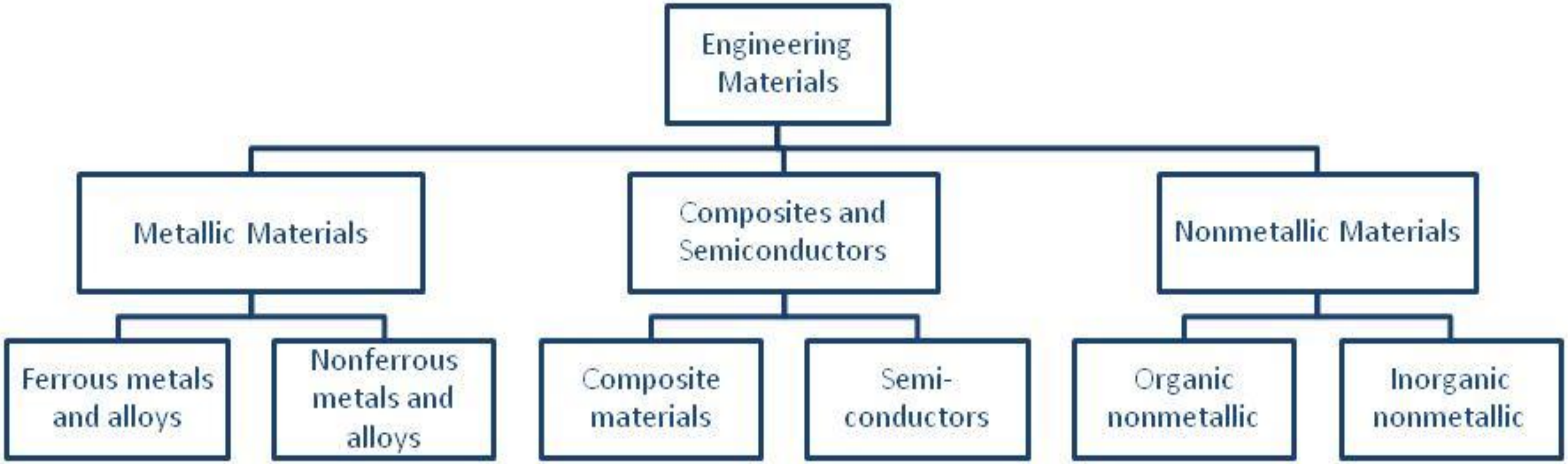
PART I

PERFORMANCE OF MATERIALS IN SERVICE

Figure A1 Classes of Engineering materials



Performance of Materials in Service I

Part I discusses the different types of failure and how to prevent, or at least delay, such failures by selecting appropriate materials.

Failure of engineering components occurs by several mechanisms, which can be arranged in order of importance as follows:

- **Corrosion**, which can be defined as the unintended destructive chemical or electrochemical reaction of a material with its environment, represents about 30% of the causes of component failures in engineering applications.
- **Fatigue**, which occurs in materials when they are subjected to fluctuating loads, represents about 25% of the causes of component failures in engineering applications.

Performance of Materials in Service II

- **Brittle fractures** are accompanied by a small amount of plastic deformation and usually start at stress raisers. They represent about 15-20% of the causes of failure of engineering components.
- **Ductile factures** are accompanied by larger amount of plastic deformation and normally occur as a result of overload. They represent about 10-15% of the causes of failure.
- **Creep and stress rupture**, thermal fatigue, high temperature corrosion and corrosion fatigue, occur as a result of a combination of causes including high temperature, stress, and chemical attack. They represent about 10-15% of the causes of failure of engineering components.
- Other minor causes of failure include wear, abrasion, erosion, and radiation damage.

Performance of Materials in Service III

Failure occurs as a result of a variety causes:

- **Poor selection of materials** represent about 40% of the causes of failure of engineering components.
- **Manufacturing defects**, as a result of fabrication imperfections and faulty heat treatment, represent about 30% of the causes of failure of engineering components.
- **Design deficiencies** about 20% of the causes of failure.
- **Exceeding design limits**, overloading, and inadequate maintenance and repair represent about 10% of the causes of failure of engineering components.

Part I Outcomes

After completing Part I, the reader will be able to:

- Understand the behavior of engineering materials, including similarities and difference between the different types
- Assess the effect of mechanical loading and service environment on the performance of engineering materials
- Recognize the different types of failure of components as a result mechanical loading and environmental attack
- Perform experimental and analytical failure analysis on failed components and products and determine the probable causes of failure
- Select the appropriate materials and processes that can resist a given type of loading or a source of failure.

CHAPTER 2
FAILURE UNDER MECHANICAL LOADING

The objectives of the chapter are to:

1. Examine the relationships between material properties and failure under static loading.
2. Discuss the different types of fatigue loading and factors affecting the fatigue strength of materials.
3. Review the categories of elevated-temperature failures.
4. Describe some failure analysis experimental and analytical techniques.

Types of mechanical failure

Failure under mechanical loading is either a result of permanent change in the dimensions or a result of actual fracture:

1. Yielding of the material under static loading.
2. Buckling of slender columns under compressive loading.
3. Creep failure when strain exceeds allowable limits or by rupture.
4. Failure due to excessive wear in components.
5. Failure by fracture due to static overload, can be ductile or brittle.
6. Fatigue failure due to overstressing, material defects, or stress raisers.
7. Failure due to the combined effect of stresses and corrosion.
8. Fracture due to impact loading.

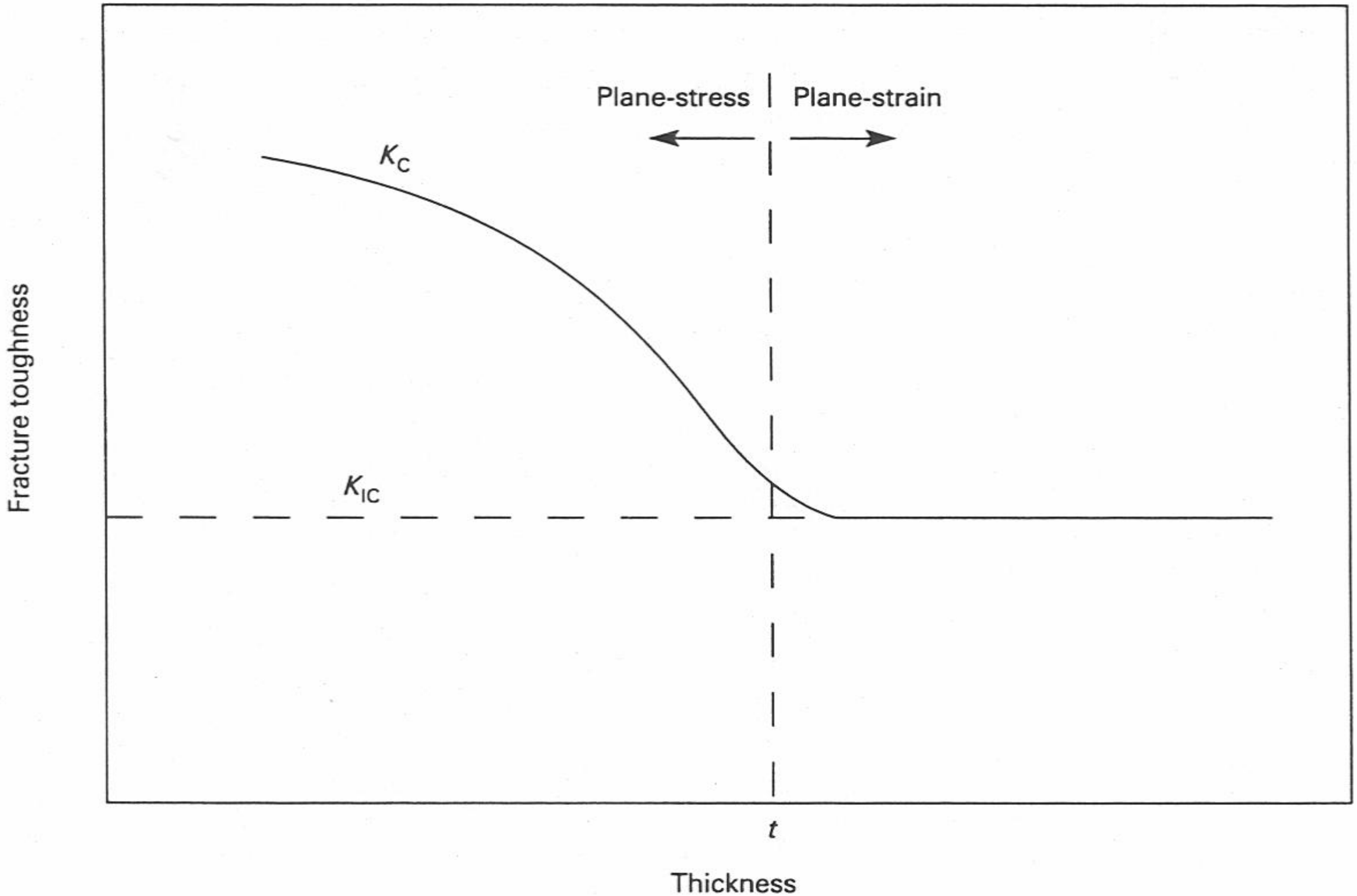


Figure 2.1 Effect of thickness on fracture toughness behavior.

Fracture toughness

The critical stress intensity factor, K_{IC}, is a material property and is related to the flaw size, $2a$:

$$\sigma_f = K_{IC} / Y (\pi a)^{1/2} \qquad (2.3)$$

- Y is a correction factor which depends on the geomtry and can be taken as 1 in most cases
- $2a$ is the flaw size for center crack and a for edge crack.
- The units of K_{IC} are [MPa (m)$^{1/2}$] or [psi (in)$^{1/2}$].

It can be used it to determine the flaw size that can be tolerated in a component for a given applied stress level or the stress level that can be safely used for a flaw size that may be present in a component.

Table 2.1 Nondestructive methods of crack detection

Method	Applications and standard covering the practice
Visual examination. The naked eye	Surface cracks
Penetrant test. Liquids that enter surface discontinuities by capillary action.	Defects open to the surface of metallic and nonmetallic materials.
Radiographic examination. X rays and gamma rays	Radiographs show the size and shape of discontinuities.
Magnetic -particle method.	Detects surface crack in magnetic materials.
Ultrasonic tests.	Internal defects in ferrous and nonferrous metals and alloys.
Eddy current inspection.	Used for inspection surface and subsurface defects in electrically conducting materials.

Design example 2.1

A plate with a crack of length 2a.

K_{IC} = 27.5 MPa (m)$^{1/2}$ and σ_y = 400 MPa

Calculate the fracture stress σ_f and compare it to the yield strength σ_y for different values of crack lengths to determine whether failure will take place by yielding or fracture.. Assume Y = 1.

Solution:

a (mm)	1	2	4	6	8	10
σ_f (MPa)	490.6	346.9	245.3	200.3	173.5	155.2
σ_f/σ_y	1.23	0.87	0.61	0.50	0.43	0.39

With the smallest crack, yielding occurs before fracture. However, longer cracks cause fracture before yielding.

Design example 2.2 Using fracture toughness in material selection

If the available NDT equipment can detect flaws > 4 mm, can we safely use either of the following alloys for designing a component that will be subjected to a stress of 400 MPa?

Ti-6 Al-4 V [K_{IC} = 60 MPa (m)$^{1/2}$] and

Al AA7075 alloy [K_{IC} = 24 MPa (m)$^{1/2}$]

Solution:

From Eq. (2.3) and taking $Y = 1$,

- For Ti-6 Al-4 V: $\sigma_f = 400 = 60/(\pi\, a)^{1/2}$ 2a = 14 mm
- For AA7075: $\sigma_f = 400 = 24/(\pi a)^{1/2}$ 2a = 2.3 mm

The critical crack can be detected in titanium but not in aluminum. Titanium alloy can be used safely but not the aluminum alloy.

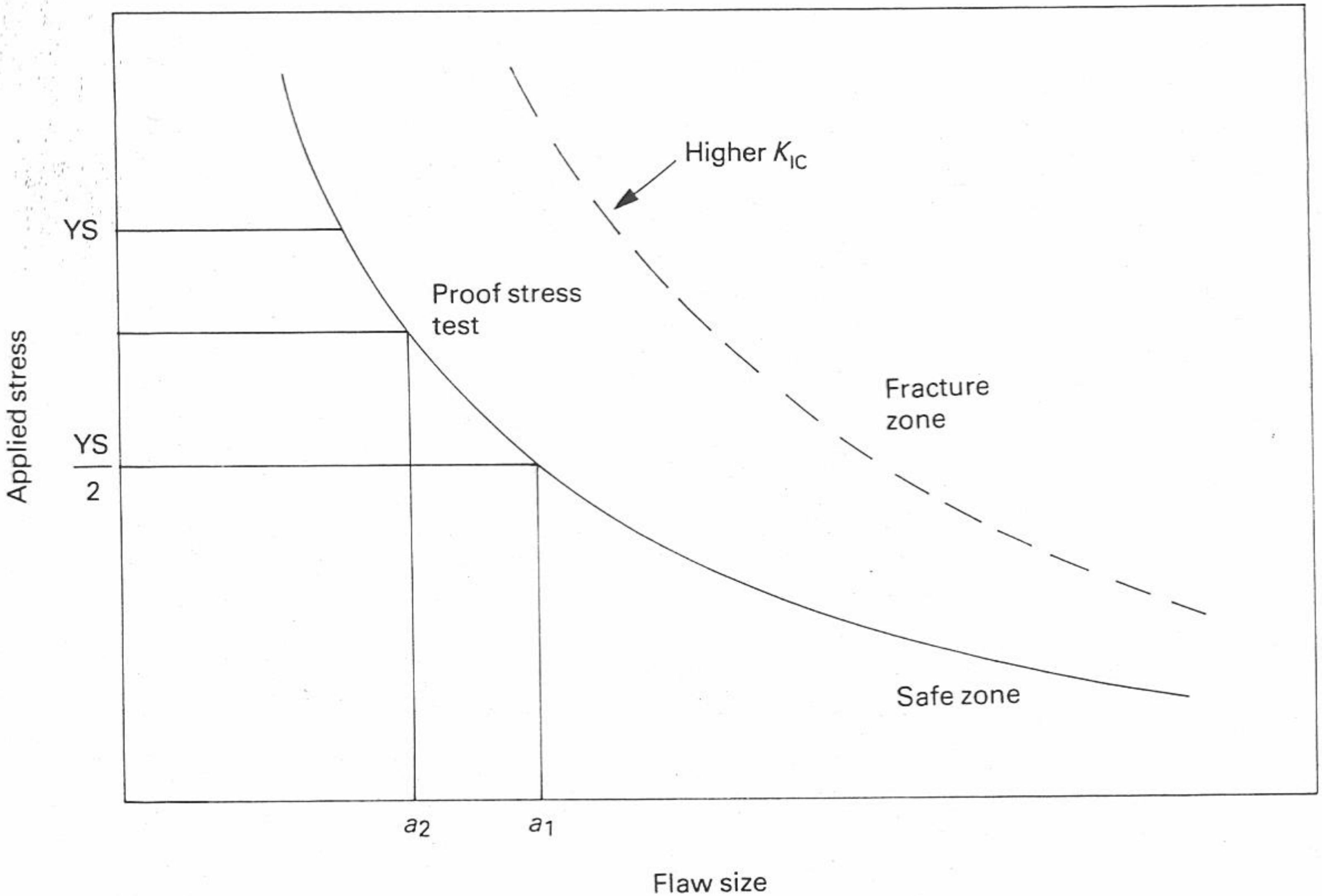


Figure 2.2 Schematic relationship between stress, flaw size, and fracture toughness.

Ductile and brittle fractures

- Ductile fractures result as a result of design errors, incorrect selection of materials, improper fabrication, overload or abuse.
- Materials with K_{IC} < 15 MPa. $m^{1/2}$ or impact toughness <15 ft.lb (20.3 J) are considered brittle.
- Brittle fracture usually initiates at stress raisers (inclusions, cracks, surface defects, or notches)
- Once started, brittle fracture propagates at high speed until total failure occurs or until it runs into conditions favorable for its arrest.

Case study 2.3
Ductile fracture

Ladder made of

AA6061 T4

RB 25-30 in most parts

But RB 20 in S2, which yielded causing S3 yield.

Load redistribution caused S1 and S4 to yield.

Change treatment to T6, with hardness RB 45-55 and yield strength about twice as T4

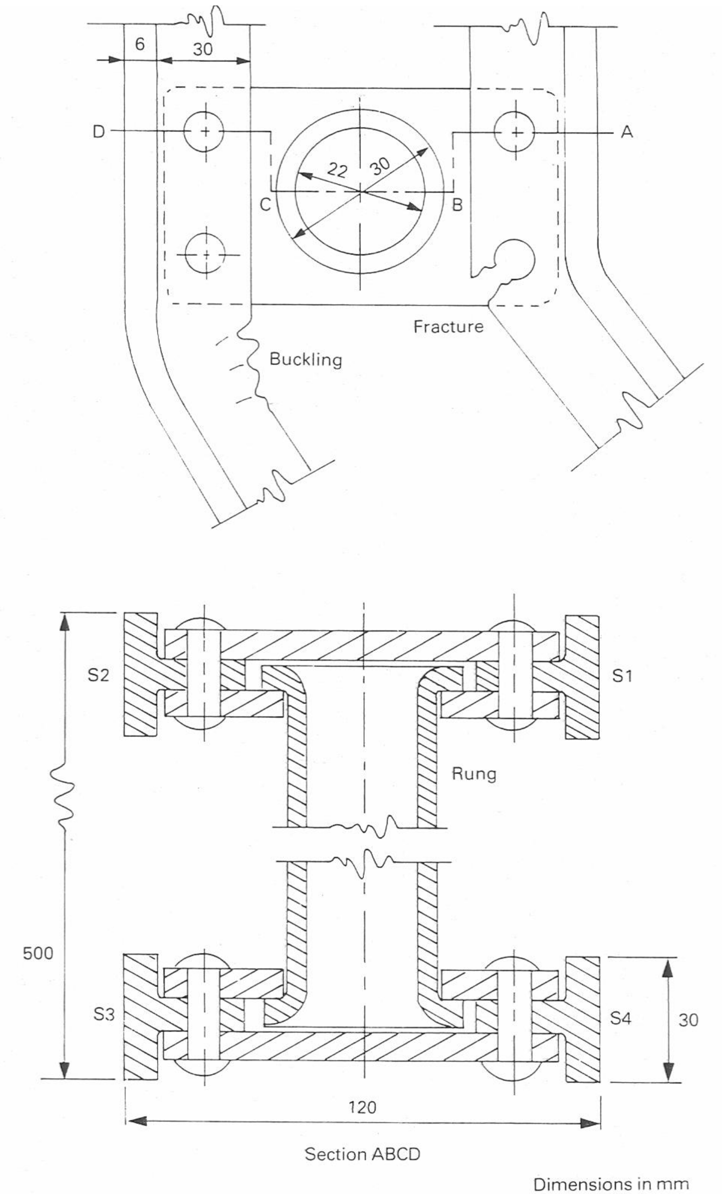


Figure 2.3 Failure of aluminum ladder.

Brittle fracture

Brittle fractures are normally initiated at stress raisers and run at high speed.

The chevrons can be considered as arrows pointing to the origin of fracture.

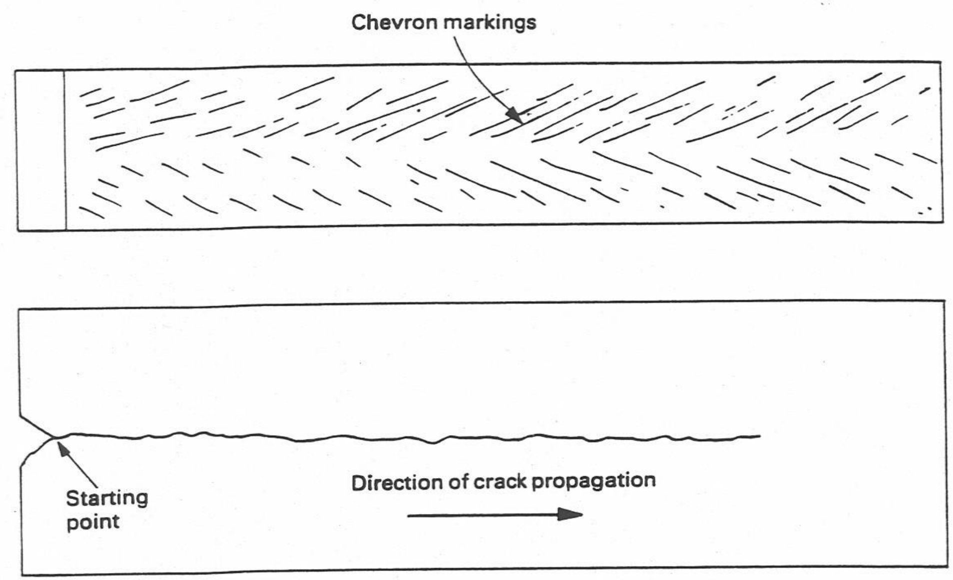


Figure 2.4(b)

Figure 2.4 Chevron patterns in brittle fracture. (a) Chevron markings in steel. From Rollason (1977). (b) Schematic representation.

Ductile Brittle Transition Temp.

At 50% of fracture surface is brittle or at 20.3 J

(15 ft lb)

or at 1% lateral contraction at notch

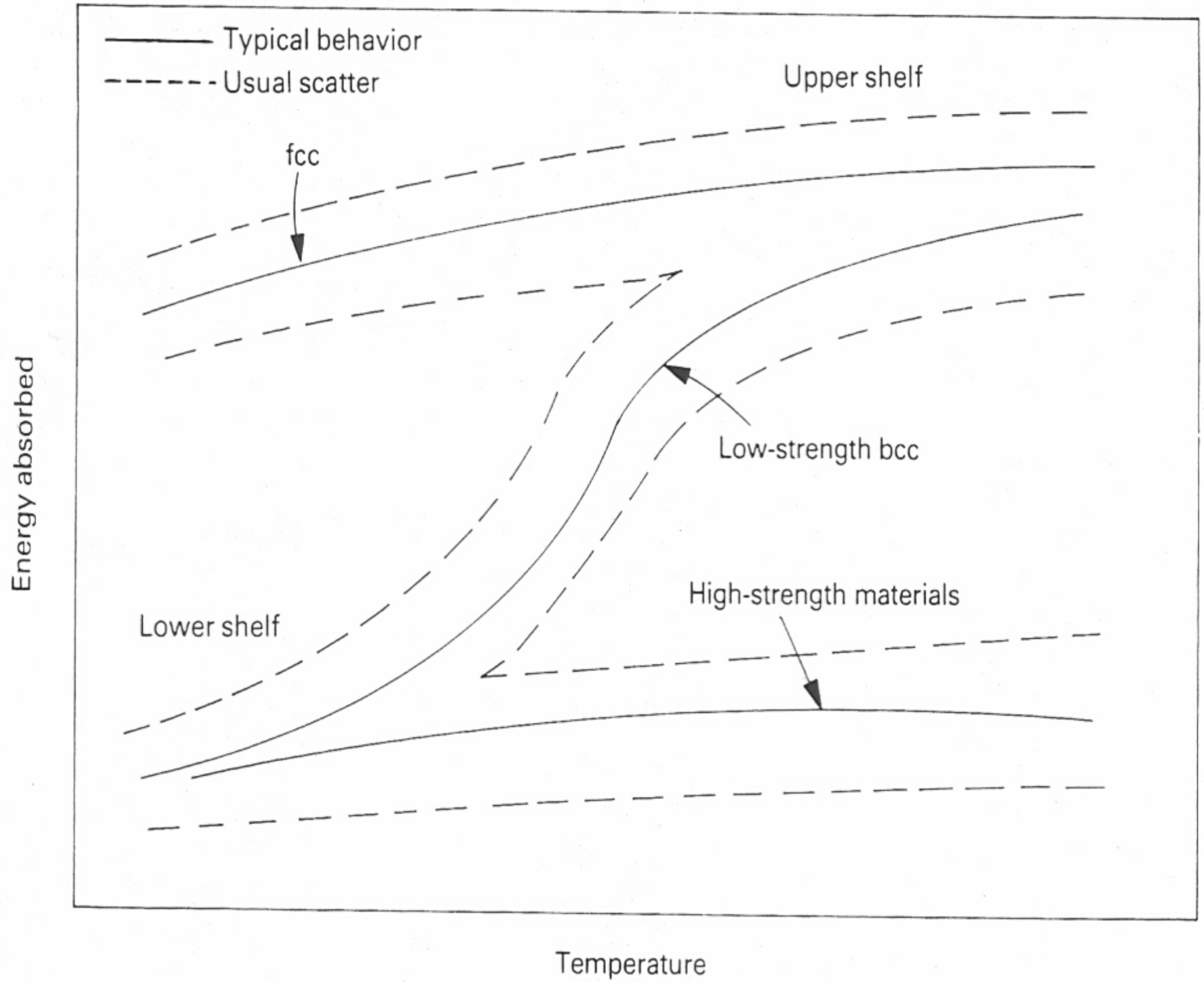


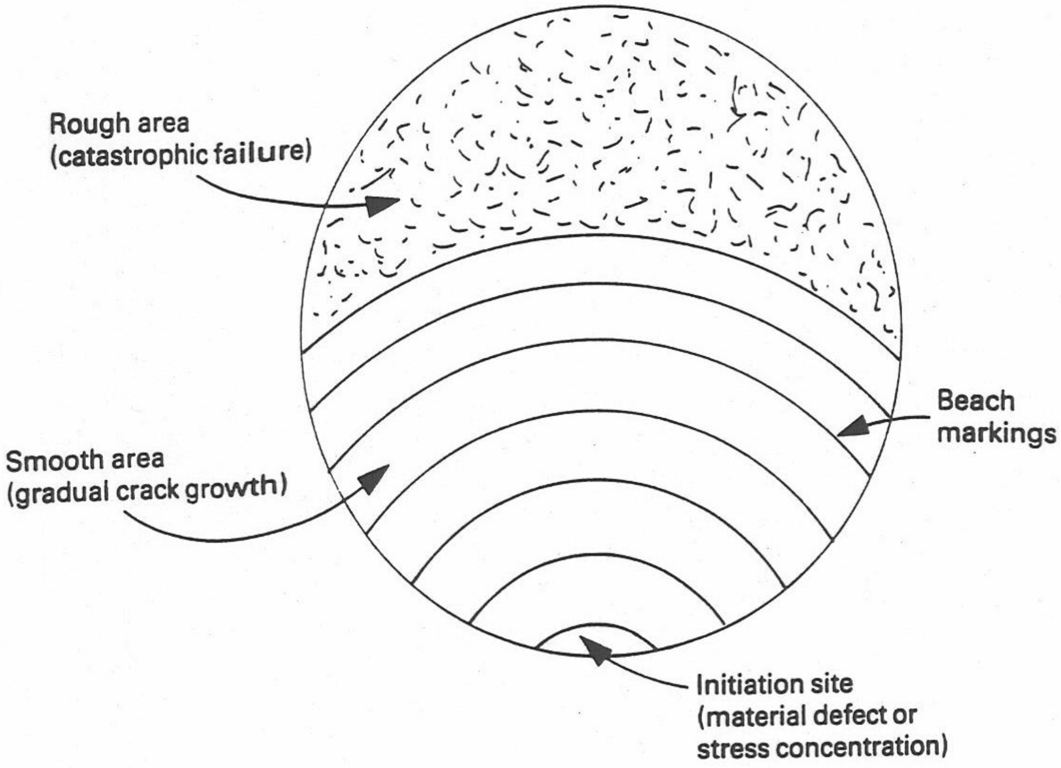
Figure 2.5 Schematic representation of the effect of temperature on the energy absorbed in fracture.

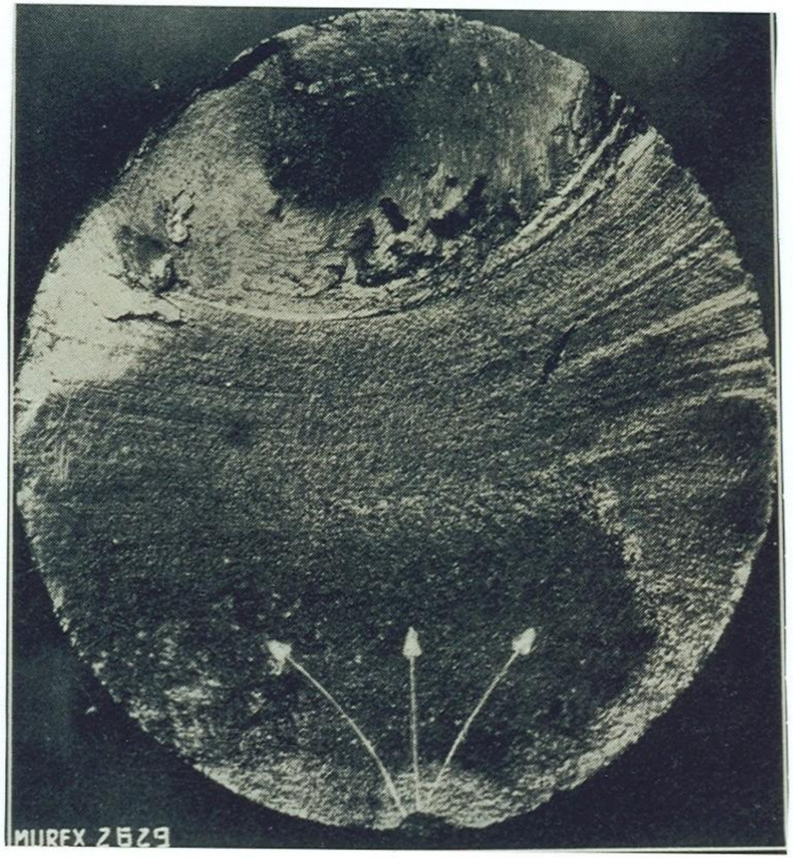
Avoiding brittle fracture

The design and fabrication precautions that should be taken to avoid brittle fracture include:

1. Abrupt changes in section should be avoided in order to avoid stress concentrations and thickness should be kept to a minimum to reduce triaxial stresses.
2. Welds should be located clear of stress concentrations and of each other, and they should be easily accessible for inspection.
3. Whenever possible, welded components should be designed on a failsafe basis.

Fatigue failure of automotive axel shaft





Case Study 2.4

Failure of a pressure line

Excessive vibrations in the exit pipe caused fatigue failure at the base.

Solution

Move the weld to a lower stress area and support the pipe

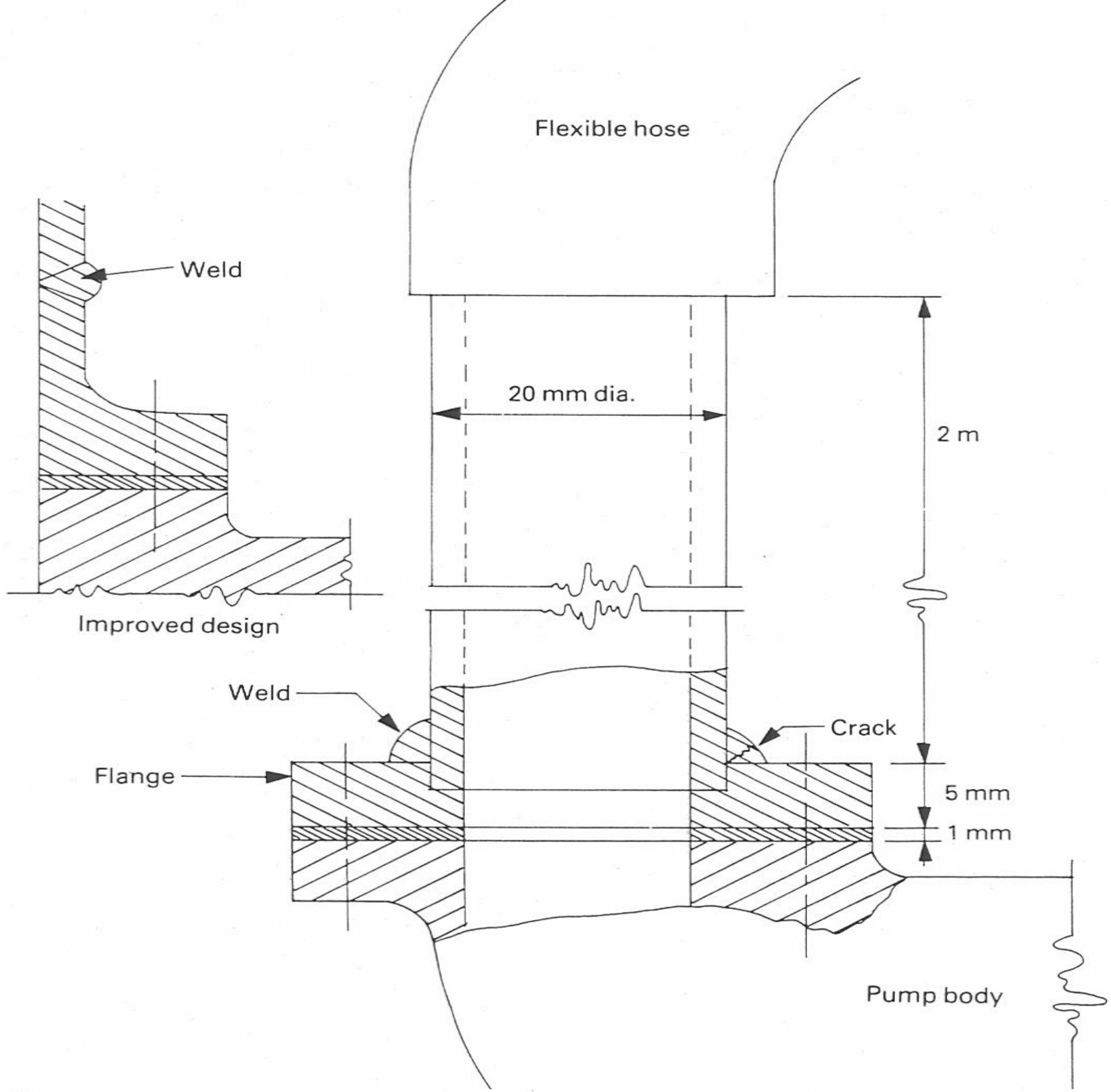


Figure 2.7 Failure of pressure line of a hydraulic pump.

Case Study 2.5: Comet Aircraft Failures I

Background

- The de Havilland DH 106 Comet was the first commercial airliner to be powered by jet engines. This allowed it to fly at higher altitudes in order to take advantage of the lower air resistance, which also meant pressurizing the fuselage to maintain atmospheric pressure inside the cabin.

Problem

- The first flight of the Comet with passengers was in May 1952. During the period March 1953 and January1954 three planes crashed killing all those on board.
- As a result, the Comet fleet was grounded and several design modifications introduced and flights resumed. However, another crash occurred April 1954 and the fleet was grounded again.

Case Study 2.5: Comet Aircraft Failures II

Analysis

- Inspection parts of the fuselage that were recovered from crash sites showed beach marks on the fracture surfaces, which indicated possible fatigue failure.
- This was confirmed by testing a full length fuselage in a specially constructed water tank to simulate the compression and decompression during flight and landing. After about 3,000 cycles the fuselage burst open at a sharp corner of the forward port-side escape hatch cutout. Several fatigue cracks were also found at rivet holes, which were produced by punching.

Case Study 2.5: Comet Aircraft Failures III

Solutions

- All the remaining Comets were withdrawn from service and new versions were built with rounded corners for all openings and windows in order to reduce stress concentration.
- The skin sheeting was also made thicker.
- Rivet holes were drilled instead of punching to produce smoother surfaces.
- A periodic inspection procedure was also introduced.

With these changes, commercial flights of the new Comet resumed in 1958 and successfully continued for nearly 30 years.

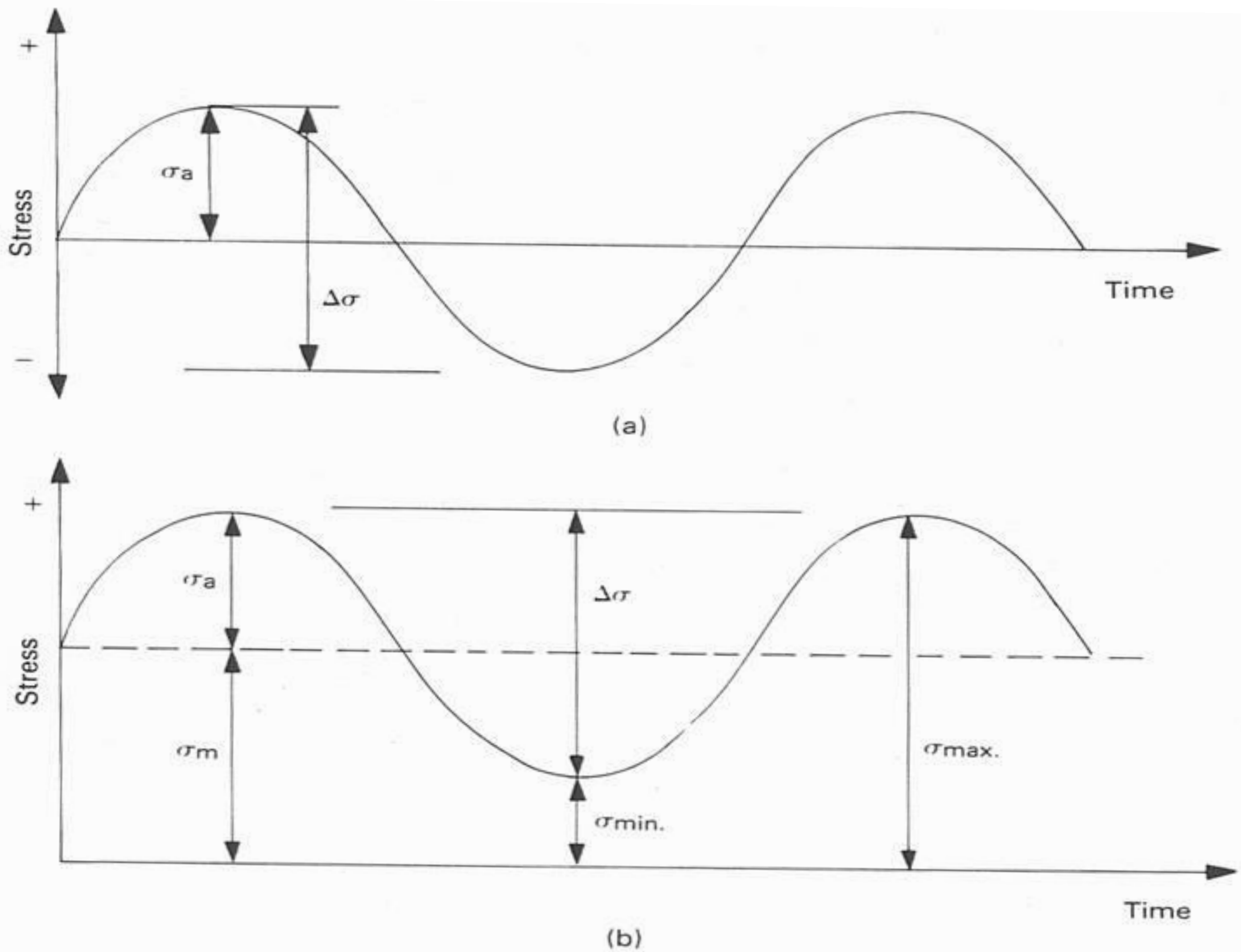


Figure 2.8 Types of fatigue loading. (a) Alternating stress, $R = -1$. (b) Fluctuating stress

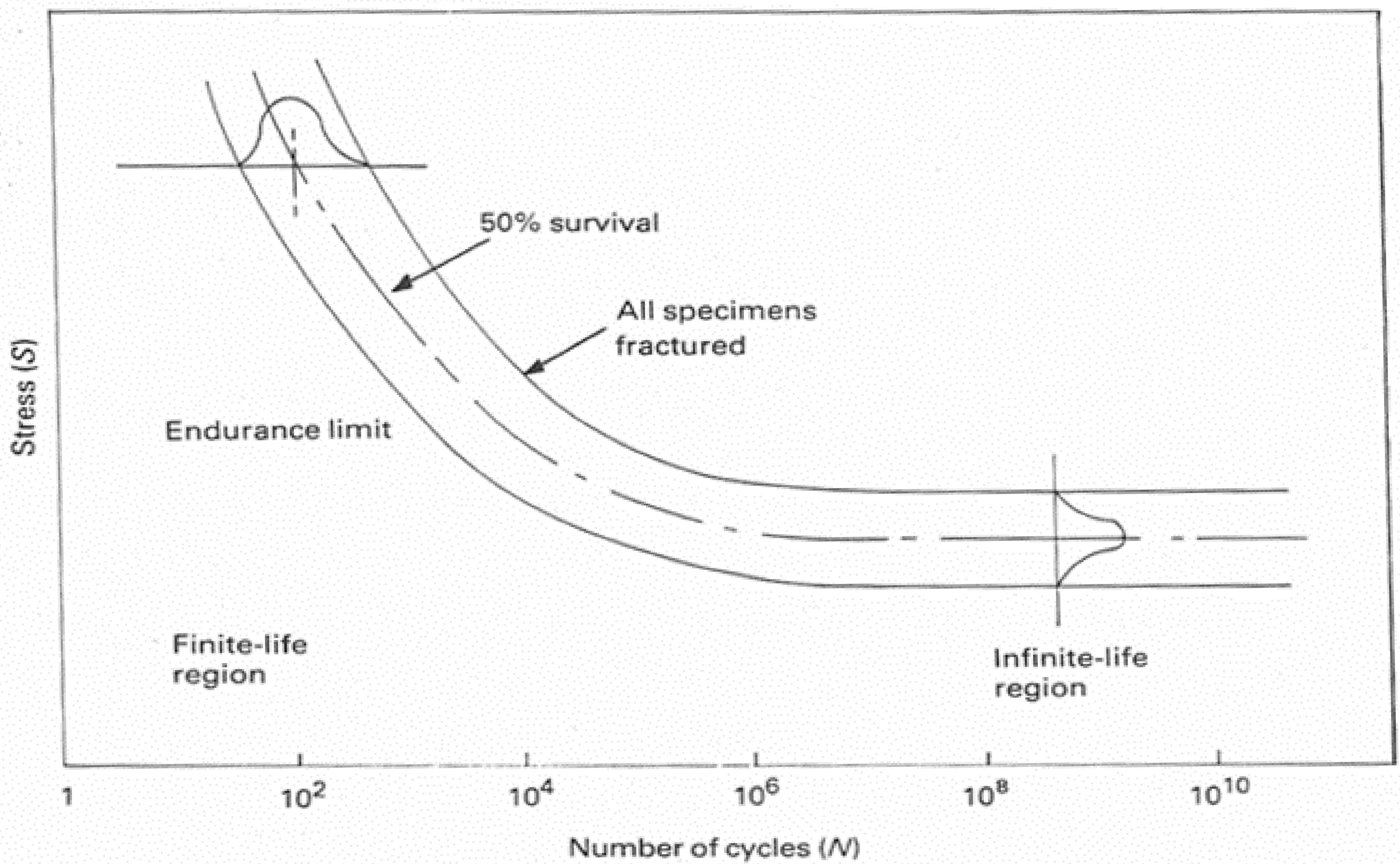


Figure 2.9 Representation of fatigue test results on $S-N$ curve.

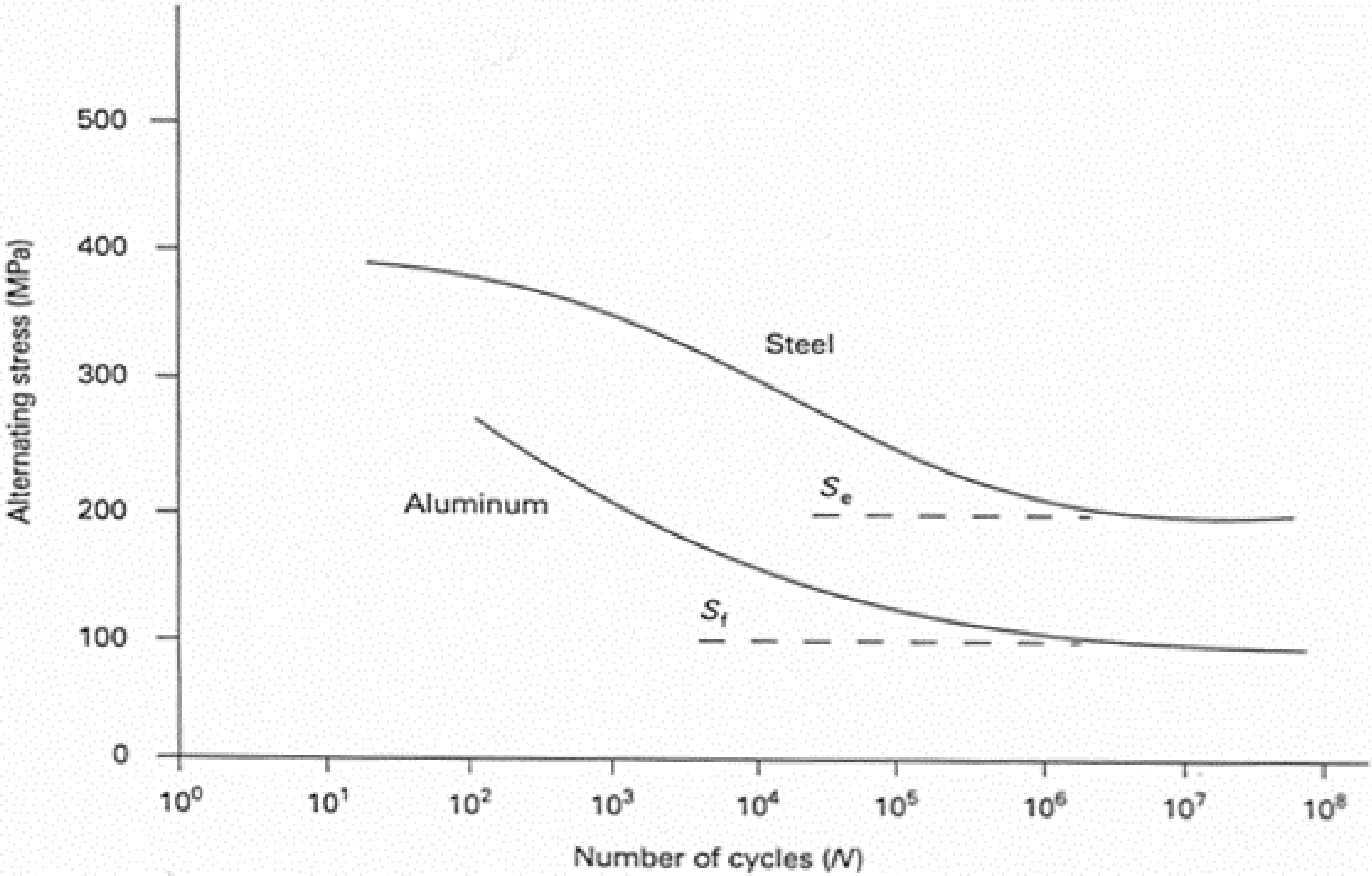


Figure 2.10 Fatigue results as represented by the $S-N$ curves. Steel exhibits an endurance limit and its curve levels off at S_e. Aluminum does not exhibit an endurance limit and its curve continues to decline for all values of N.

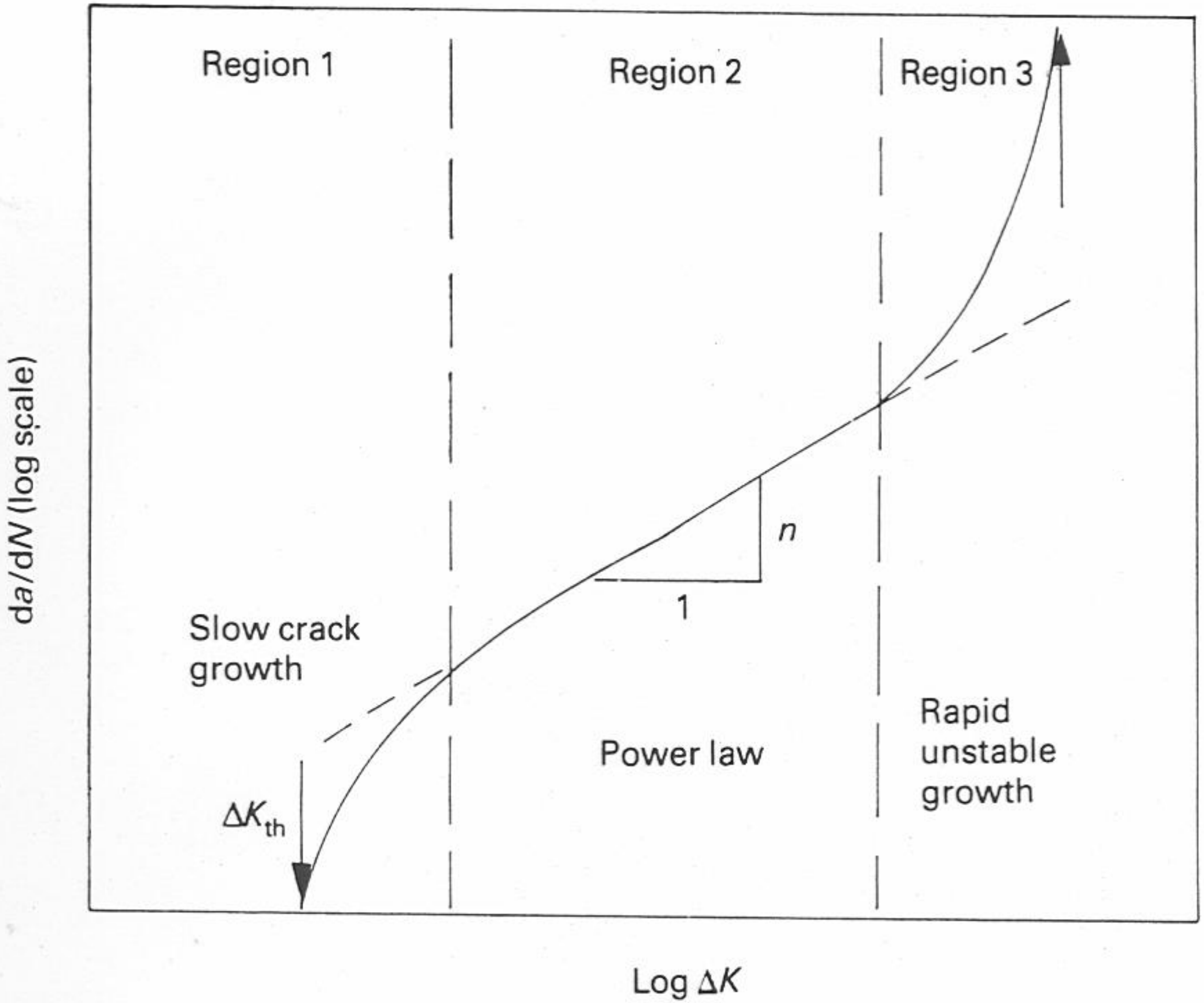


Figure 2.11 Schematic illustration of the effect of the range of the stress intensity factor (ΔK_I) on fatigue crack growth rate (da/dN).

Design Example 2.6
Prediction of the fatigue life of a component I

Problem

- A rotating shaft in a power generation system has been inspected by nondestructive tests that can only reveal surface cracks larger than 2 mm.
- The shaft is made of AISI 4340(T260^{o}C) steel of K_{IC} = 50 MPa m$^{1/2}$.
- The loading conditions of the shaft cause an alternating stress of 200 MPa. Estimate the fatigue life of the shaft.

Design Example 2.6
Prediction of the fatigue life of a component II

Solution

- As the maximum stress is at the surface of the shaft, surface cracks should not grow to cause fracture at the maximum stress of 200 MPa.
- The critical surface crack size is19.9 mm, from: $$\sigma_f = \frac{K_{IC}}{Y(\pi a)^{1/2}}$$
- The fatigue life of the shaft can be

  measured in terms of the number of cycles needed to extend the crack from 2 mm to 19.9 mm.
- This can be estimated from $$\frac{da}{dN} = C(\Delta K_I)^n$$

  C = 1.0 x 10^{-12} and n = 3.
- da = 1.0 x 10^{-12} x $(50)^3$ x dN = (19.9 – 2) x 10 $^{-3}$
- Approximate fatigue life of the shaft = N = 1.4 x 10^5 cycles

Elevated temperature failure

The effect of service environment on material performance at elevated temperature can be divided into three main categories:

1. Mechanical effects, such as creep and stress rupture.
2. Chemical effects, such as oxidation.
3. Microstructural effects, such as grain growth and overaging.

Combined creep and fatigue

Thermal fatigue

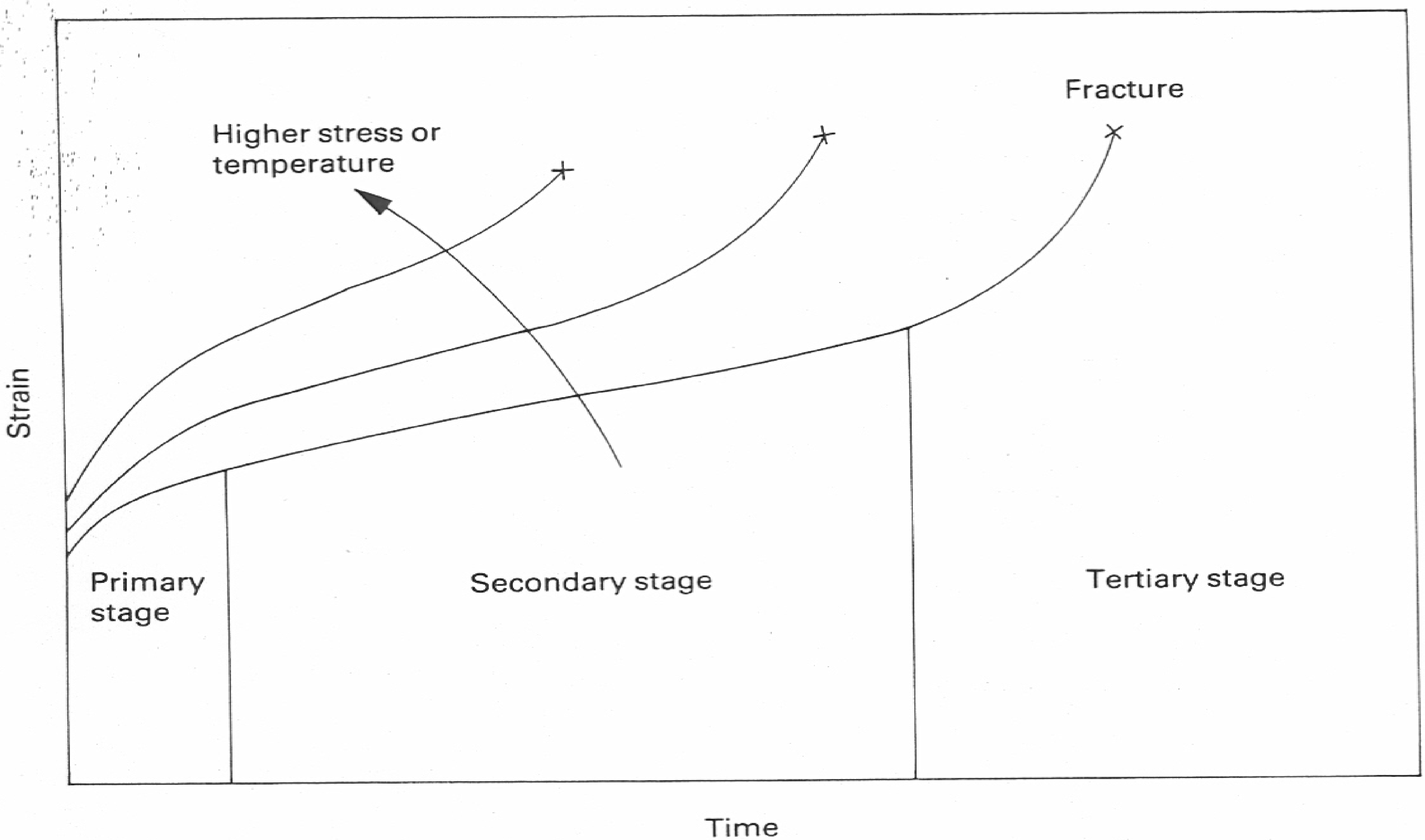


Figure 2.12 Schematic creep curve under tensile loading.

Design Example 2.7: Designing for steady state creep using Norton's equation I

Problem

- A cylindrical pressure vessel has an internal diameter of 45 cm, a wall thickness of 20 mm and operates at 800^{o}C.
- When operating at the design pressure the vessel diameter is expected to reach its maximum allowable increase in diameter of 5 mm in 4 years.
- As a result of increasing demand, it was decided to increase the operating pressure by 25%.
- Calculate the expected decrease in life of vessel as a result of this action.

Design Example 2.7: Designing for steady state creep using Norton's equation II

Solution

- Norton Index m can be assumed as 4.
- Creep strain rate under the original design conditions ($\varepsilon\cdot$) is:
- $\varepsilon\cdot = (5)/450 \text{x} 4 \text{x} 360 \text{x} 24 = 2.5 \text{ x } 10^{-7} \quad = B\, \sigma^4$
- Creep strain rate under conditions of increased pressure:
- $\varepsilon\cdot_n = B\,(1.25\,\sigma)^4 = 2.5 \text{ x } 10^{-7} \text{ x } (1.25)^4$
- Expected life of vessel under increased operating pressure = $(5)/450 \text{x} 360 \text{x} 24 \text{x} 2.5 \text{x} 10^{-7}$ = 2.1 years
- Remark: an increase of 25% in stress has resulted in about 50% reduction in expected life.

Failure analysis – experimental methods

Steps of systematic failure analysis:

- Collect background information about the function, source, fabrication, materials used, and service history of the component.
- Visual examination and select the parts to be used for further laboratory investigation.
- Macroscopic, microscopic, chemical analysis, nondestructive, and destructive tests to locate possible material and manufacturing defects.
- Identify the origin of failure, direction of crack propagation, and sequence of failure.
- Write a report to document the findings.

Case Study 2.8 - Failure of a welded steel component I

First ensure that the failure zone does not have cavities or cracks and that the load did not exceed the design limit, and that the weld was not placed in a stress concentration zone.

Next answer the following questions:

- What was the grade of the welding electrodes? Could it have introduced hydrogen in the weldment?
- What is the composition of the alloy steel and what is its hardenability? Was there martensitic structure in the fracture zone?

Case Study 2.8 - Failure of a welded steel component II

- What was the welding procedure? Was appropriate preheating and post-welding heating applied?
- Was there severe grain growth in the heat-affected zone where fracture occurred?
- Did the parent metal have inclusions that could have caused stress concentration?

Answers to the above questions should be helpful in identifying the cause of failure.

Failure analysis – analytical techniques

Several analytical techniques have been developed to help in solving failure problems, including:

- Root Cause Analysis
- Fault tress analysis (FTA)
- Failure logic model
- Failure experience matrix
- Expert systems

Case study 2.9: Failure of a crank shaft of an auxiliary power generation diesel engine I

Problem

- The crank shaft of an auxiliary power generation diesel engine failed after two years of service.

Analysis

- The failed crank shaft is made of forged steel.
- Fatigue failure with crack initiating at a surface defect
- The major causes for surface defect:
  - Casting defect in ingot before forging,
  - Defect during the forging process,
  - Surface defect during heat treatment after forging.
- Table 2.3 gives a simplified root cause analysis for the failure.
-

Table 2.3 Root cause analysis of a forged steel crank shaft

<table>
<tr><th colspan="8">Surface defect of forged crank shaft</th></tr>
<tr><th colspan="5">Casting defect in ingot</th><th colspan="2">Forging defect</th><th>Heat treatment defect</th></tr>
<tr><td colspan="2">Non-metallic inclusion</td><td colspan="2">Shrinkage cavity</td><td>Gas porosity</td><td>Surface lap</td><td>Hot shortness</td><td>Quenching crack</td></tr>
<tr><td>Chemical analysis</td><td>Filtering process</td><td>Casting temperature</td><td>Metal flow rate</td><td>Gas content</td><td>Metal flow in the die</td><td>Forging temperature</td><td>Quenching medium</td></tr>
<tr><td>Likely to occur</td><td>Likely to occur</td><td>Unlikely</td><td>Unlikely</td><td>Unlikely</td><td>Likely to occur</td><td>Likely to occur</td><td>Unlikely</td></tr>
<tr><td>Check with chemical analysis</td><td>Check with optical microscopy</td><td rowspan="2">No further action is needed</td><td rowspan="2">No further action is needed</td><td rowspan="2">No further action is needed</td><td>Check with optical microscopy for the low of grains</td><td>Check with optical microscopy for grain size</td><td rowspan="2">No further action is needed</td></tr>
<tr><td>Ensure that impurities are within permissible limits</td><td>Improve filtering process and use new filters</td><td>Better die design and less surface oxidation on reheating</td><td>Better control of reheating furnace temperature</td></tr>
</table>

Case study 2.9: Failure of a crank shaft of an auxiliary power generation diesel engine II

Conclusion

- Table 2.3 shows that four root causes
- The recommended tests to verify the most likely cause include chemical analysis and optical microscopy.
- The recommended preventive action will be based on the test results and can include better control of impurities in the steel, better filtering process of the liquid steel, better design of the forging dies and better control of the reheating furnace temperature.
- Recommended preventive actions include nondestructive inspection for surface defects; these include visual inspection, liquid penetrant test and magnetic particle tests

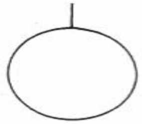
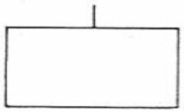
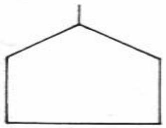
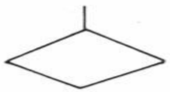
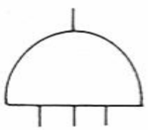
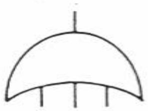
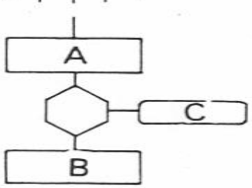
Symbol	Event
	Basic event that requires no further development and does not depend on other parts of the system for its occurrence.
	An event which results from a combination of basic events and needs further analysis to determine how it can occur. It is the only symbol on the fault tree that can have a logic gate and input events below it.
	Switch. Used to include or exclude parts of the tree which may or may not apply to certain situations.
	An event which depends upon lower events but has not been developed further.
	A connection to another part of the tree. A line from the apex indicates a transfer-in while a line from the side indicates a transfer-out.
	AND gate. Failure of next higher part will occur only if all inputs fail (parallel redundancy).
	OR gate. Failure of next higher part will occur if any input fails (series reliability).
	Inhibit gate. Combines AND and IF logic. Event A will occur if B occurs and C's value lies in some predetermined range.

Figure 2.13 Some standard symbols used in failure tree analysis.

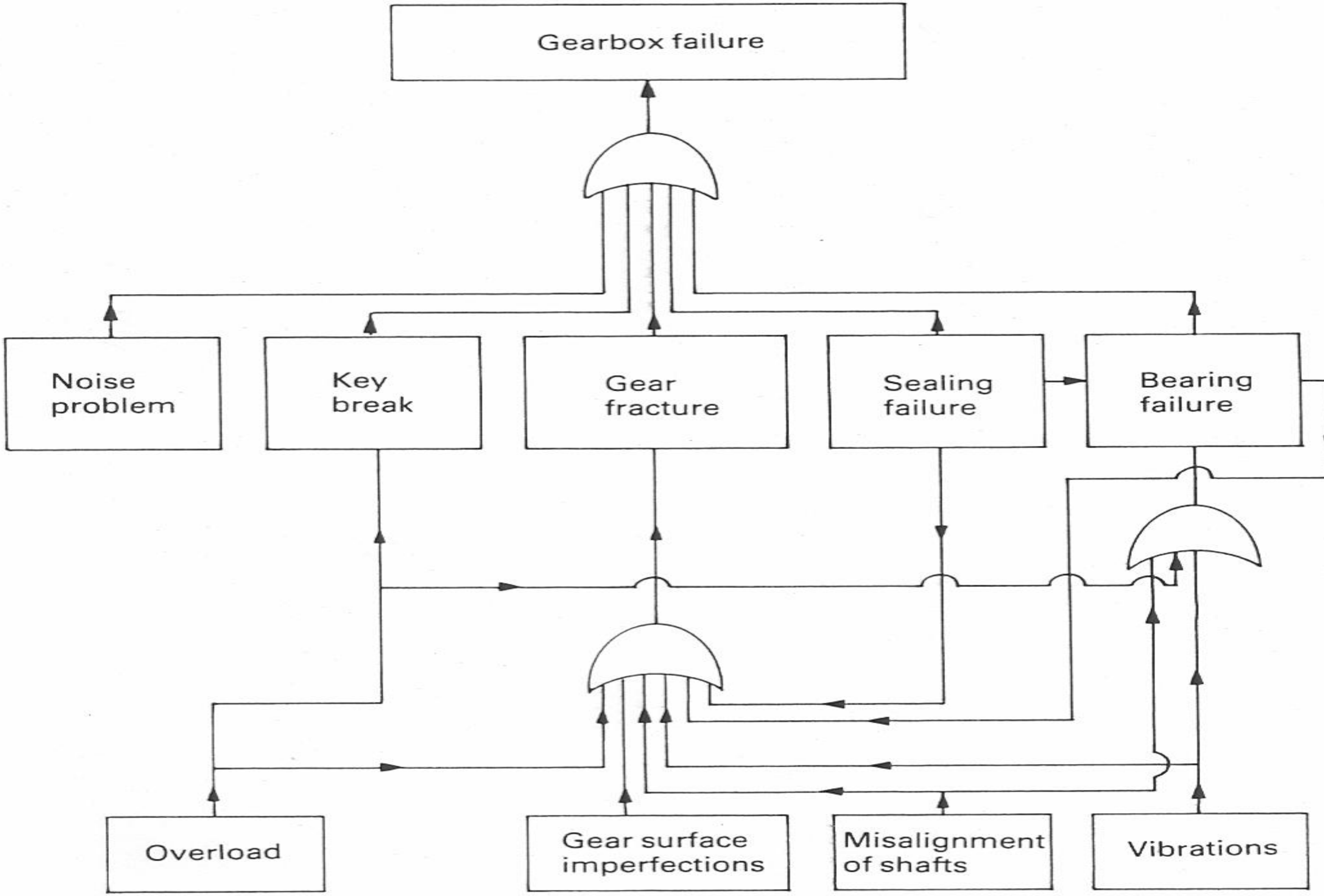


Figure 2.14 Simple analysis of a gearbox failure.

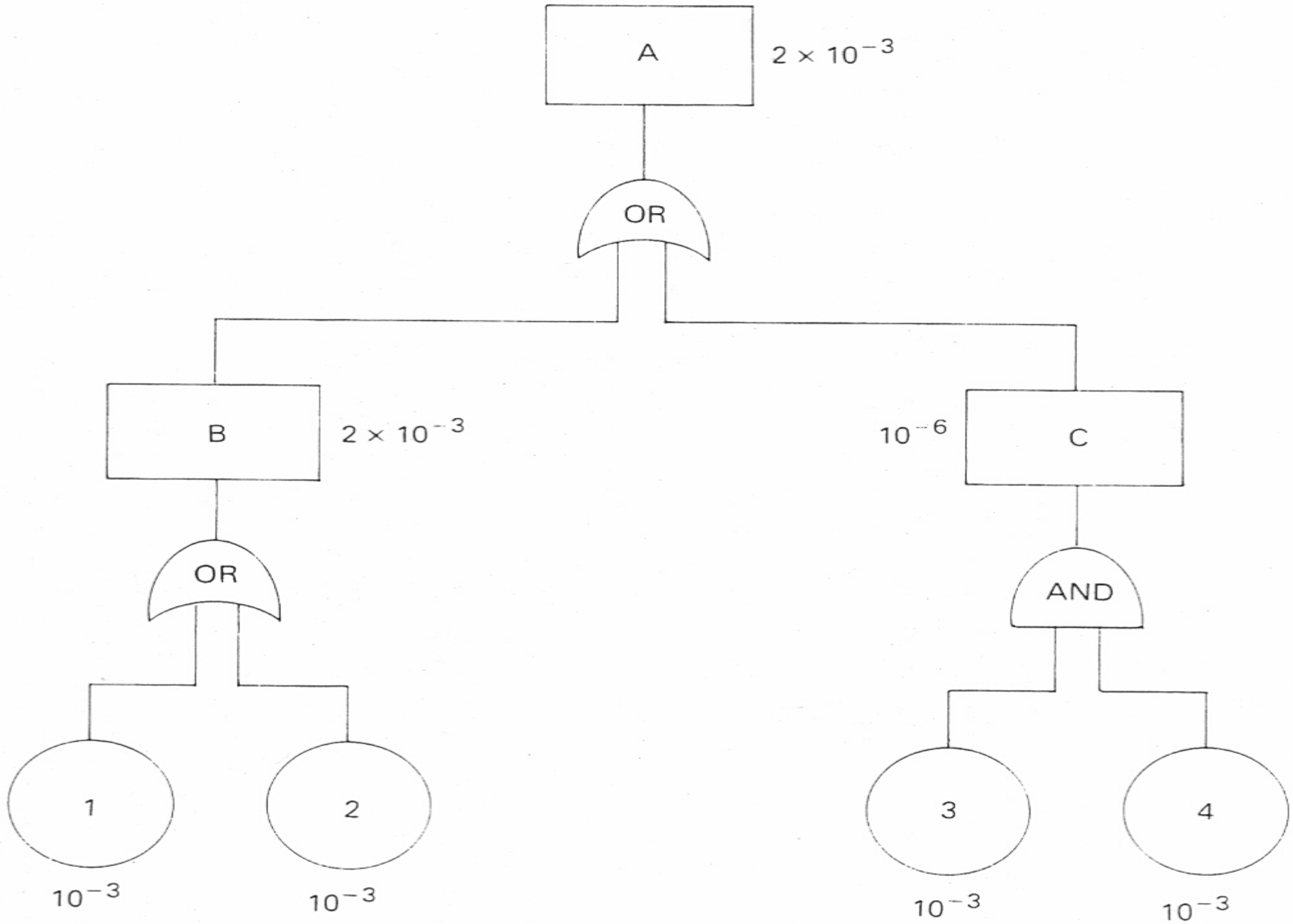


Figure 2.15 Sensitivity of system reliability to probabilities of failure of various components. Numbers beside each event represent probabilities.

Case study 2.11 - Use of MFLM in failure analysis I

A welded steel pressure vessel failed at less than operating load.

The failure event can be described as:

$$F = A.B.(C1 + C2).D.E.G.H. \qquad (2.8)$$

A = low alloy steel,

B = heat treatment defect resulting in brittle structure

C1 = welding defect, C2 = residual stress from welding

D = presence of corrosive environment

E = high residual stresses resulting from faulty post-weld heat treatment

G = failure of nondestructive tests to detect initial defect

H = failure to detect incorrect heat treatment of material

( ).( ) = Boolean AND operator ( ) + ( ) = Boolean OR operator

Case study 2.11 - Use of MFLM in failure analysis II

In this case, either of the following logic events could have been sufficient to cause failure:

1) F1 = A.B.C1.G.H. (2.9)

- This means that that the initial defect, combined with the brittle structure, constituted a major risk.

2) F2 = A.B.C2.D.E.H. (2.10)

- This means that stress corrosion cracking is likely to lead to crack growth even in the absence of initial defect.

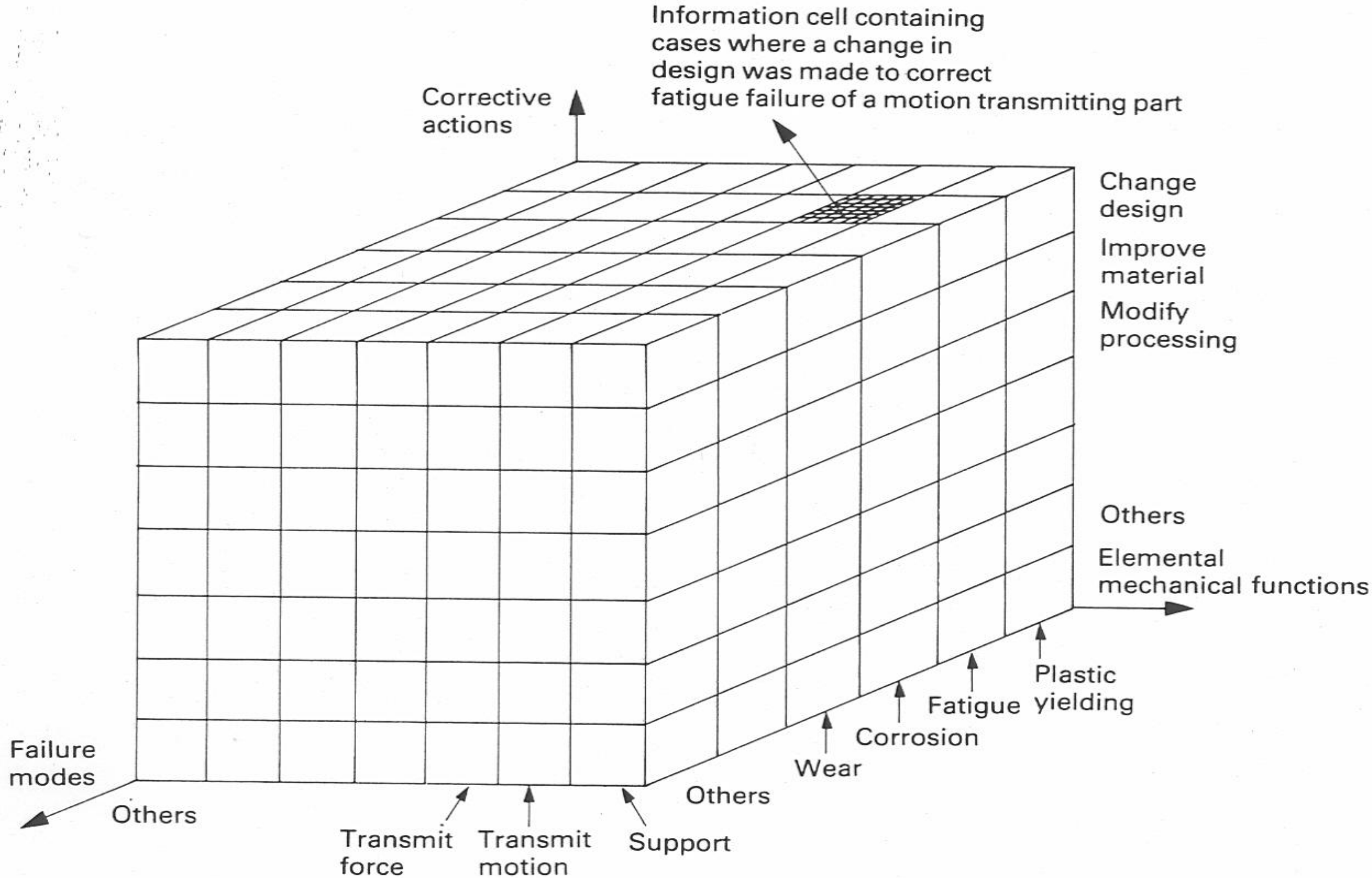


Figure 2.16 Part of failure experience matrix which can be used to store failure information.

Design Example 2.12
FMEA of a Water Storage Tank

- Construct a FMEA for a water storage tank.
- The tank consists of a welded steel shell, an inlet valve system and an exit filter system. Table 2.4 gives an analysis of the failure modes, consequences of such failures, possible causes and likelihood of detection.
- The scales described in section 2.10 are used to evaluate RPN and criticality.
- The analysis shows that clogged filter and stuck inlet valve have the highest RPN and criticality followed by cracked welds and cracked filter.
- Table 2.4 gives recommended actions to reduce risk of failure in various parts of the storage tank.

Table 2.4 Using FMEA in designing water storage tank

Product: Water storage tank

Subsystems/parts: tank shell, inlet valve system, outlet filter system

System / subsystem / Part	Function	Possible failure mode	Consequence of failure	Severity (S)	Possible cause of failure	likelihood of occurrence (O)	Ease of detecting failure (D)	RPN (S . O . D)	Criticality (S . O)	Action to reduce risk
Tank shell	Contains water	Water leak	Loss of water	7	a) Cracks in welds b) General corrosion	a) 5 b) 4	a) 7 b) 5	a) 245 b) 140	35 28	a) Inspect welds b) Weld filler same as tank material c) Galvanic protection
Inlet valve system	Controls water entering the tank	a) Valve is not shut when tank is full b) Valve is shut when tank is empty	a) Water floods surroundings b) No water supply from tank	8	Valve stuck open Valve stuck shut	5 5	7 7	a) 280 b) 280	40 40	a) Use corrosion resistant material for valve b) Better tolerance for moving valve parts
Outlet filter system	Ensures no debris in water out of tank	a) Filter does not let water through b) Filter lets debris through	No water supply from tank Debris in water from tank	8	Filter clogged Filter broken	6 4	6 7	a) 288 b) 224	48 32	a) Improve filter design b) Use better filter material

Chapter 2 summary I

1. Causes of failure of components can be attributed to
   - design deficiencies,
   - poor selection of materials,
   - manufacturing defects,
   - exceeding design limits and overloading, and/or
   - inadequate maintenance.
2. The general types of mechanical failure include yielding, buckling, creep, wear, fracture, stress corrosion, and failure under impact loading.
3. Fracture toughness is defined as the resistance of materials to the propagation of an existing crack and is a function of the critical stress intensity factor *KIC*.

Chapter 2 summary II

4. Brittle fractures of metals are usually associated with low temperatures and usually take place at stress raisers such as sharp corners, surface defects, inclusions, or cracks.

5. Fatigue failures account for the largest number of mechanical failures in practice and occur in components that are subjected to fluctuating loads. The fatigue strength of most steels is usually about 0.4 - 0.6 the tensile strength.

6. Creep is a major factor at high temperatures and can cause fracture at strains much less than fracture strains in tensile tests.

Chapter 2 summary III

7. Thermal fatigue takes place as a result of repeated changes in temperature. Factors encouraging thermal fatigue:
   - Faster changes in temperature,
   - lower thermal conductivity,
   - higher elastic constant,
   - higher thermal expansion coefficient,
   - lower ductility, and
   - thicker sections.

8. Several experimental and analytical techniques are available for the analysis of failure and for predicting its occurrence at the design stage. Failure mode effects analysis (FMEA) is a step-by-step process for identifying all possible scenarios of failures and the consequences of each of them. Failures are prioritized and actions are then be taken to eliminate or reduce such failures, starting with the highest-priority ones.