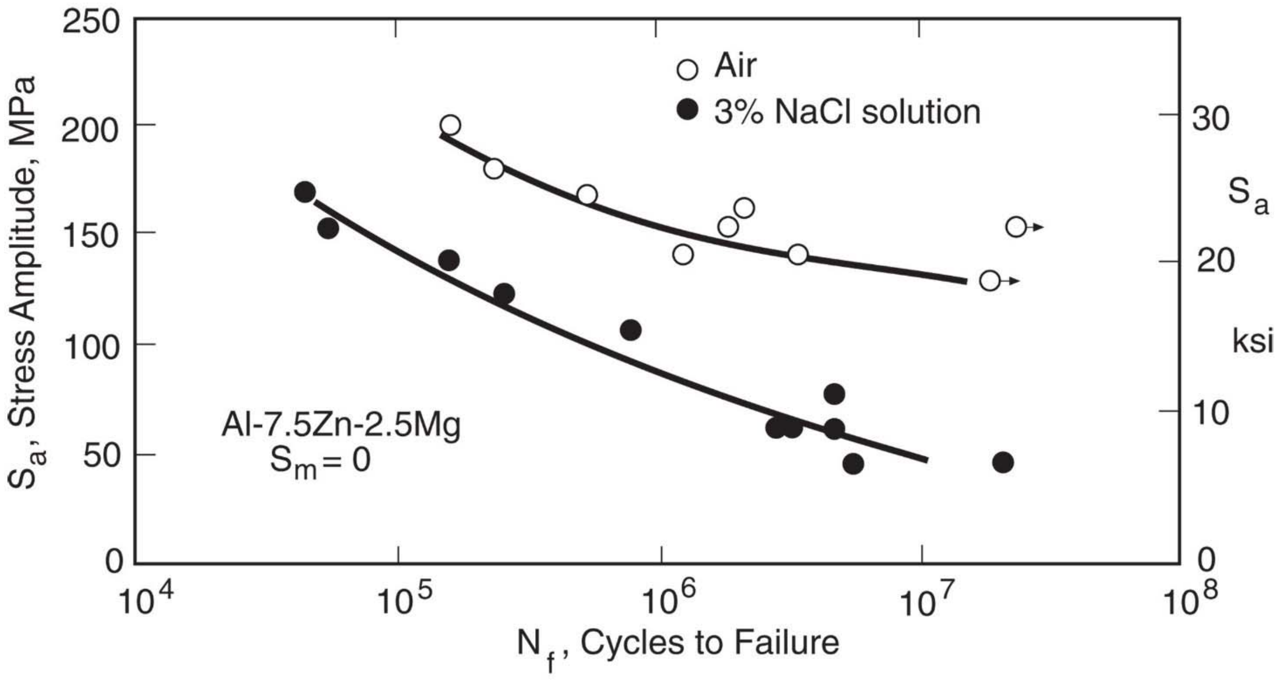


Figure 9.28 Effect of a salt solution similar to seawater on the bending fatigue behavior of an aluminum alloy. (Data from [Stubbington 61].)

9.6.2 Effects of Environment

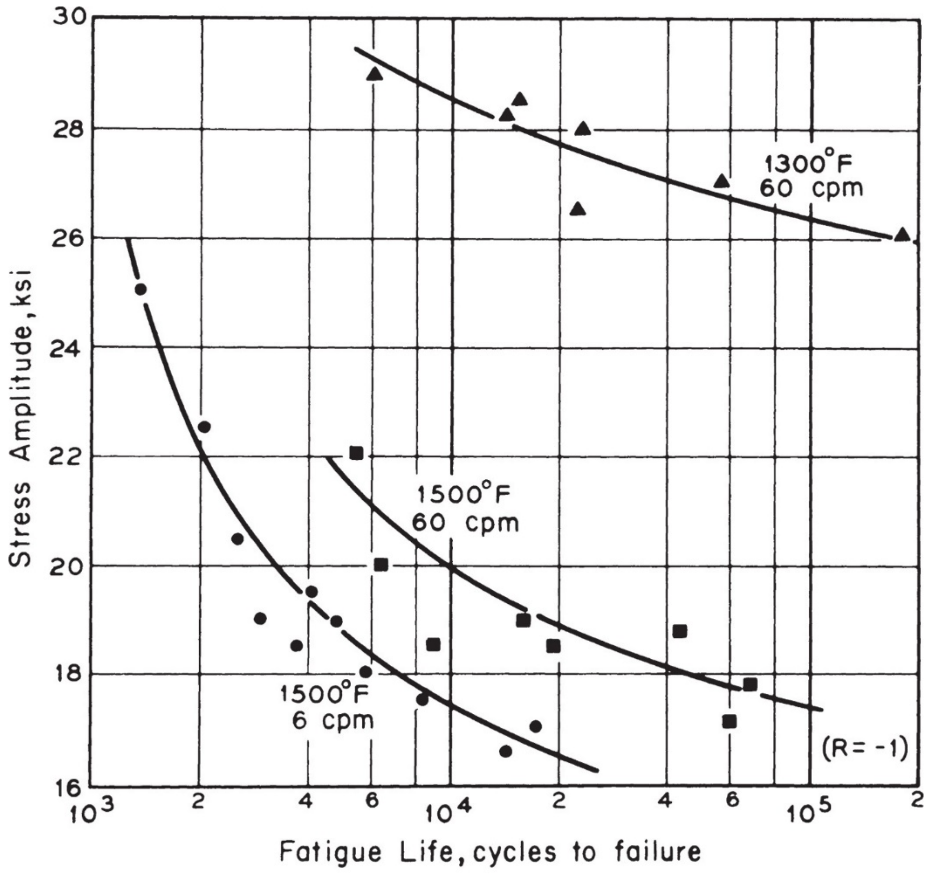


Figure 9.29 Temperature and frequency effects on axial S-N curves for the nickel-base alloy Inconel. (Illustration from [Gohn 64] of data in [Carlson 59]; used with permission.)

* cpm: harsh condition cycles per minute

9.6.3 Effects of Microstructure

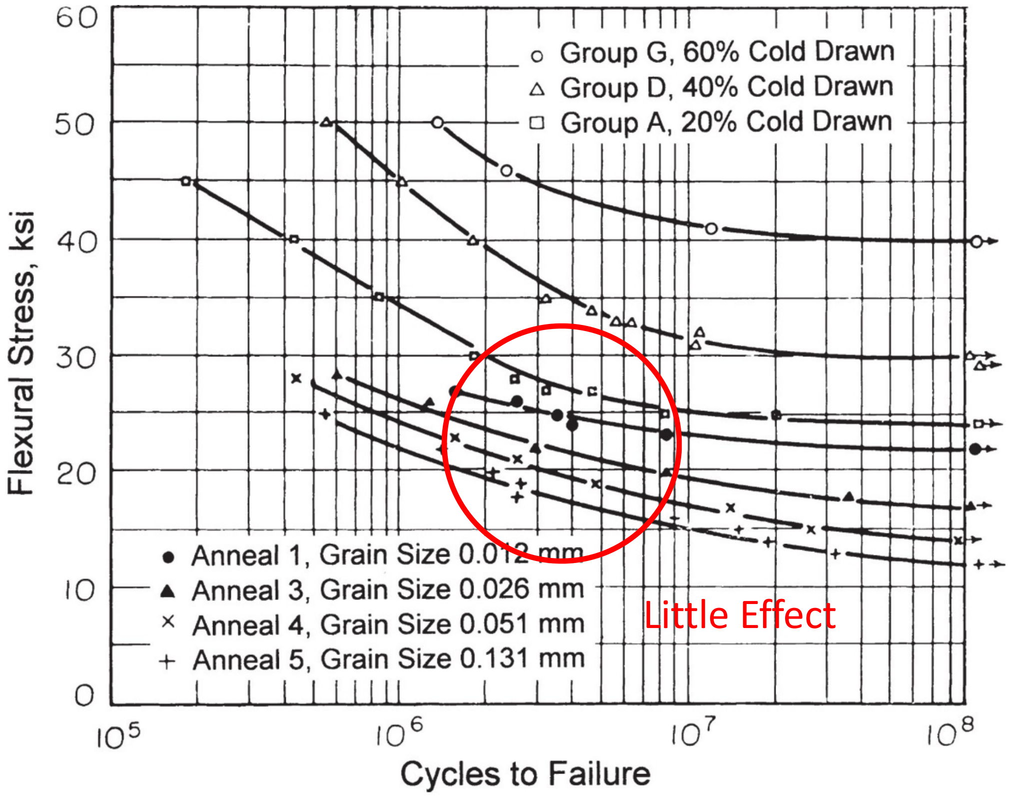


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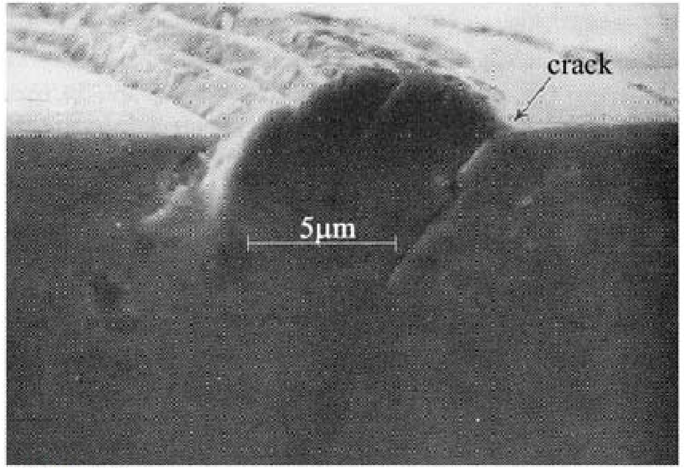
Figure 9.30 Influence of grain size and cold work on rotating bending S-N curves for 70Cu-30Zn brass. (From [Sinclair 52]; used with permission.)

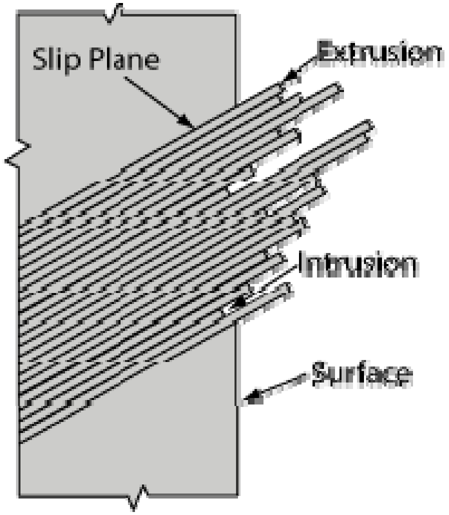
Grain size, Dislocation, and Fatigue

What is the relationship between dislocation and fatigue failure?

- The fatigue life has two parts, initiation and propagation.
- A dislocation plays a major role in the fatigue crack initiation.
- After a large number of loading cycles, dislocations pile up and form structures called persistent slip bands.
- Persistent slip bands are areas that rise above (extrusion) or fall below (intrusion) the surface of the component due to movement of material along slip planes.
- This leaves tiny steps in the surface that serve as stress raisers where fatigue cracks can initiate.



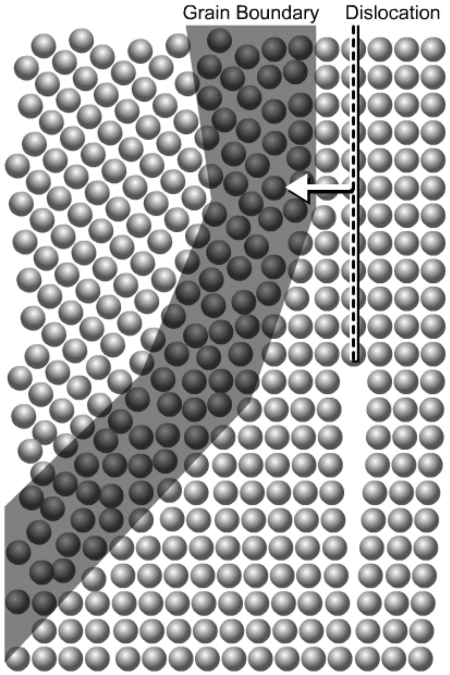
(Suresh 1991)



*https://www.ndeed.org/EducationResources/CommunityCollege/Materials/Structure/fatigue.htm

Grain size, Dislocation, and Fatigue

Why does the small grain size make material more resistant to fatigue failure?

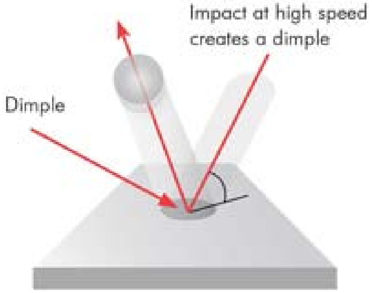


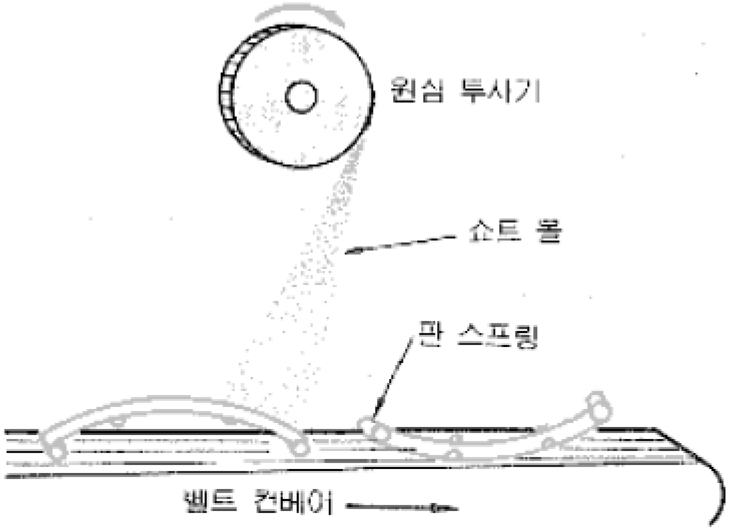
- A dislocation could move from one atomic plane to another with the defect like a wave traveling over the sea.
- However, a dislocation cannot carry on moving forever.
- A dislocation will run into a grain boundary, and stuck here.
- If the grain size is decreased, there will be an increase in area of the grain boundary compared to the number dislocations in the grain.

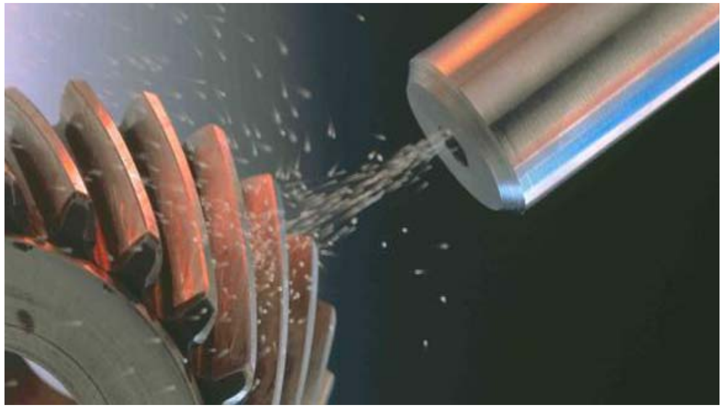
Why is it so difficult for the dislocation to travel through the boundary and what other problems would face it if it were to jump the gap?

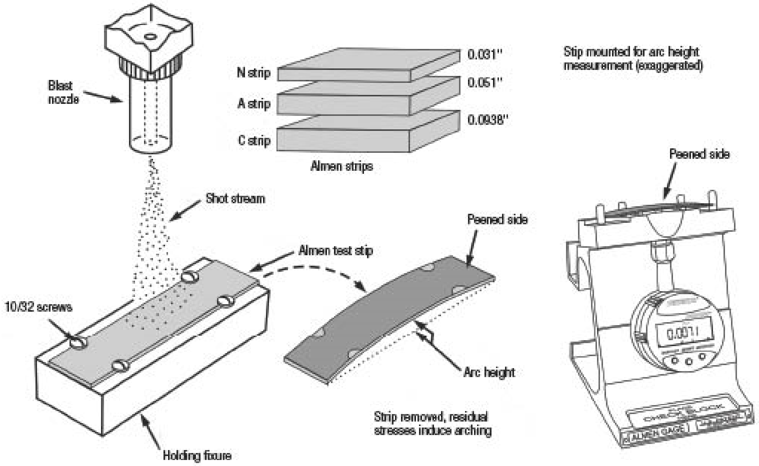
- Inside the grain boundary, the atoms are jumbled. As a result additional energy is required to force the dislocation through the boundary.

9.6.4 Residual Stress and Other Surface Effects
: Peening









*http://www.metalimprovement.co.uk/controlled-shot-peening.html

9.6.4 Residual Stress and Other Surface Effects

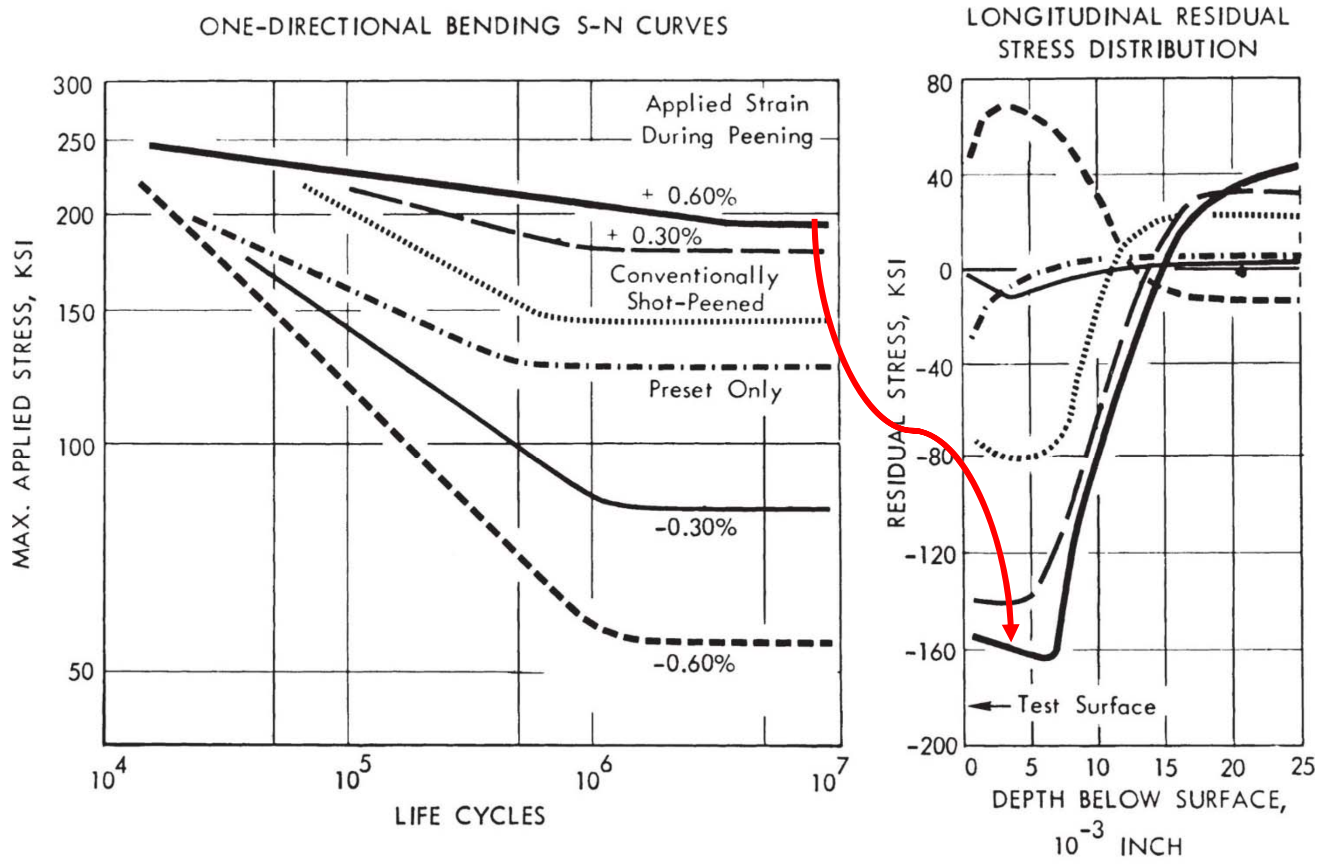


Figure 9.31 S-N curves for zero-to-maximum bending, and residual stresses, for variously shot peened steel leaf springs. (From [Mattson 59]; courtesy of General Motors Research Laboratories.)

9.6.5 Fatigue Limit Behavior

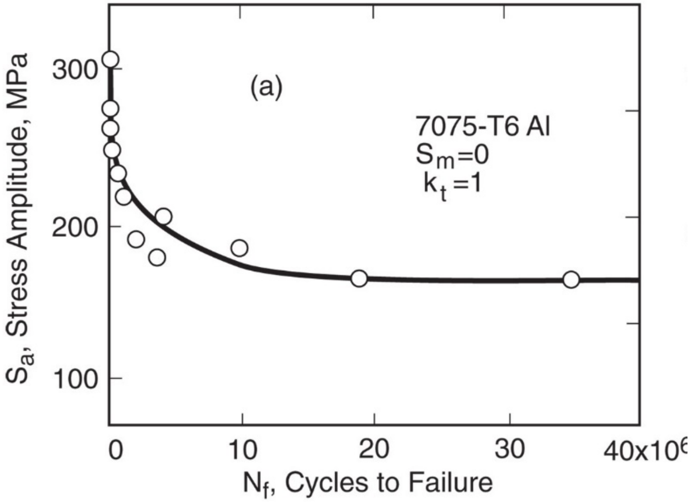


Figure 9.4

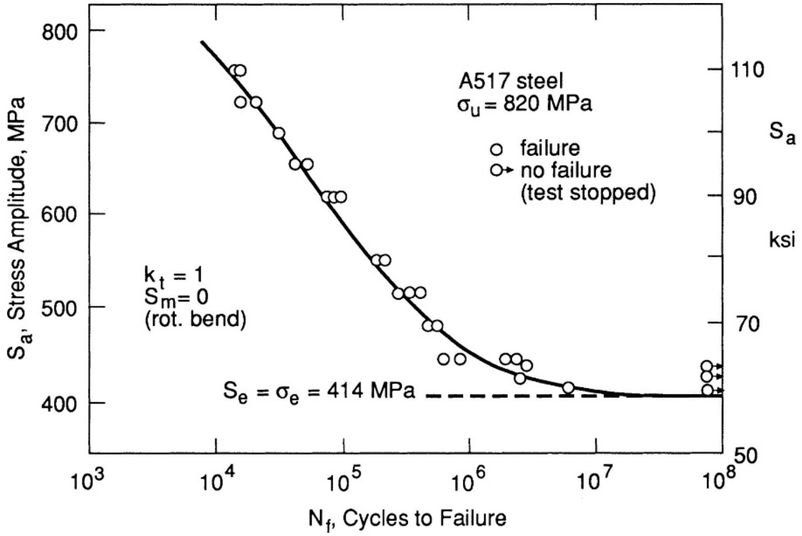


Figure 9.5

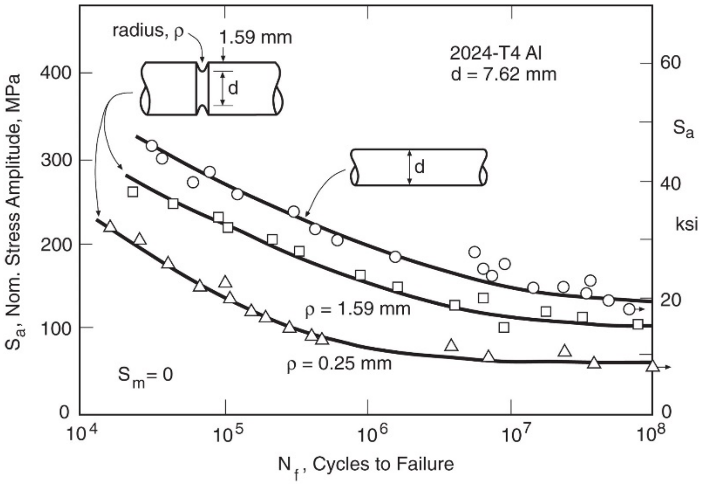


Figure 9.27

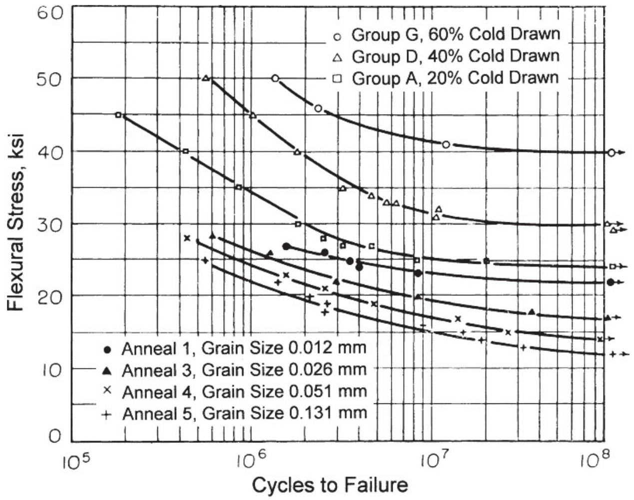


Figure 9.30

9.6.5 Fatigue Limit Behavior

- **Fatigue occurs below the fatigue limit**
- **Two competing mechanisms of fatigue failure:**
  - Failure that begins from surface defects (up to around 10^7 cycles)
  - Failure that begins from internal nonmetallic inclusions (at lower stresses up to around 10^9-10^{10} cycles)
- **Hence, where very large numbers of cycles are applied in service, the concept of a safe stress may not be valid.**
- **If the fatigue process can somehow start, then it can proceed below the fatigue limit.**
  - Corrosion may cause small pits. Surface damage allows fatigue cracks.
  - A similar effect can occur where large numbers of cycles at low stresses are combined in the loading history with occasional severe cycles. The occurrence of a small number of severe cycles can cause damage that can then be propagated to failure by stresses below the usual fatigue limit.

9.6.5 Fatigue Limit Behavior

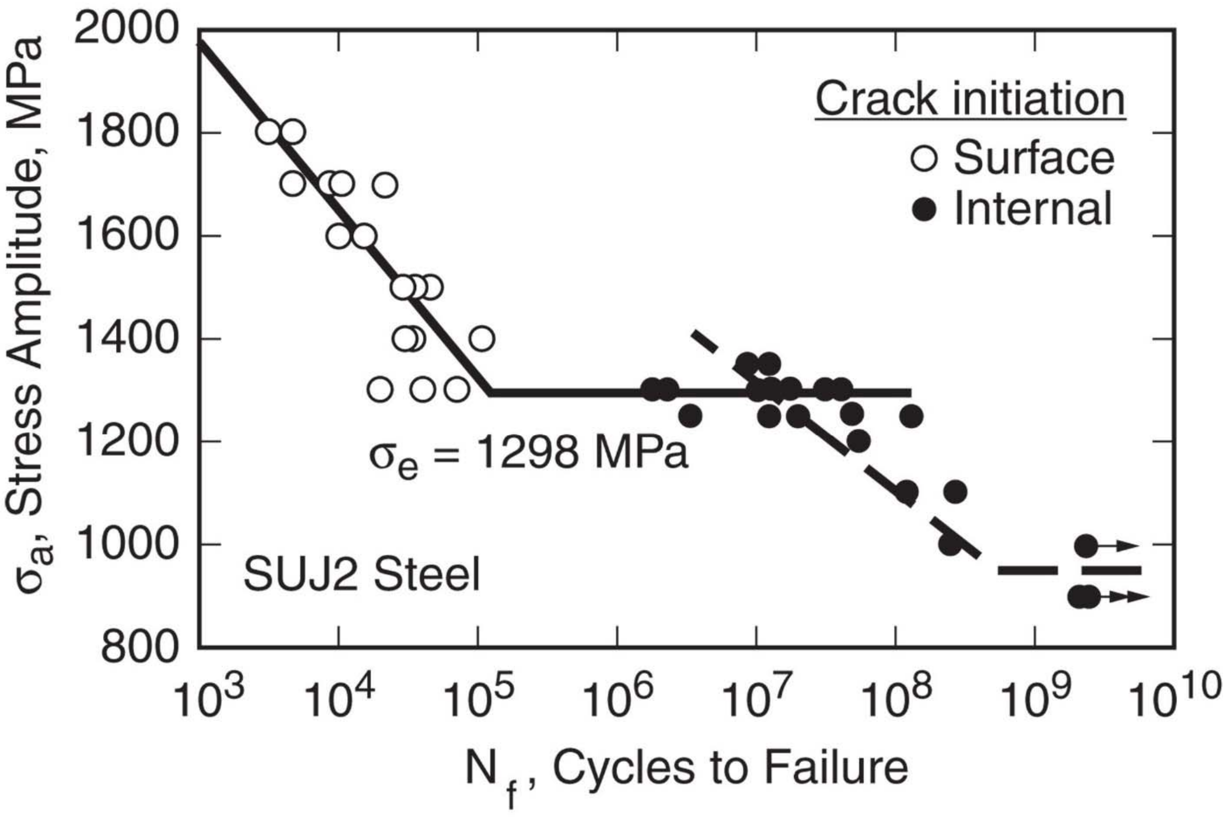
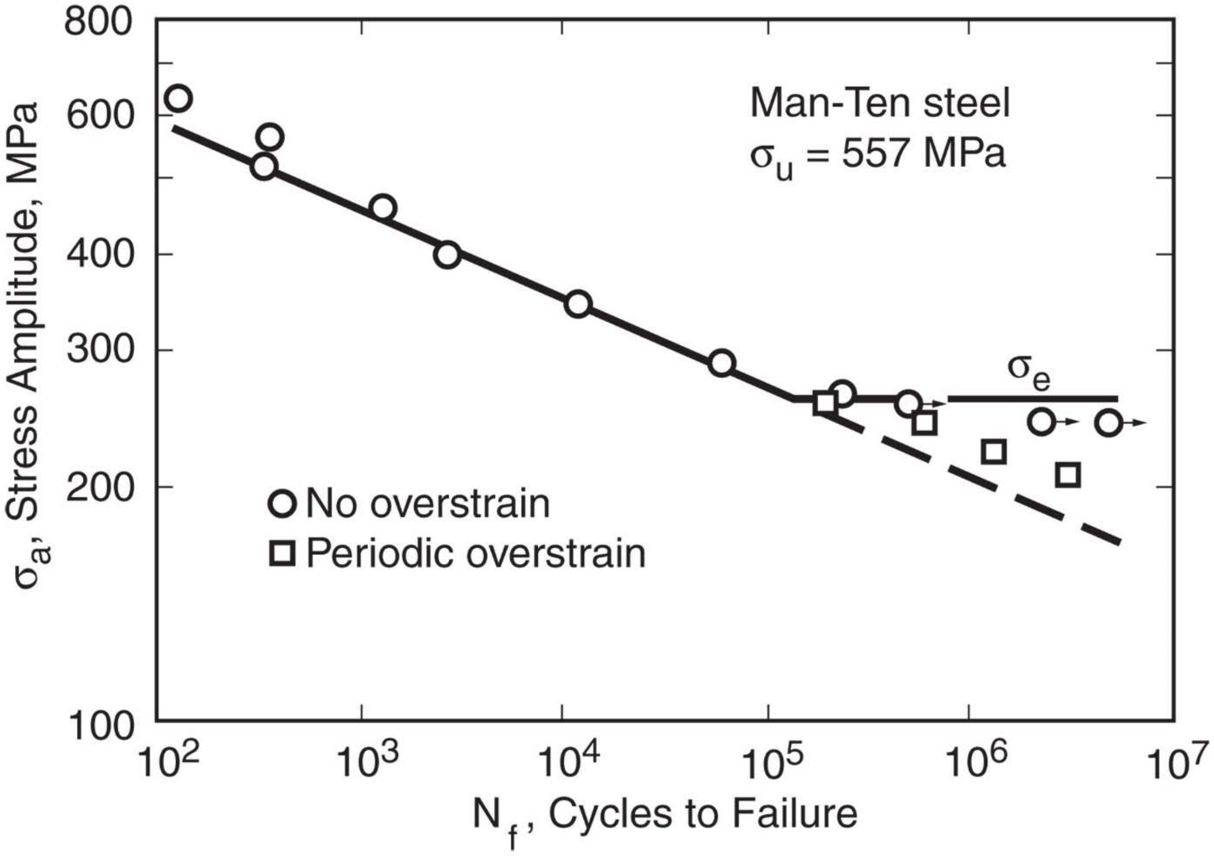
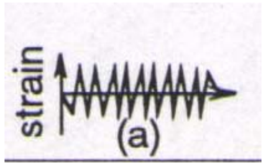


Figure 9.32 Stress–life curve extending into the very long life range for a bearing steel with hardness HV = 778, corresponding to $\sigma_u \approx 2350$ MPa, containing 1% carbon and 1.45% chromium.

9.6.5 Fatigue Limit Behavior





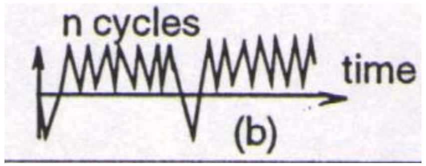


Figure 9.33 Stress–life data for a low-strength steel tested under constant amplitude cycling with zero mean stress. Periodic overstrain tests included severe cycles applied every 10^5 cycles, but with their ΣN/Nf not exceeding a few percent. (Data from [Brose 74].)

9.6.6 Statistical Scatter

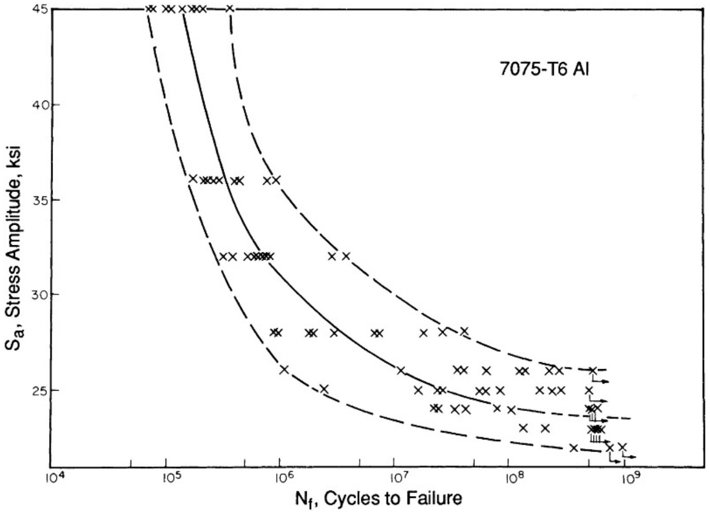


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Figure 9.34 Scatter in rotating bending S-N data for an unnotched aluminum alloy. (Adapted from [Grover 66] p. 44.)

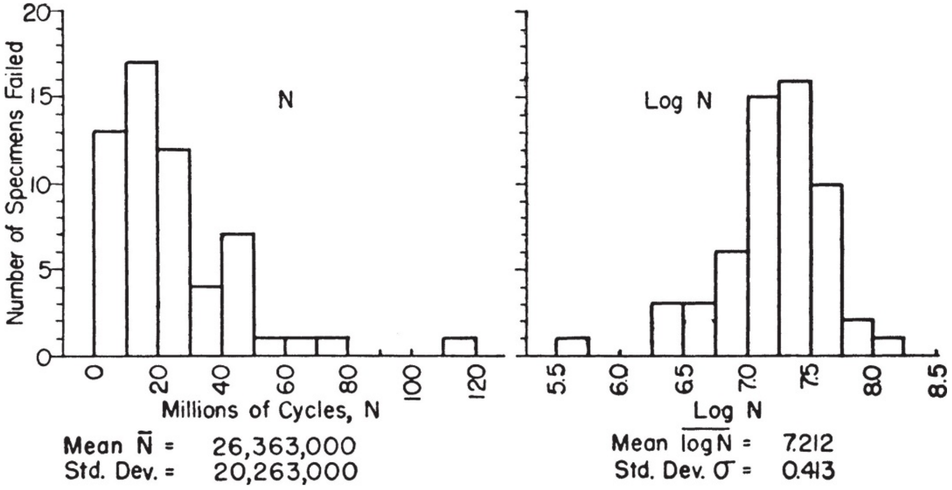

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Figure 9.35 Distribution of fatigue lives for 57 small specimens of 7075-T6 aluminum tested at S_a = 207 MPa (30 ksi) in rotating bending.

Contents

9.7.1 Presentation of Mean Stress Data

- One procedure used for developing data on mean stress effects is to select several values of mean stress, running tests at various stress amplitudes for each of theses.
- An alternative presentation means, a constant-life diagram, shows that to maintain the same life, increasing the mean stress in the tensile direction must be accompanied by a decrease in stress amplitude.

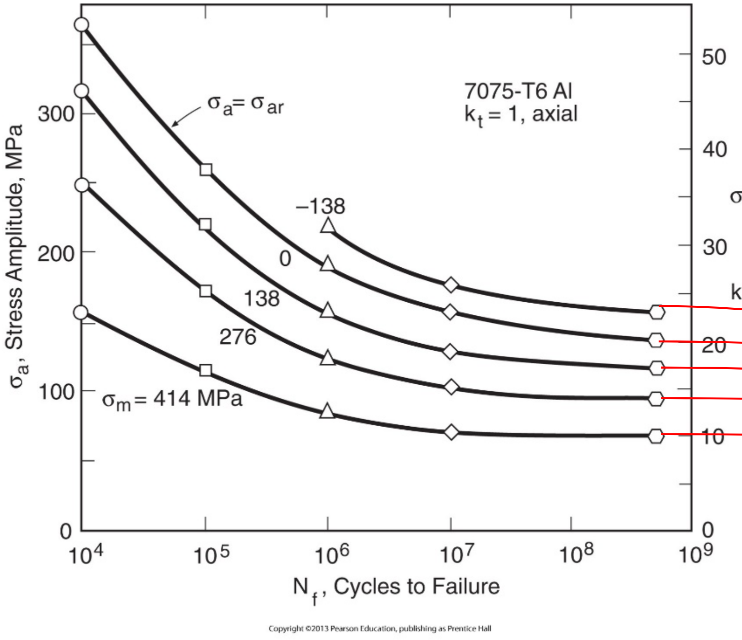
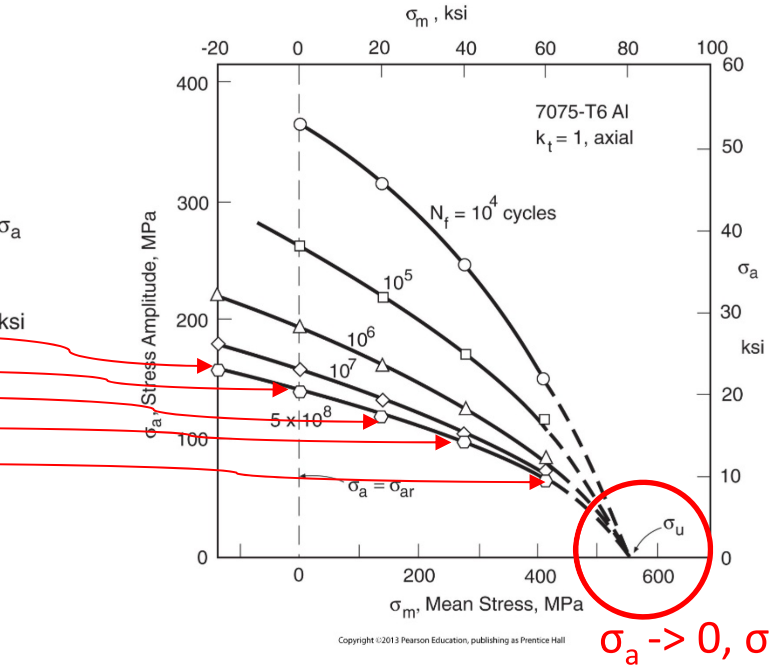


Figure 9.26 Axial loading S-N curves at various mean stresses



σ_a -> 0, σ_m-> σ_u

Figure 9.37 Constant-life diagram taken from the S-N curves

9.7.2 Normalized Amplitude-Mean Diagrams

- On a constant-life diagram, σ_{ar} (or S_e) is thus the intercept at σ_m=0 of the curve for any particular life.
- The graph can be normalized by plotting values of the ratio σ_a/σ_{ar} versus the mean stress $\sigma_{m.}$ (σ_m, σ_a/σ_{ar})

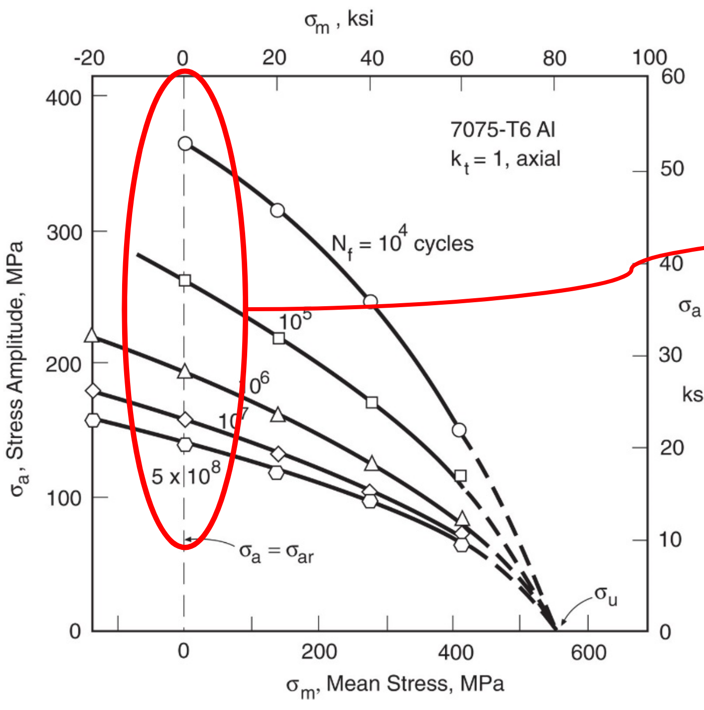


Figure 9.37 Constant-life diagram taken from the S-N curves

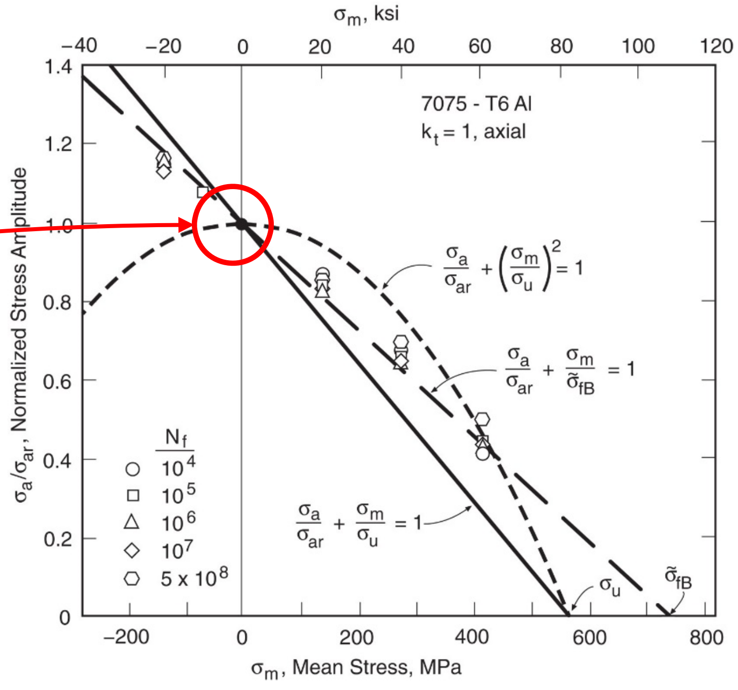


Figure 9.39 Normalized amplitude-mean diagram

9.7.2 Normalized Amplitude-Mean Diagrams
9.7.1 Additional Mean Stress Equations

- Several empirical relationships have been developed.
- For most fatigue design situations (i.e., small mean stress in relation to alternating stress), there is little difference in the theories.

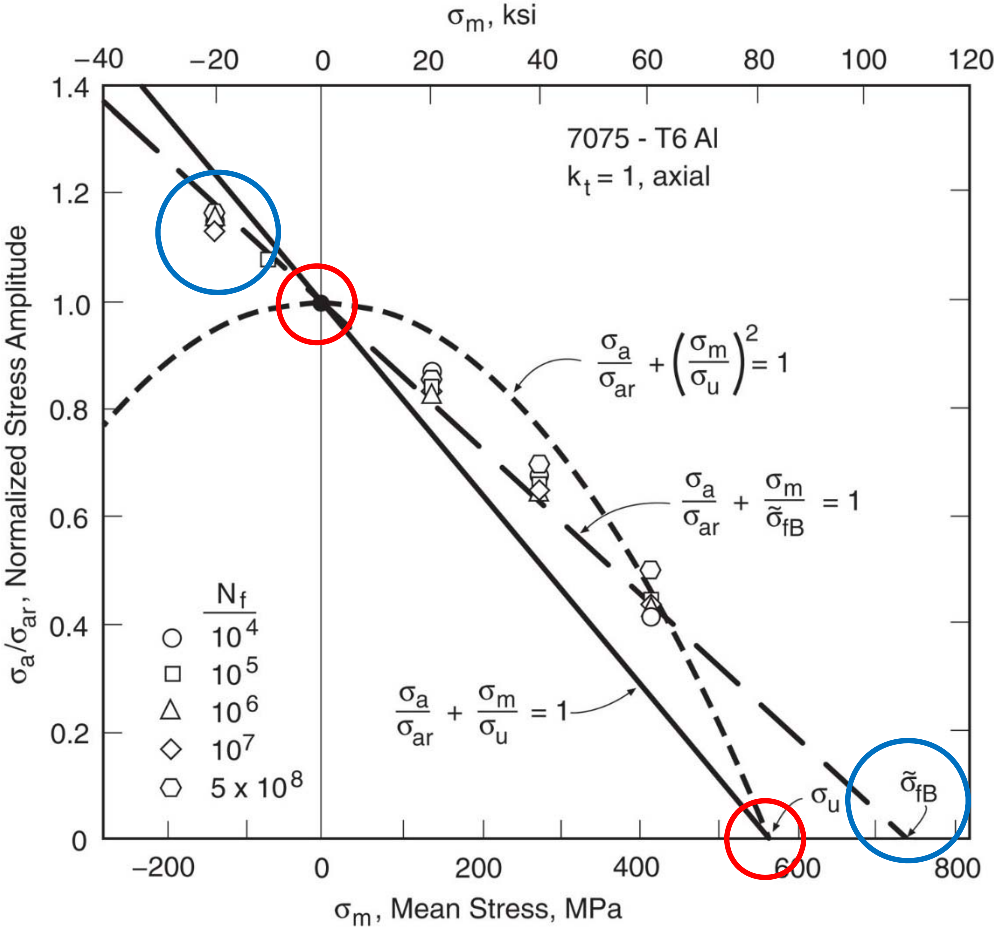


Figure 9.39 Normalized amplitude-mean diagram

Goodman (England, 1899)	$\frac{\sigma_a}{\sigma_{ar}} + \frac{\sigma_m}{\sigma_u} = 1$	- Conservative line
Gerber (Germany, 1874)	$\frac{\sigma_a}{\sigma_{ar}} + \left(\frac{\sigma_m}{\sigma_u}\right)^2 = 1$	- Incorrect for compressive stress
Morrow (USA, 1960s)	$\frac{\sigma_a}{\sigma_{ar}} + \frac{\sigma_m}{\tilde{\sigma}_{fB}} = 1$	- Using true fracture strength

9.7.4 Life estimates with Mean Stress

Example 9.3) The AISI 4340 Steel is subjected to cyclic loading with a tensile mean stress of σ_m=200MPa. What life is expected if the stress amplitude is σ_a=450MPa?

Solution)

From Table 9.1 (p. 406), σ_f'=1758, b=-0.0977

$$\sigma_{ar} = \sigma_f'(2N_f)^b = 1758(2N_f)^{-0.0977}MPa \quad \text{(9.7)}$$

$$\sigma_{ar} = \frac{\sigma_a}{1-\frac{\sigma_m}{\sigma_f'}} = \frac{450}{1-\frac{200}{1758}} = 507.8MPa \quad \text{(Morrow)}$$

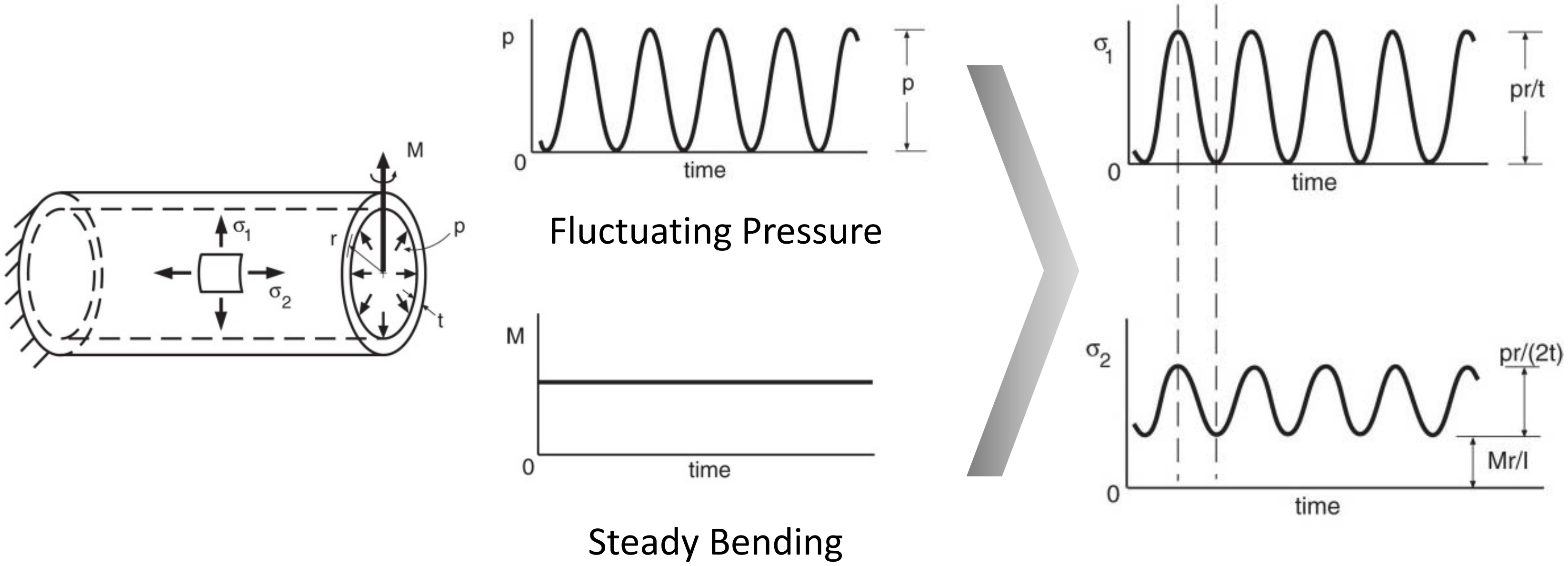
$$N_f = 166{,}000\ Cycles$$

Contents

9.8 MULTIAXIAL STRESSES (Optional)

- **Commonly, cyclic loadings cause complex states of multiaxial stress.**

  Examples)
  - Fig 9.40: Combination of cyclic pressure “P” and steady bending “M” causes biaxial stresses “σ_1, σ_2”.
  - There are different stress amplitudes and mean stresses in two directions



Fluctuating Pressure

Steady Bending

Figure 9.40 Combined cyclic pressure and steady bending of a thin-walled tube with closed ends.

9.8.1 One Approach to Multiaxial Fatigue (Optional)

- **Assumption & Situation #1**
  - All cyclic loads are completely reversed and have the same frequency.
  - No steady (noncyclic) load presents.
- **Effective stress amplitude, $\bar{\sigma}_a$**
  - The amplitudes of the principal stresses can be used to compute an *effective stress amplitude*.
  - Similar relationship employed for the octahedral shear yield criterion (Chapter 7, Eq 7.35)

$$\bar{\sigma}_a = \frac{1}{\sqrt{2}}\sqrt{(\sigma_{1a}-\sigma_{2a})^2 + (\sigma_{2a}-\sigma_{3a})^2 + (\sigma_{3a}-\sigma_{1a})^2}$$

  - By using effective stress amplitude, the fatigue life ban be estimated for completely reversed uniaxial stress. (σ_m=0)

$$\sigma_{ar} = \sigma'_f(2N_f)^b \qquad \sigma_{ar} = \frac{\sigma_a}{1-\frac{\sigma_m}{\sigma'_f}} \quad \text{(Morrow)}$$

9.8.1 One Approach to Multiaxial Fatigue (Optional)

- **Assumption & Situation #2**
  - If steady (noncyclic) loads are present
- **Effective stress amplitude, $\bar{\sigma}_a$**
  - The amplitudes of the principal stresses can be used to compute an *effective stress amplitude*.

$$\bar{\sigma}_a = \frac{1}{\sqrt{2}}\sqrt{(\sigma_{xa}-\sigma_{ya})^2+(\sigma_{ya}-\sigma_{za})^2+(\sigma_{za}-\sigma_{xa})^2+6(\tau_{xya}^2+\tau_{yza}^2+\tau_{zxa}^2)}$$

- **Effective mean stress, $\bar{\sigma}_m$**
  - Effective mean stress can be calculated from the mean stresses in the three principal directions

$$\bar{\sigma}_m = \sigma_{1m}+\sigma_{2m}+\sigma_{3m}$$

  - By using effective stress amplitude & effective mean stress, the fatigue life ban be estimated.

$$\sigma_{ar} = \sigma_f'(2N_f)^b \qquad \sigma_{ar} = \frac{\sigma_a}{1-\frac{\sigma_m}{\sigma_f'}} \quad \text{(Morrow)}$$

Contents

9.9.1 The Palmgren-Miner Rule

- **In practical applications, the variable amplitude of fatigue loadings exist.**
- **The Palmgren(in 1920s)-Miner(in 1945) Rule**
  - N_1: the number of cycles by stress amplitude σ_{a1}
  - N_{f1}: the number of cycles to failure from the S-N curve for σ_{a1}
  - N_1/N_{f1}: the fraction of the life
  - Fatigue Failure is expected when such life fractions sum to unity.

$$\frac{N_1}{N_{f1}}+\frac{N_2}{N_{f2}}+\frac{N_3}{N_{f3}}+\cdots=\sum\frac{N_j}{N_{fj}}=1, \frac{n}{N}=cycle\ ratio \qquad B_f\left[\sum\frac{N_j}{N_{fj}}\right]_{one\ rep.}=1$$

  - It is convenient to sum cycle ratios over one repetition for the summation to reach unity. B_f: the number of repetitions to failure

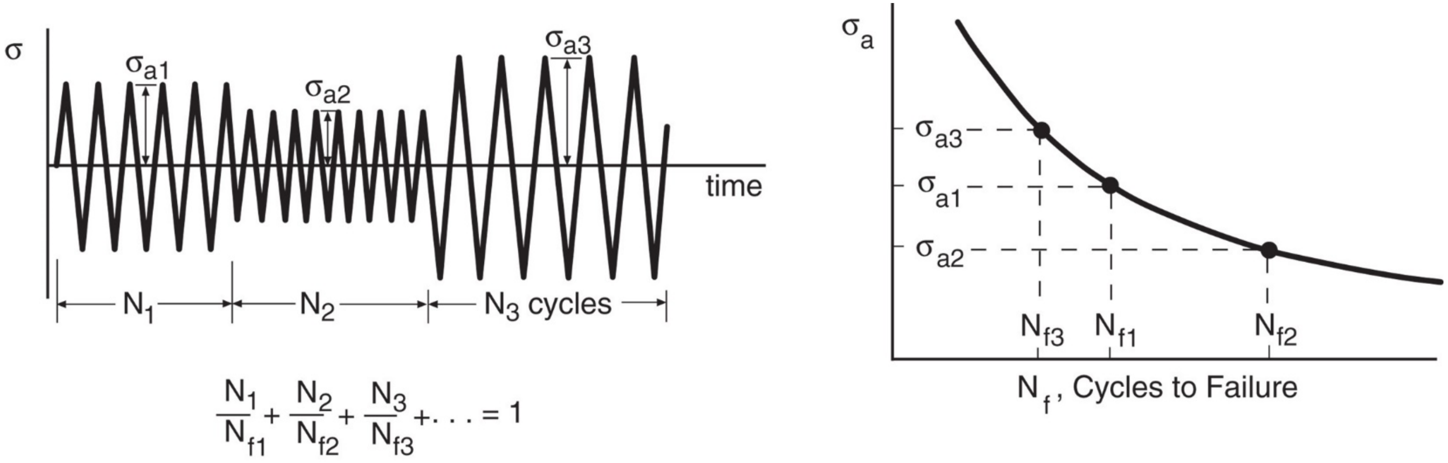


Figure 9.43 Use of the Palmgren–Miner rule for life prediction for variable amplitude.

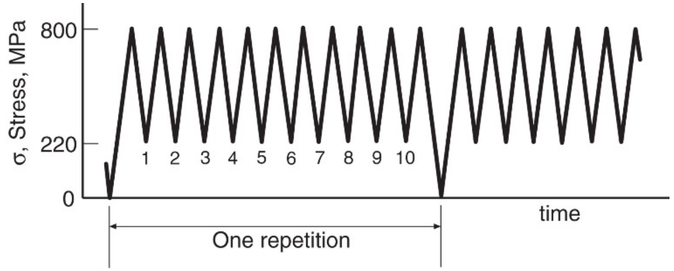
9.9.1 The Palmgren-Miner Rule

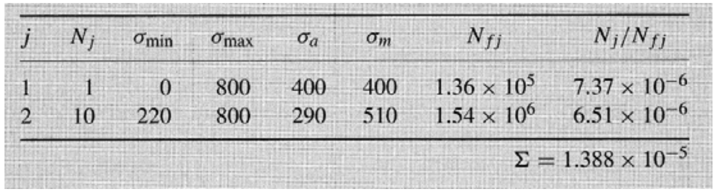
Example 9.8)

A Uniaxial stress repeatedly applied to an unnotched member made of the AISI 4340 Steel. Estimate the number of repetitions, B_f, required to cause fatigue failure.

Solution)

From Table 9.1 (p. 406), σ'_f=1758, b=-0.0977





j	N_j	$\sigma_{\min}$	$\sigma_{\max}$	σ_a	σ_m	N_{fj}	N_j/N_{fj}
1	1	0	800	400	400	1.36×10^5	7.37×10^{-6}
2	10	220	800	290	510	1.54×10^6	6.51×10^{-6}
							$\Sigma = 1.388 \times 10^{-5}$

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

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

$$\sigma_a = (\sigma'_f - \sigma_m)(2N_f)^b \quad (9.23)$$

(Morrow for nonzero mean stress)

$$B_f = \frac{1}{\left[\Sigma \frac{N_j}{N_{fj}}\right]_{one\ rep.}} = \frac{1}{1.388 \times 10^{-5}} = 72000\ rep.$$

9.9.2 Cycle Counting for Irregular Histories

- To predict the life of a component subjected to a variable load history, it is necessary to reduce **the complex history** into a number of events which can be compared to the available **constant amplitude test data**. This process of reducing a complex load history into a number of constant amplitude events involves what is termed **cycle counting**.

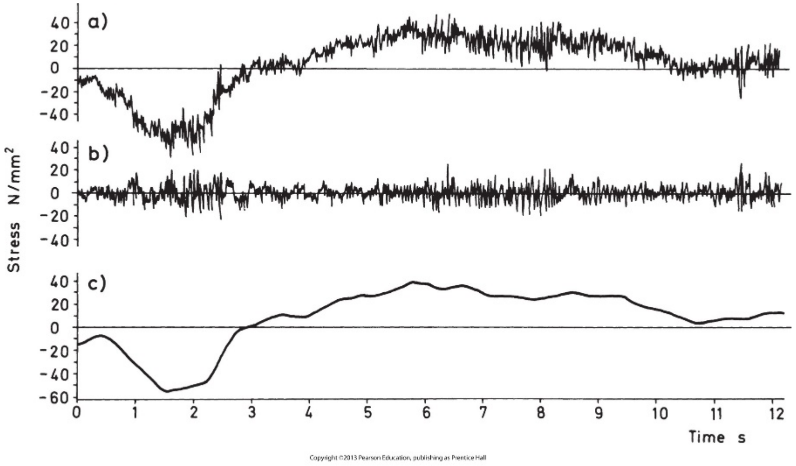


Figure 9.7

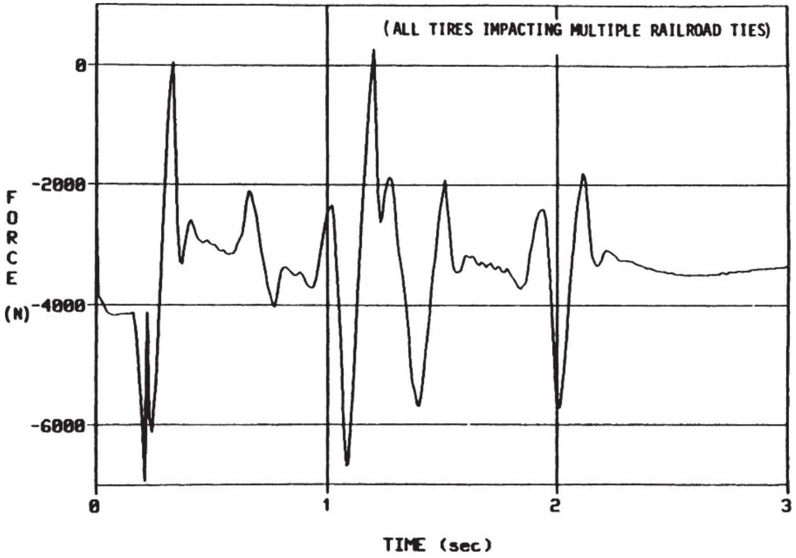
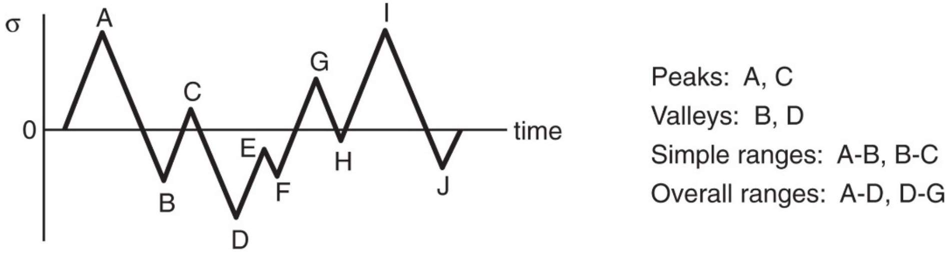


Figure 9.8

9.9.2 Cycle Counting for Irregular Histories
- Simplified Rainflow Counting for Repeating Histories

- In performing **rainflow cycle counting**, a cycle is identified or counted if it meets the criterion.
- A peak-vally-peak or vally-peak-valley combination is considered to contain a cycle



Peaks: A, C

Valleys: B, D

Simple ranges: A-B, B-C

Overall ranges: A-D, D-G

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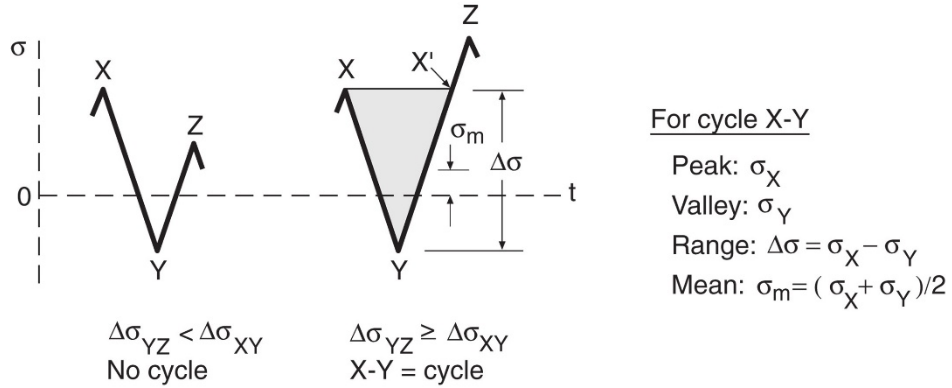
Figure 9.45 Definitions for irregular loading.



$\Delta\sigma_{YZ} < \Delta\sigma_{XY}$
No cycle

$\Delta\sigma_{YZ} \geq \Delta\sigma_{XY}$
X-Y = cycle

For cycle X-Y

Peak: σ_X

Valley: σ_Y

Range: $\Delta\sigma = \sigma_X - \sigma_Y$

Mean: $\sigma_m = (\sigma_X + \sigma_Y)/2$

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Figure 9.46 Condition for counting a cycle with the rainflow method.

9.9.2 Cycle Counting for Irregular Histories
- Simplified Rainflow Counting for Repeating Histories

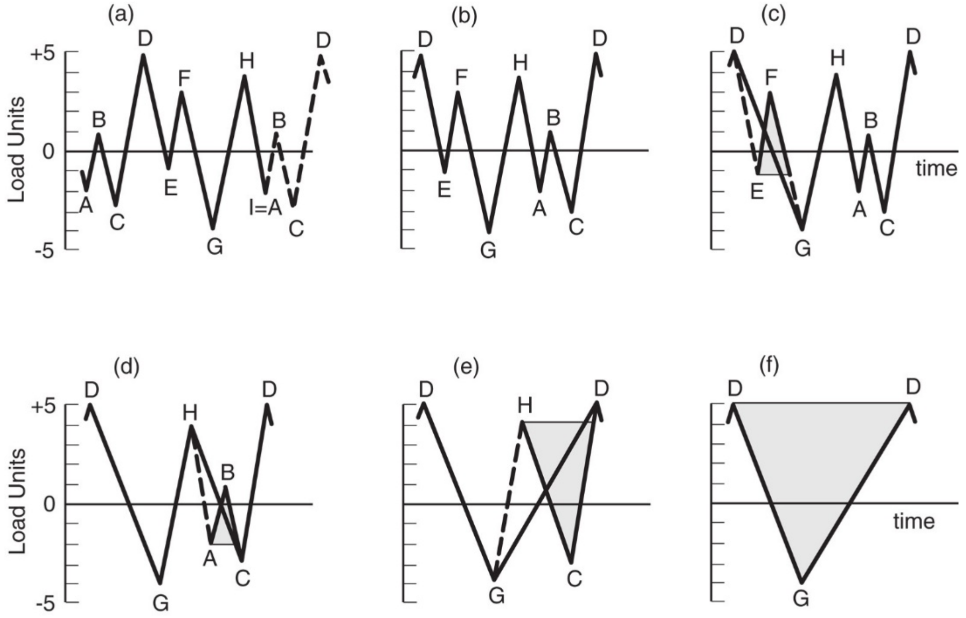


Figure 9.47 Example of rainflow cycle counting.

<Rainflow cycle counting>

(1) Assume that the stress history given is to be repeatedly applied.

(2) (a) -> (b) Arrange the history to start with either the maximum peak or the minimum valley.

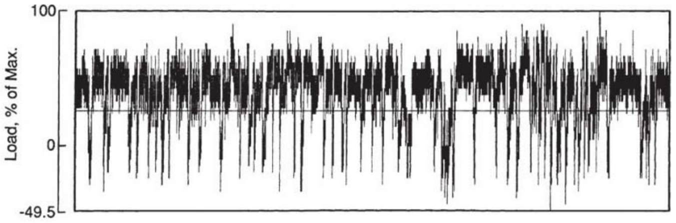
(3) If $\Delta\sigma_{YZ} \geq \Delta\sigma_{XY}$, then a cycle is counted. And its peak and valley are assumed not to exist for further cycle counting .

(4) If $\Delta\sigma_{YZ} < \Delta\sigma_{XY}$, then no cycle can be counted. And move ahead until a count can be made

Combination	Cycle Counts	Range	Mean
DE>EF	0		
EF<FG	1	4.0	1.0
GH>HA	0		
HA>AB	0		
AB<BC	1	3.0	-0.5

Combination	Cycle Counts	Range	Mean
DG>GH			
GH>HC	0		
HC<CD	1	7.0	0.5
DG=DG	1	9.0	0.5

9.9.2 Cycle Counting for Irregular Histories
- Simplified Rainflow Counting for Repeating Histories



	Mean																		
Range	−15	−10	−5	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	All
20	4	1	5	2	2	5	—	—	3	6	15	27	29	32	22	12	6	2	—	173
25	2	4	3	9	8	10	4	6	2	7	17	37	36	43	33	13	7	1	2	244
30	1	1	5	3	1	1	4	3	—	4	13	20	20	23	20	8	6	1	—	134
35	1	1	4	2	3	2	—	1	3	2	8	17	16	11	11	7	2	—	—	91
40	—	1	1	1	2	1	1	—	—	4	7	15	16	9	8	2	—	—	—	68
45	—	1	—	4	3	—	—	—	—	2	1	9	7	2	3	1	—	—	—	33
50	—	—	2	2	2	1	—	—	—	2	2	3	3	1	1	1	1	—	—	21
55	—	—	1	1	—	—	—	—	—	2	2	4	4	2	—	1	—	1	—	18
60	—	1	1	—	—	—	—	—	—	1	1	3	2	1	—	—	—	—	—	10
65	—	—	—	—	—	—	—	—	—	—	2	1	—	—	—	—	—	—	—	3
70	—	—	—	—	—	—	—	—	—	—	2	—	1	—	—	—	—	—	—	3
75	—	—	—	—	—	—	1	—	—	—	1	2	—	—	—	—	—	—	—	4
80	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
85	—	—	—	—	1	—	1	3	3	—	—	—	—	—	—	—	—	—	—	8
90	—	—	—	—	—	—	—	—	4	—	—	—	—	—	—	—	—	—	—	4
95	—	—	—	—	—	1	—	1	4	1	—	—	—	—	—	—	—	—	—	7
100	—	—	—	—	—	—	—	5	3	1	—	—	—	—	—	—	—	—	—	9
105	—	—	—	—	—	—	—	3	3	3	—	—	—	—	—	—	—	—	—	9
110	—	—	—	—	—	—	—	—	2	3	—	—	—	—	—	—	—	—	—	5
115	—	—	—	—	—	—	—	—	3	—	—	—	—	—	—	—	—	—	—	3
120	—	—	—	—	—	—	1	—	1	1	—	—	—	—	—	—	—	—	—	3
125	—	—	—	—	—	—	—	—	2	—	—	—	—	—	—	—	—	—	—	2
130	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
135	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	1
140	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
145	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
150	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	1

Figure 9.48 An irregular load vs. time history from a ground vehicle transmission, and a matrix giving numbers of rainflow cycles at various combinations of range and mean. The range and mean values are percentages of the peak load; in constructing the matrix, these were rounded to the discrete values shown. (Load history from [Wetzel 77] pp. 15–18.)

Thank You

Back Up

9.1 Introduction - Wind Turbines Fatigue

Figure 9.1 Large horizontal-axis wind turbine in operation on the Hawaiian island of Oahu. The blade has a tip-to-tip span of 98 m. (Photo courtesy of the NASA Lewis Research Center, Cleveland, OH.)

- Wind turbines are subjected to cyclic loads due to **rotation** and **wind turbulence**, making fatigue a critical aspect of the design of the blade and other moving parts.

수식

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

(9.2) $\sigma_{max} = \sigma_m + \sigma_a \qquad \sigma_{min} = \sigma_m - \sigma_a$

(9.3) Stress Ratio, $R = \frac{\sigma_{min}}{\sigma_{max}}$ Amplitude Ratio, $A = \frac{\sigma_a}{\sigma_m}$

(9.4) $\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{max}}{2}(1 - R) \quad \sigma_m = \frac{\sigma_{max}}{2}(1 + R) \qquad R = \frac{1 - A}{1 + A} \quad A = \frac{1 - R}{1 + R}$

(9.5) Log-linear plot, $\sigma_a = C + D\log N_f$

(9.6) Log-log plot, $\sigma_a = AN_f^B$

(9.7) Different Log-log plot, $\sigma_a = \sigma_f'(2N_f)^b$

(9.8) $A = 2^b\sigma_f'$

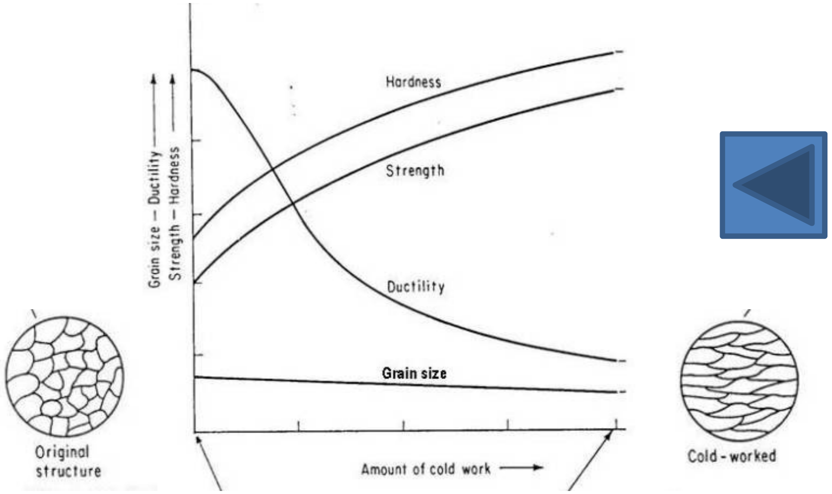
$B = b$

(9.9) The safety factor in stress, $X_S = \frac{\sigma_{a1}}{\hat{\sigma}_a}, (N_f = \hat{N})$

(9.10) The safety factor in life, $X_N = \frac{N_{f2}}{\hat{N}}, (\sigma_a = \hat{\sigma}_a)$

열간압연 vs. 냉간압연

열간압연 강판	특성	냉간압연 강판
재결정온도 이상에서 압연	온도	재결정온도 이하에서 압연
성형이 쉬움	성형성	성형이 어려움
낮은 극한 응력	기계적 성질	높은 극한응력
흑피 형성(불순물 층) -> 피로, 충격에 약함	불순물	표면 깨끗함 (굳은 불순물 제거됨, 더 이상 불순물이 분리되지 않는 온도)
정수치 불가	가공 두께	두께 균일(분자 구조 안정) -> 코일 형태 보관 가능



- Stress was used as the control parameter and stress-life (or S-N) curves characterized the material or component response to cyclic loading. This approach was used widely until the 1970s when the new methods started to be used by industry. Unfortunately, there are quite a few inherent problems with the stress-life approach which cause a large amount of scatter in the experimental fatigue life results. In some companies, due to the extensive use of the stress-life method in past years, a large quantity of S-N curves and experience have been accumulated. In this case, the stress-life method offers compatibility with previous work and may therefore be more appropriate.

- The stress-life approach is still used today for situations which are not easily modeled using the local strain methods, such as welded structures and cast irons. Due to the inherent defects in these materials which act more like cracks, fatigue damage should really be modeled with LEFM crack propagation tools. Another group of materials which appear to be best modeled using the stress-life approach are anisotropic and inhomogeneous materials such as composites. However, there are complications even with composites, since the mean stress correction models used in connection with metals do not apply to all composites.

9.2.3 Stress Versus Life (S-N) Curves

Fitting test data for unnotched axial specimens tested under completely reversed loading

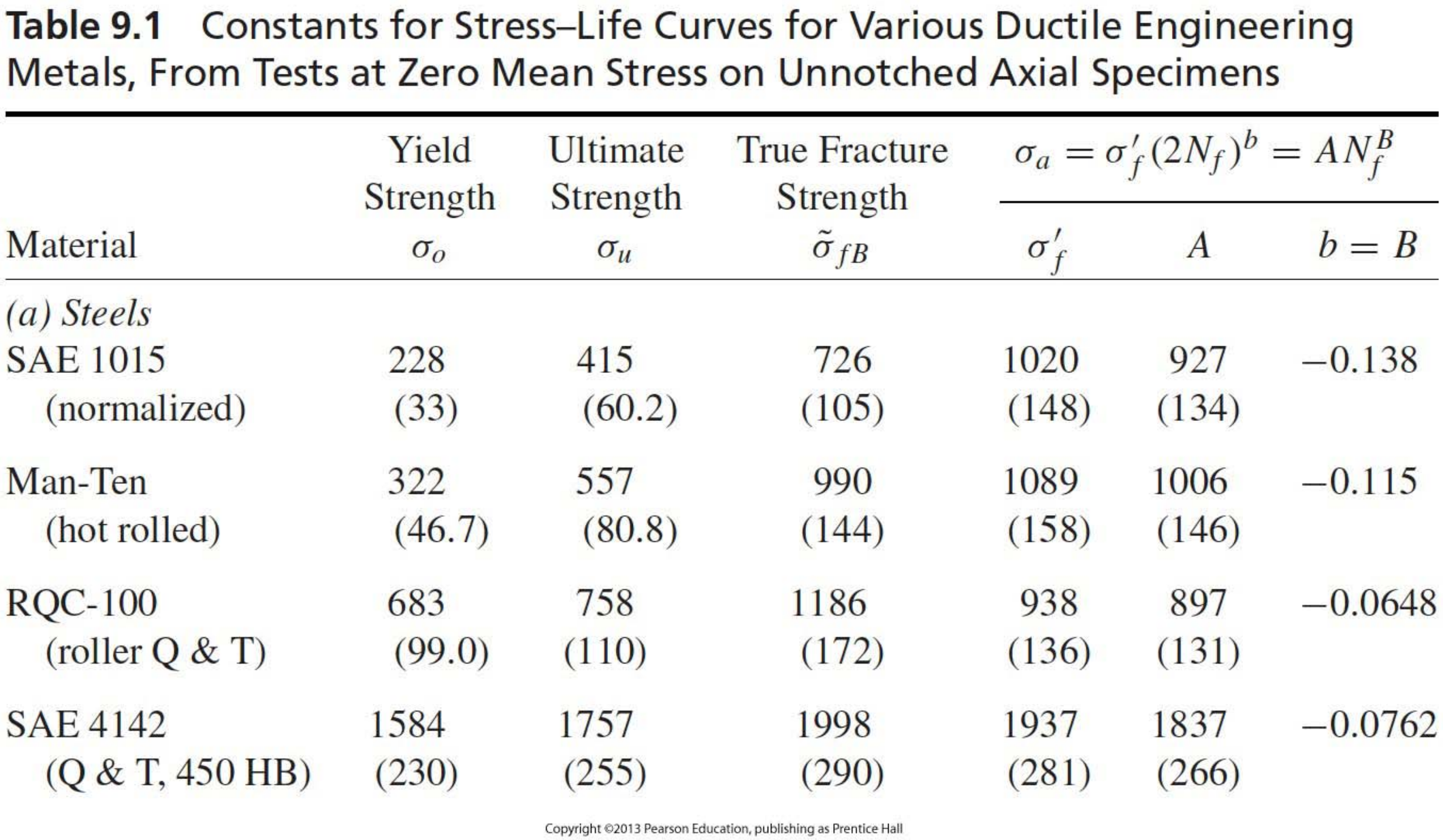


Table 9.1 Constants for Stress–Life Curves for Various Ductile Engineering Metals, From Tests at Zero Mean Stress on Unnotched Axial Specimens

Material	Yield Strength σ_o	Ultimate Strength σ_u	True Fracture Strength $\tilde{\sigma}_{fB}$	$\sigma_a = \sigma'_f(2N_f)^b = AN_f^B$		
				σ'_f	A	$b = B$
(a) Steels						
SAE 1015	228	415	726	1020	927	−0.138
(normalized)	(33)	(60.2)	(105)	(148)	(134)	
Man-Ten	322	557	990	1089	1006	−0.115
(hot rolled)	(46.7)	(80.8)	(144)	(158)	(146)	
RQC-100	683	758	1186	938	897	−0.0648
(roller Q & T)	(99.0)	(110)	(172)	(136)	(131)	
SAE 4142	1584	1757	1998	1937	1837	−0.0762
(Q & T, 450 HB)	(230)	(255)	(290)	(281)	(266)	

9.2.3 (S-N) Curves - Forms of Fatigue

- **High Cycle Fatigue [HCF]**
  - Low Amplitude High Frequency Elastic Strain
  - Tuning Fork Vibration

- **Low Cycle Fatigue [LCF]**
  - High Amplitude Low Frequency Plastic Strain
  - Bend Tuning Fork