5. Failure

Structural metallic materials

A Boeing 737-200 commercial aircraft(Aloha Airline flight 243) that experienced an explosive decompression and structural failure on April 28,1988.

(1969----------75000) VS (1988---89680--19)

rank 2 (20year)

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Structural metallic materials

Aloha 243 was a watershed accident

- Very clear precursors that were not acted upon
- Basic lack of airplane level awareness
- Errors in basic design and certification philosophies
- Catastrophic unintended effects
- “Aviation Safety Research”

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Structural metallic materials

"Island-hopping"

•Preflight inspection and noted nothing unusual

• Airplane initially flew 3 round trip flights from Honolulu to Hilo, Maui, and Kauai. All flights were uneventful

• No requirement for visual inspection between flights, and none were conducted

• Accident flight departed Hilo at 1:25 pm with flight crew and 89 passengers on board flight

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Structural metallic materials

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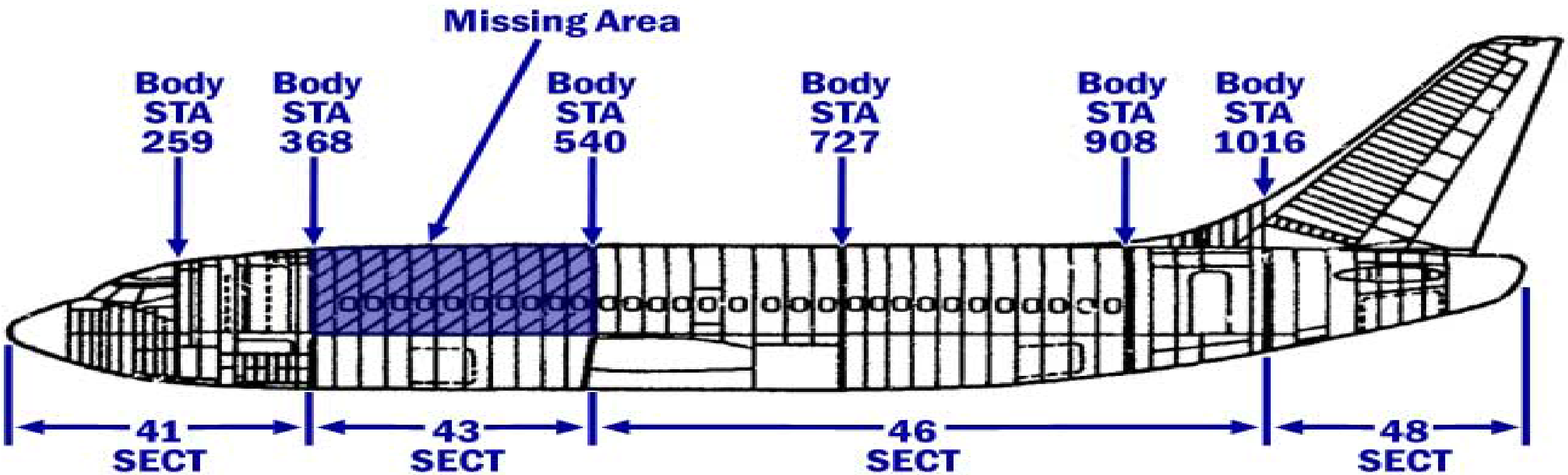
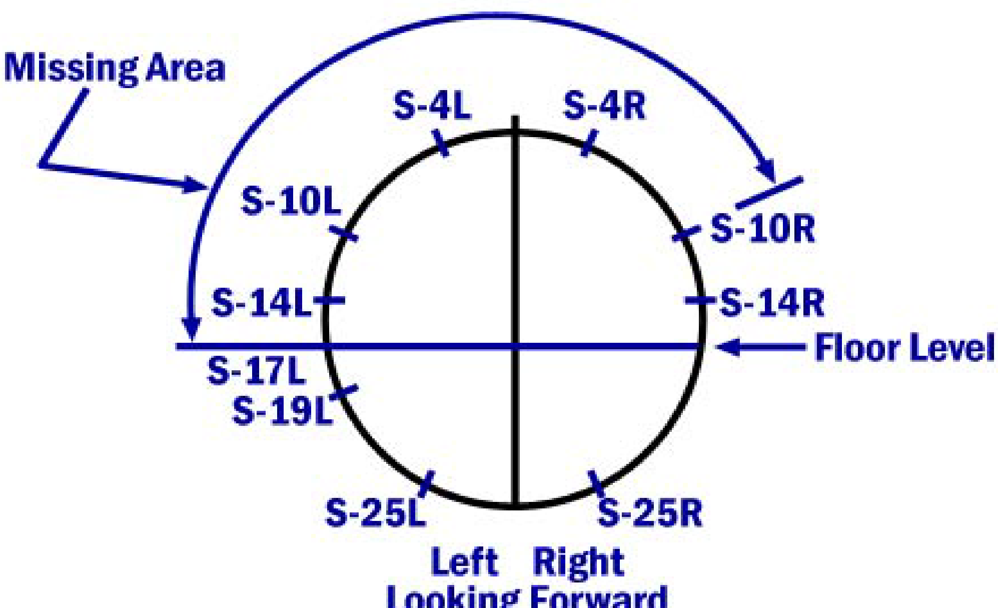
Damage Summary





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Accident was caused by pressurization related cyclic fatigue of fuselage lap joint

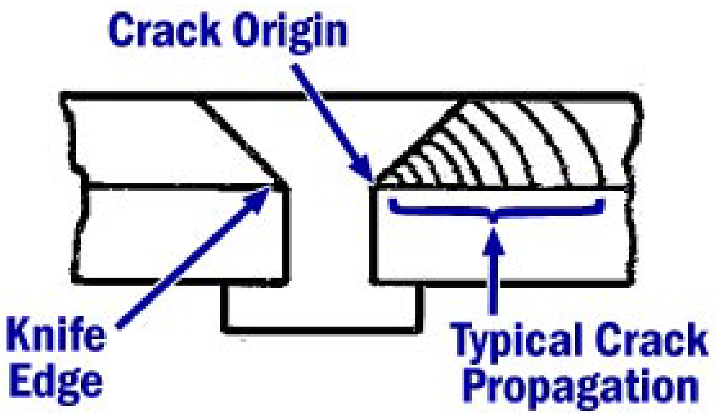
•Disbonding of joint led to improper load distribution, and fatigue cracking

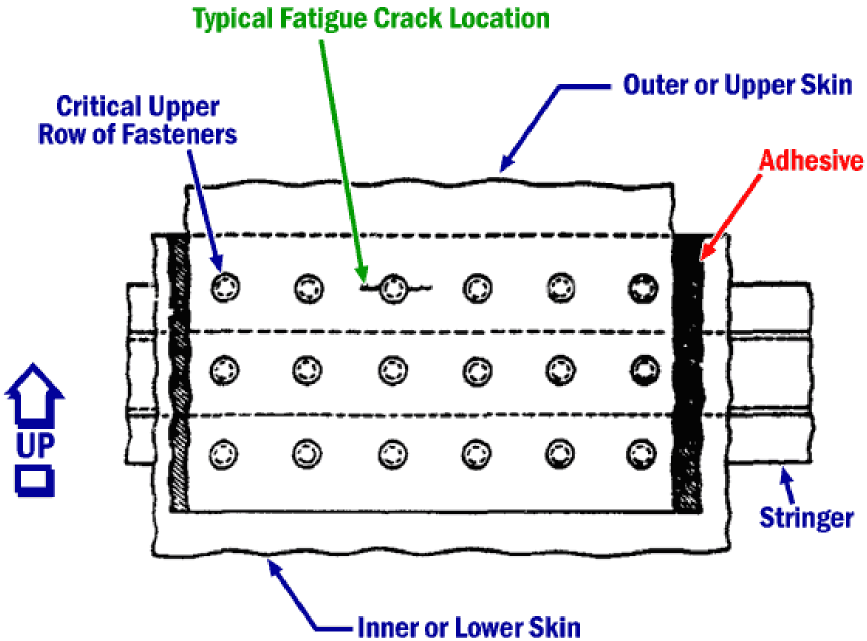
•Joint disbonding also led to corrosion, which contributed to joint failure

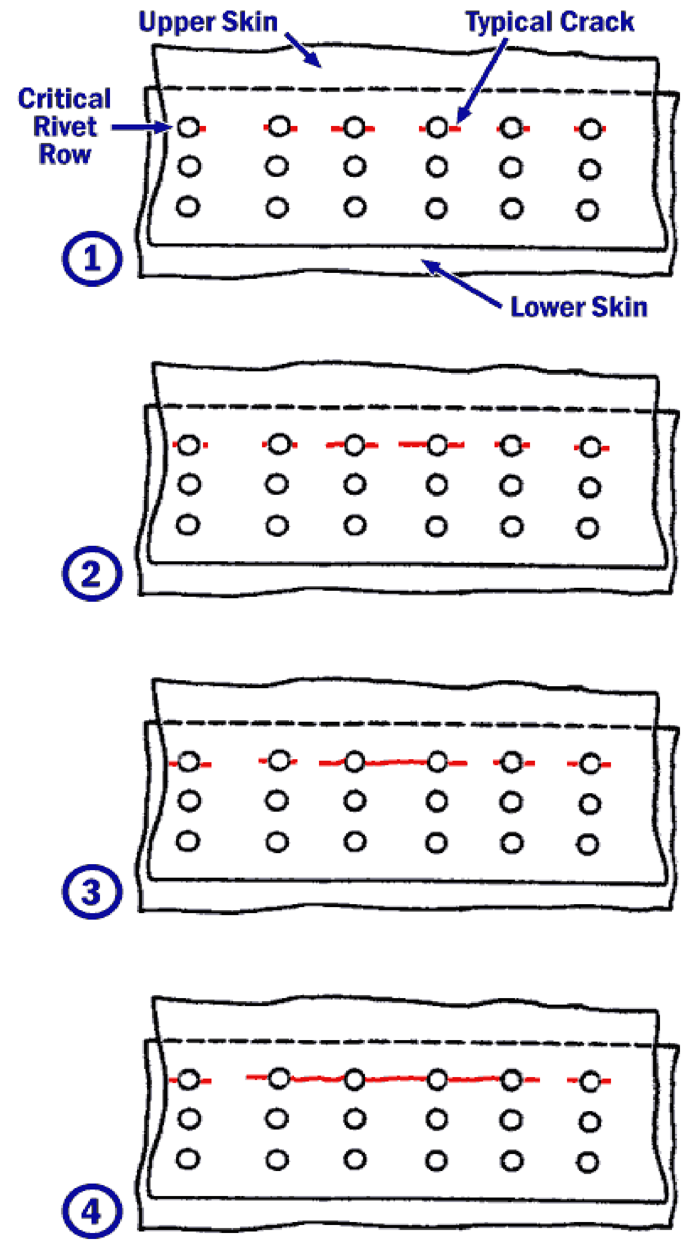
•Lap joints in other locations had been the subject of AD, but none in the area(s) of failure

Structural metallic materials

Crack growth

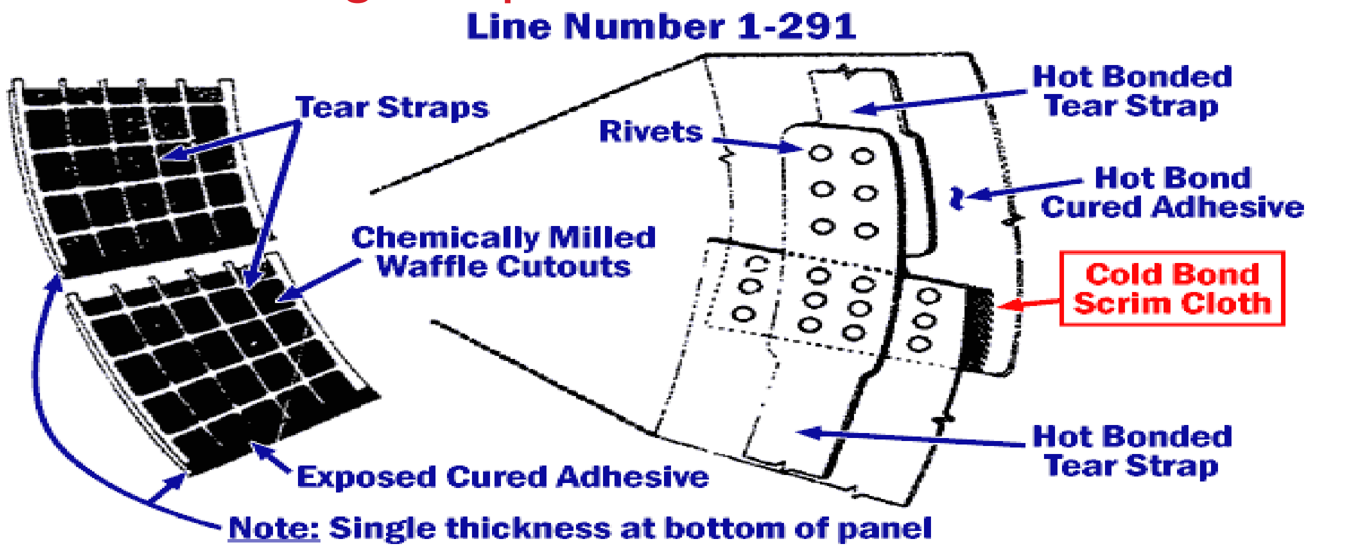


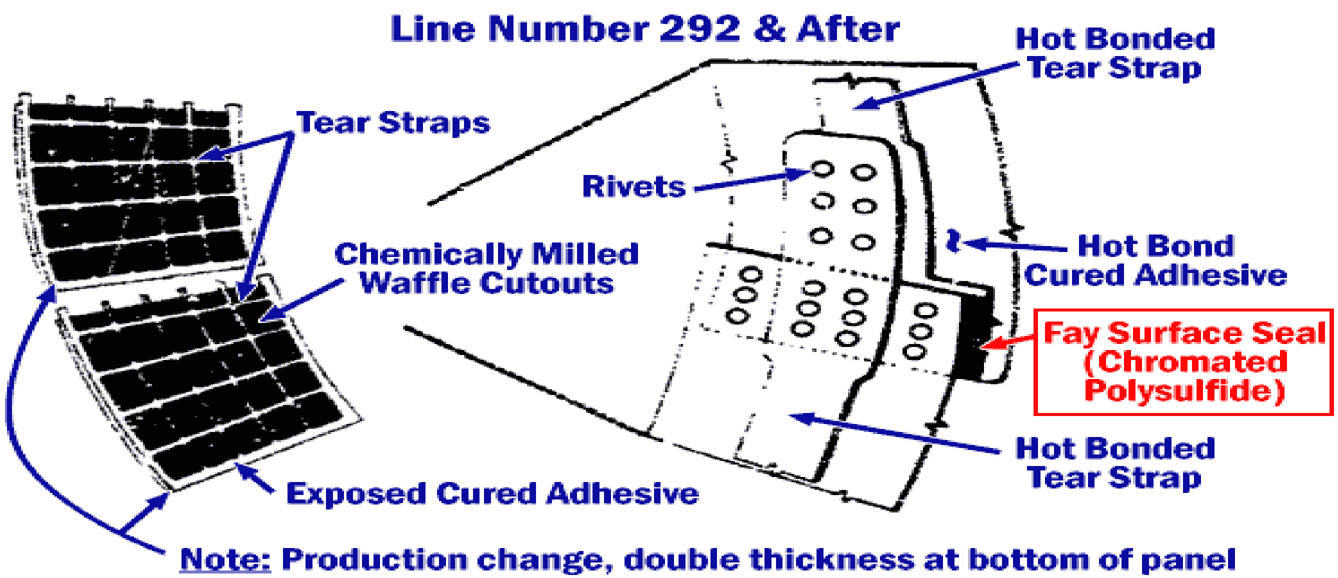




Structural metallic materials

Fuselage Lap Joint Construction





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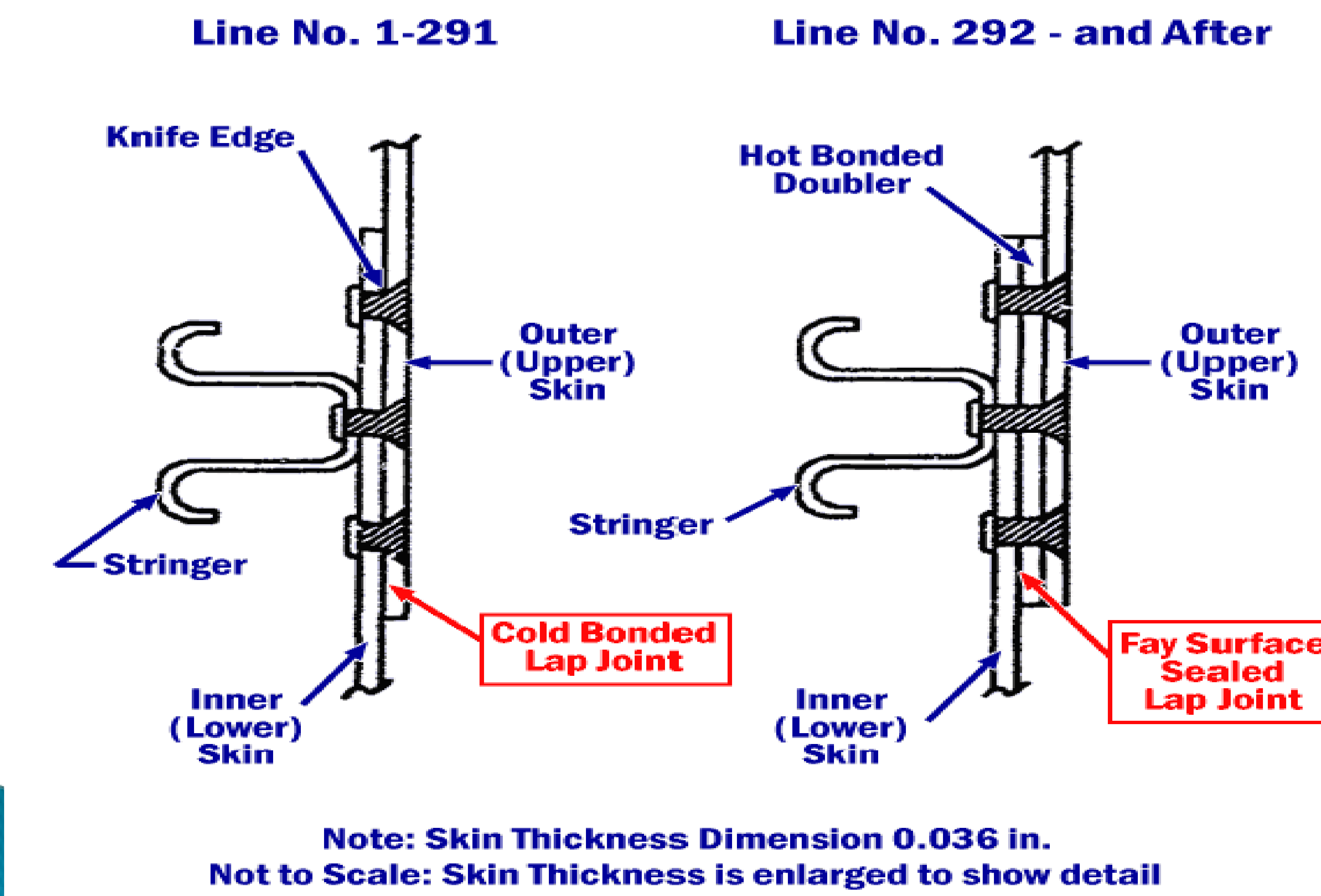
Structural metallic materials



Structural metallic materials

Example Learned

•Basic Design and Safety Assumptions need to be validated

•Mandatory repair/modification/replacement of Principal Structural Elements

•Requirement to develop a limit of validity for WFD, and application in airlines maintenance programs

Structural metallic materials

Important date:
1860---- wohler: rotating bending test
1920----Griffith: theory of brittle rupture
1956----Irwin: theory of brittle rupture with confined plasticity
1960----Paris: concept of damage tolerance
1970----crack in fatigue /complex loading
Today---local approach of cracking

Structural metallic materials

Approach Strength of Materials

Applied Stress

Yield Stress or Ultimate Tensile Stress

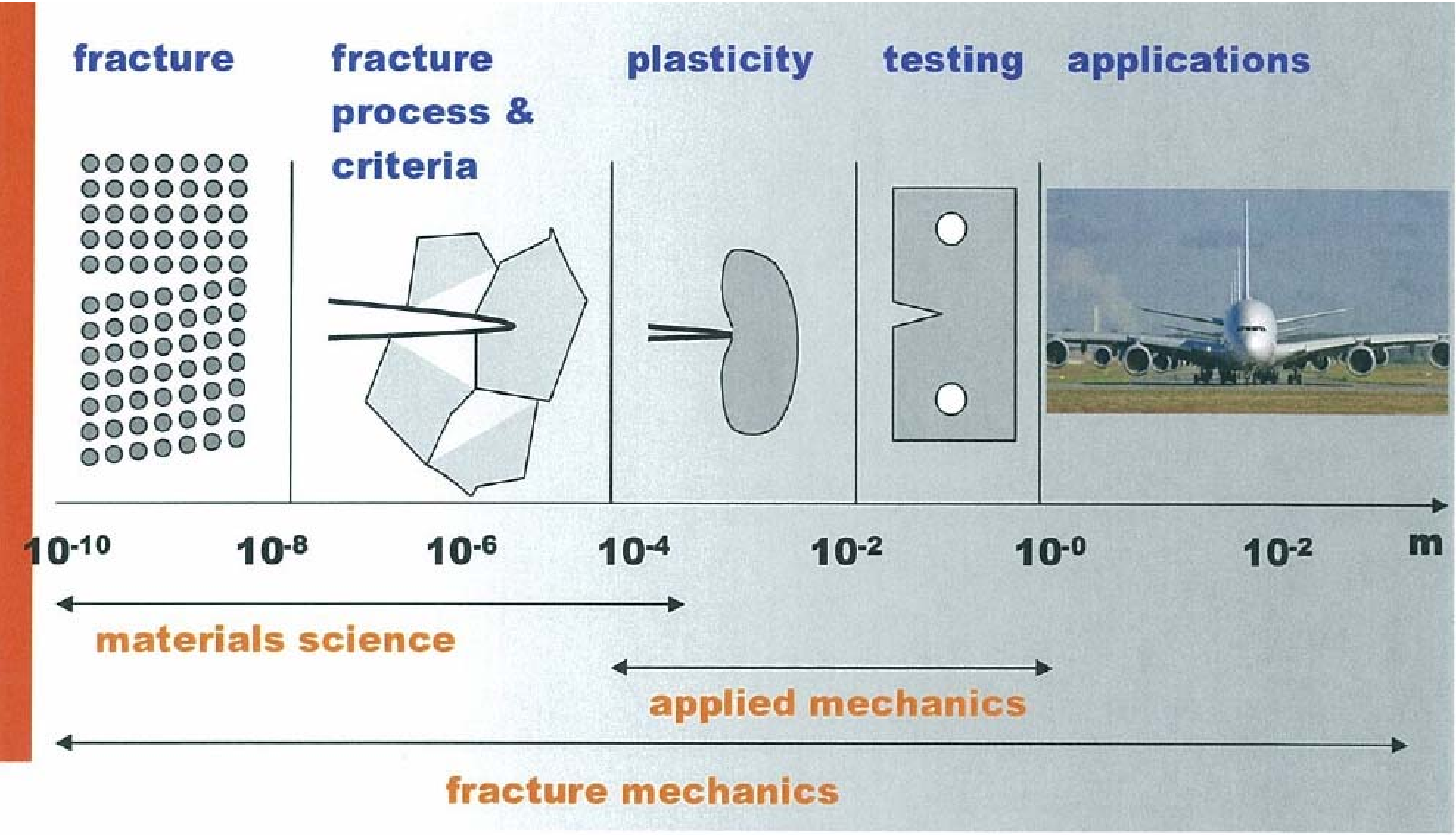
Approach Fracture Mechanics

Applied Stress

Size of Crack

Toughnes
s

Structural metallic materials



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Fracture

Complete Fracture:

Incomplete fracture:

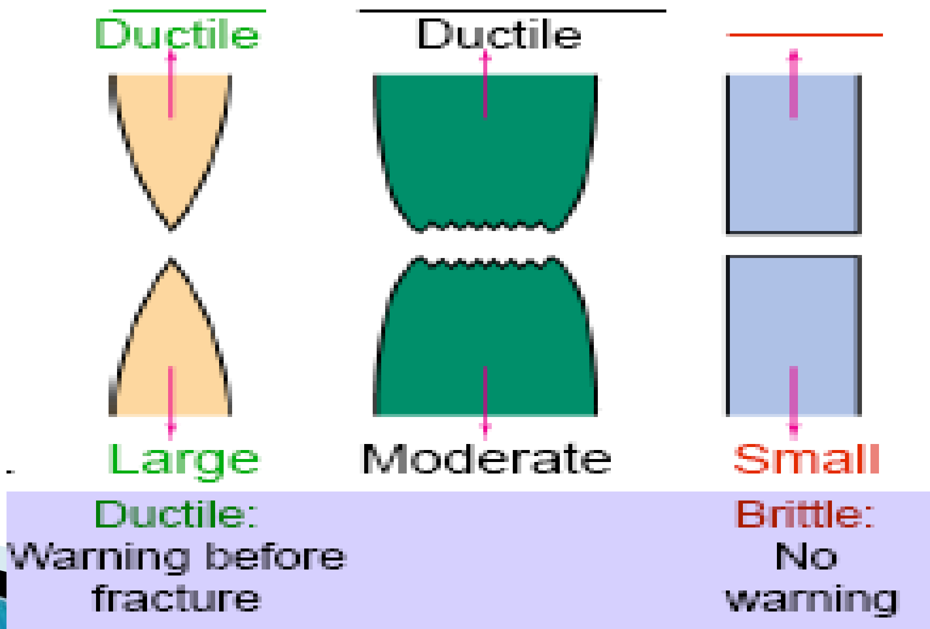
•fatigue fracture-
•creep fracture-
•stress corrosion cracking-

Structural metallic materials

5.1 FUNDAMENTALS OF FRACTURE

Ductile fracture: a model of fracture that is attended by extensive gross plastic deformation

Brittle fracture: Fracture that occurs by rapid crack propagation and without appreciable macroscopic deformation



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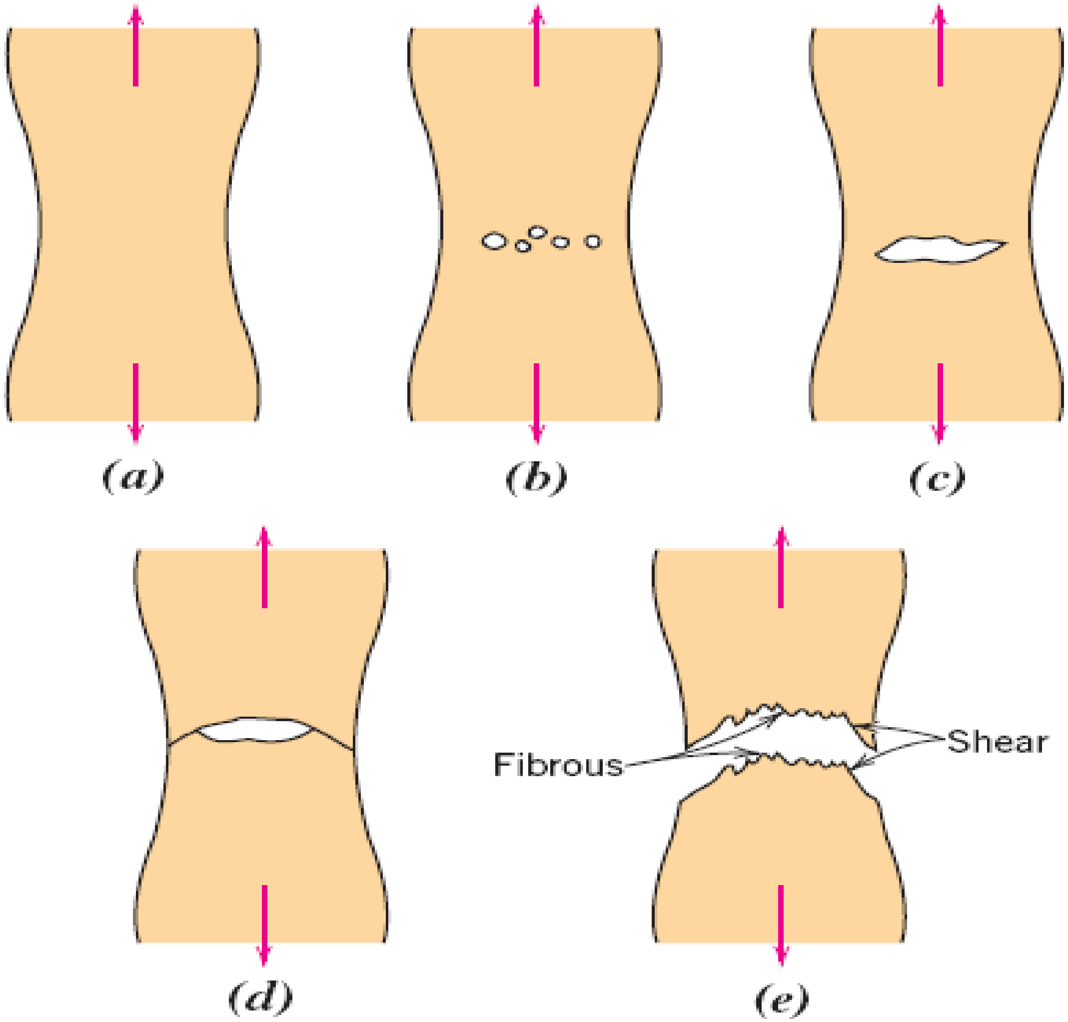
5.2 DUCTILE FRACTURE



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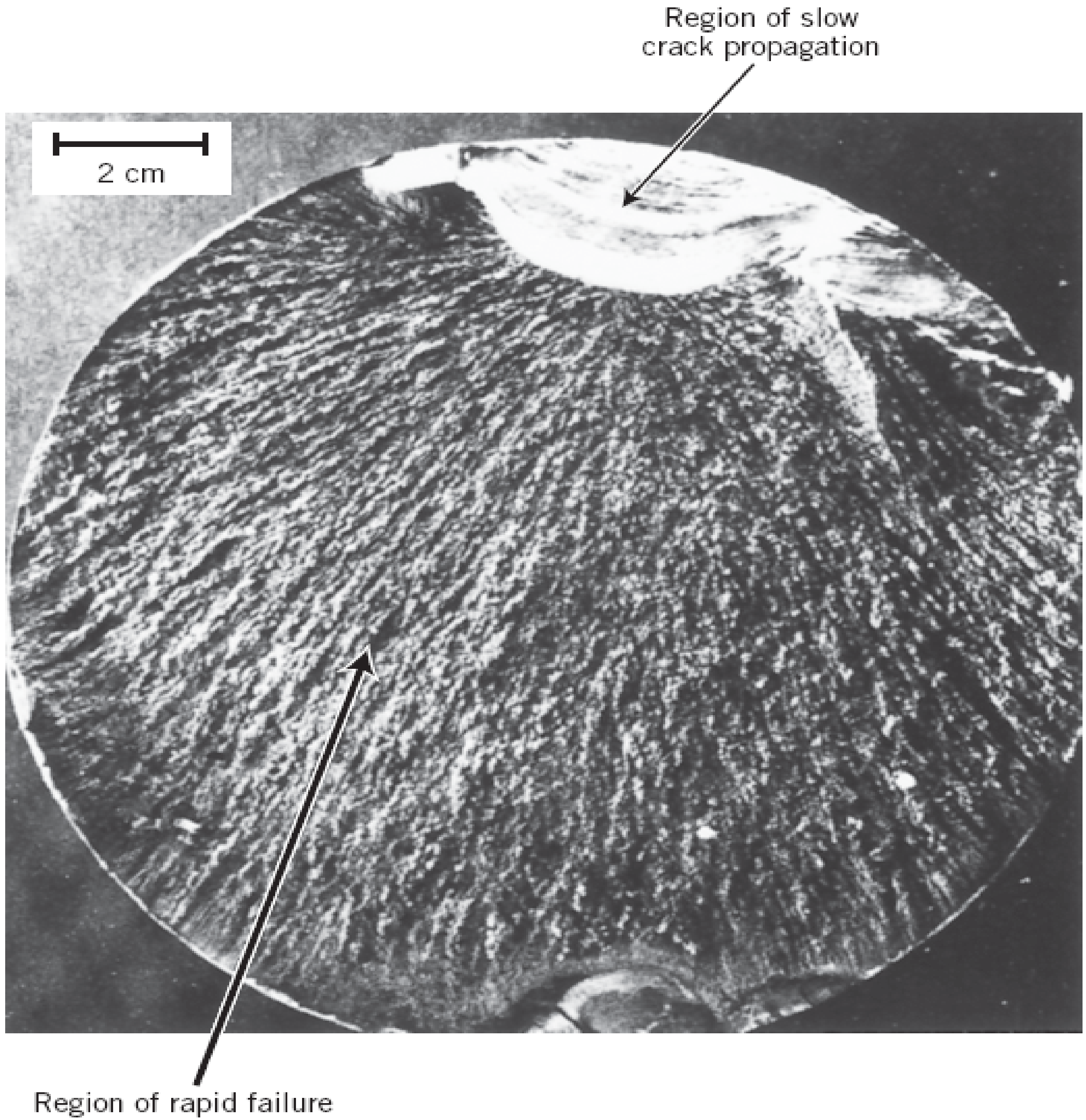
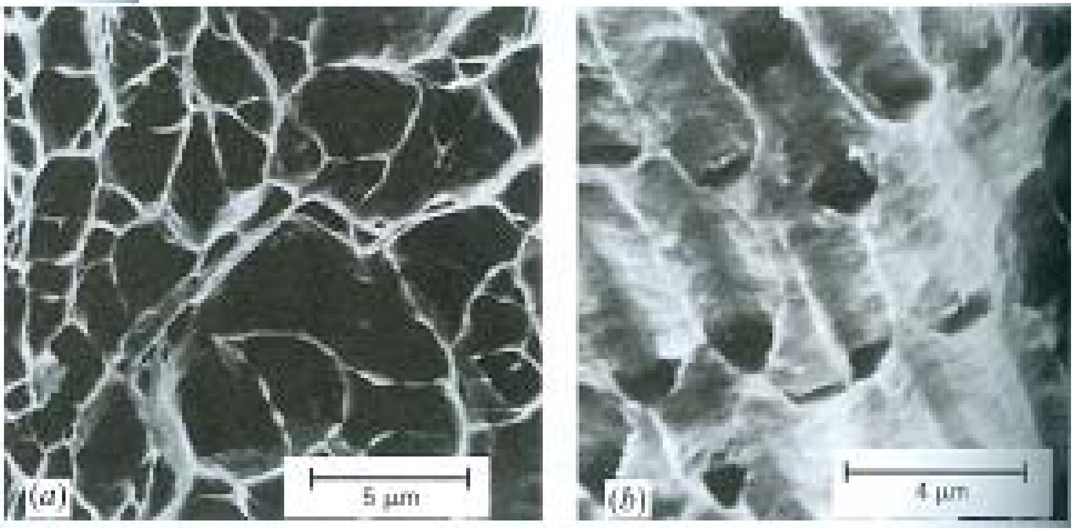

Region of slow
crack propagation
2 cm
Region of rapid failure

Structural metallic materials

5.2 DUCTILE FRACTURE



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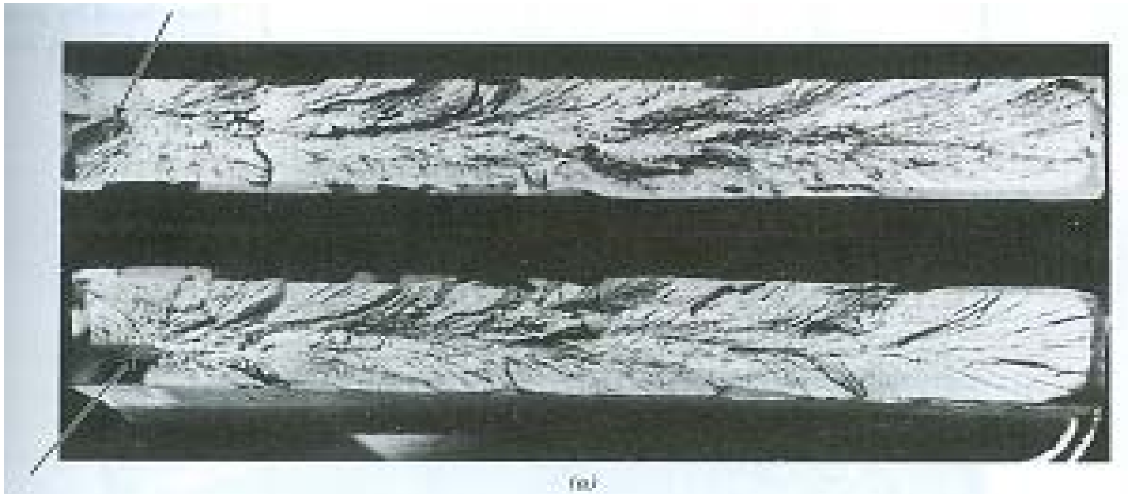
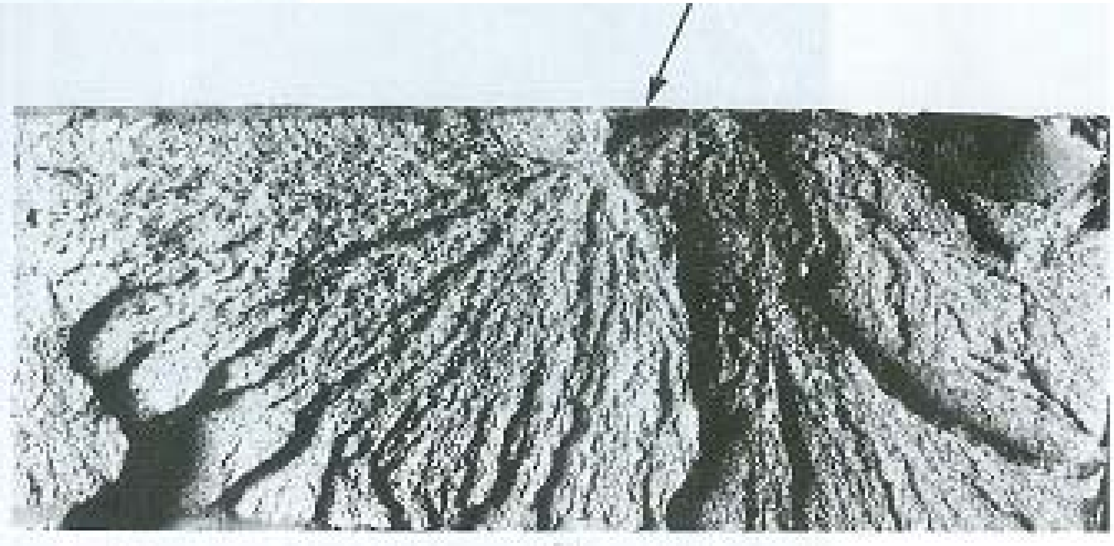
5.3 BRITTLE FRACTURE



(a)



(b)

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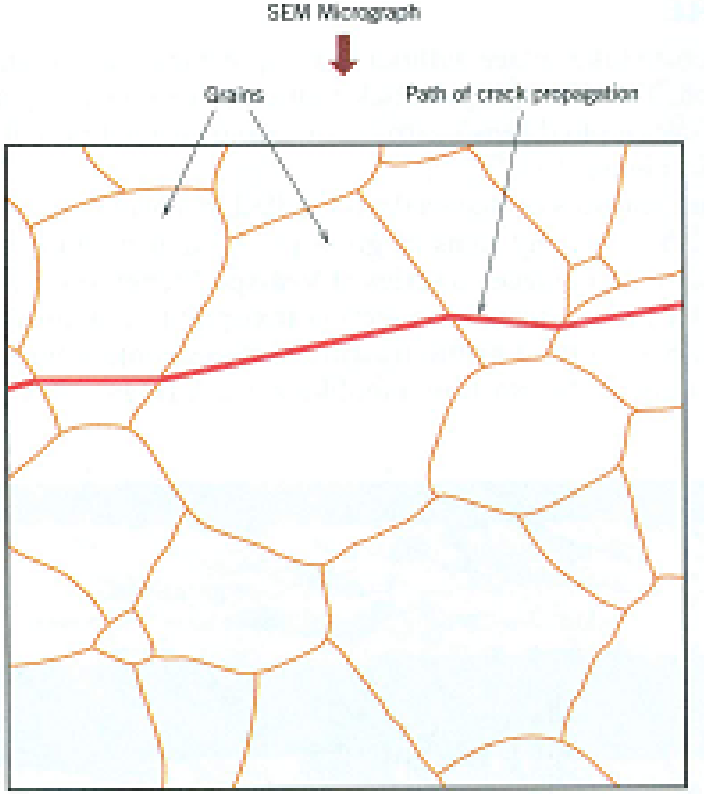
5.3 BRITTLE FRACTURE



(a)


(b)

Transgranular fracture: fracture of polycrystalline materials by crack propagation through the grains

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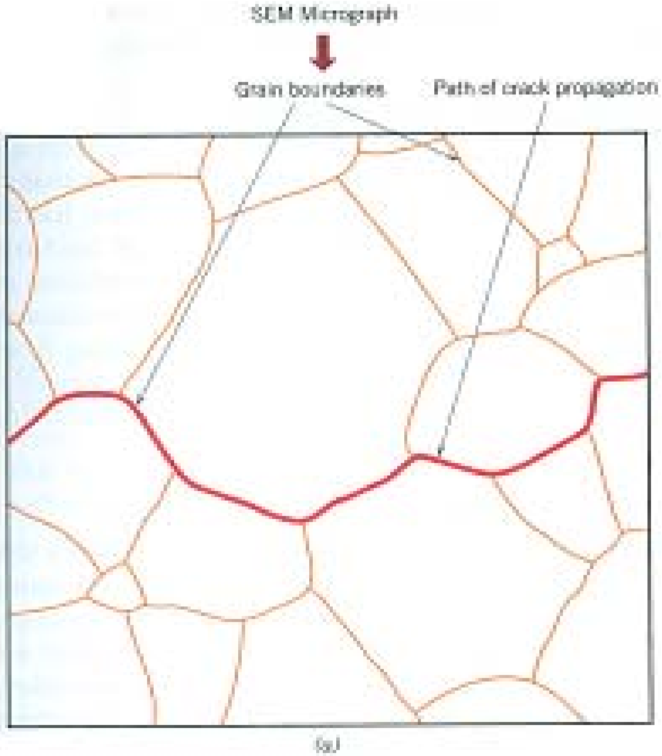
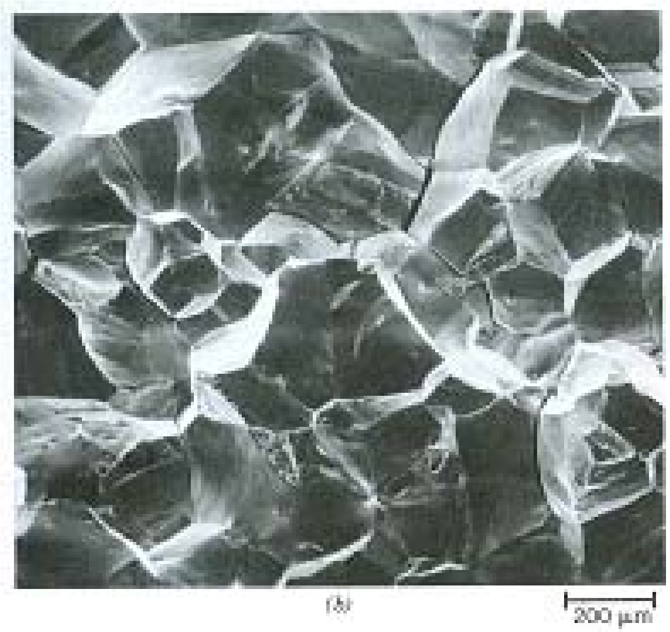
Structural metallic materials

5.3 BRITTLE FRACTURE





intergranular fracture: fracture of plolycrystalline materials by crack propagation along grain boundaries.

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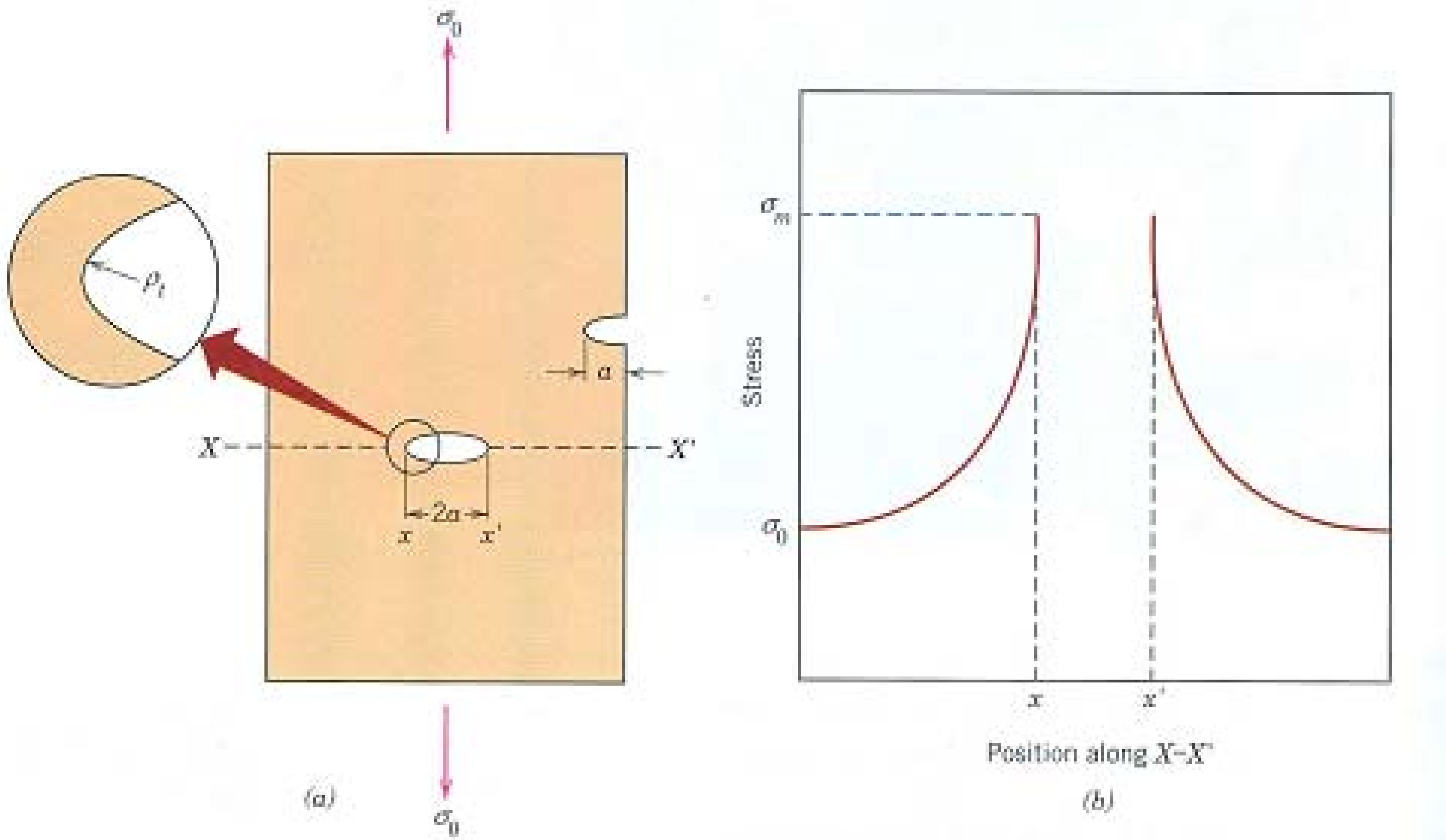
Fracture mechanics



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Structural metallic materials

5.4 Fracture Toughness

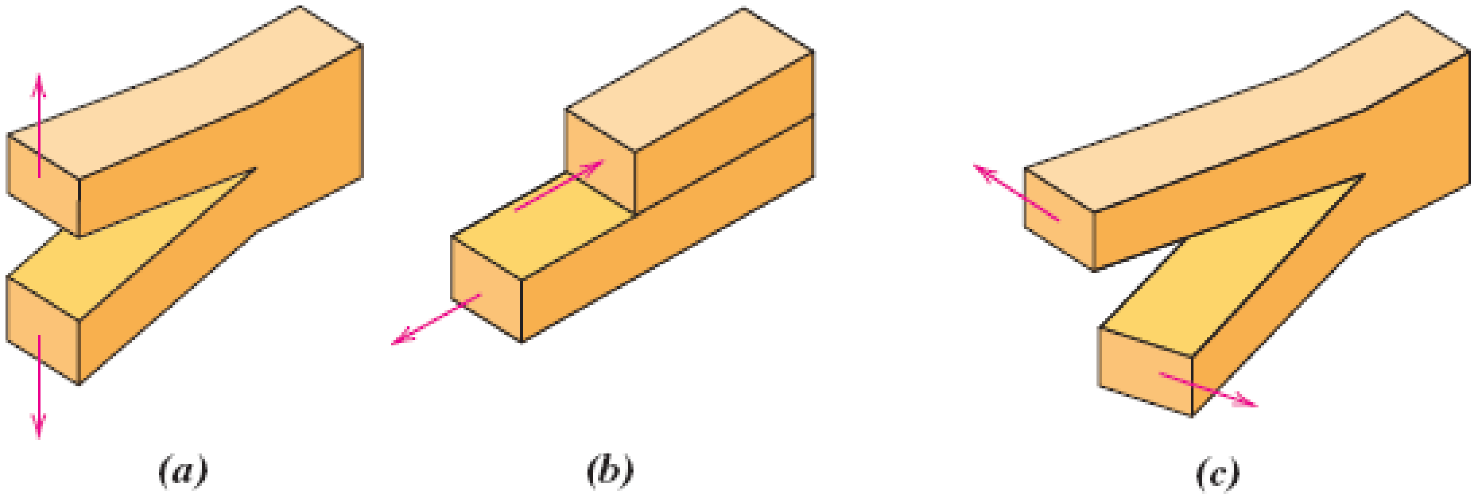
Fracture toughness: the measure of a material' resistance to fracture when a crack is present.

$$K_{I_c} = Y\sigma\sqrt{\pi a}$$

Dependence on critical stress for crack propagation and crack length

Structural metallic materials

5.4 Fracture Toughness



- (a) Mode Ⅰ ,opening or tensile
- (b) Mode Ⅱ ,sliding
- (c) ModeⅢ,tearing mode

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Structural metallic materials

5.4 Fracture Toughness

Plane strain fracture toughness: the K_c value for this thick-specimen situation

$$K_{I_c} = Y\sigma\sqrt{\pi a}$$

Plane strain fracture toughness for mode Ⅰ

crack surface displacement

$$\sigma_c = \frac{K_{I_c}}{Y\sqrt{\pi a}}$$

Computation of design stress

$$a_c = \frac{1}{\pi}\left(\frac{K_{I_c}}{Y\sigma}\right)^2$$

Computation of maximum allowable flaw length

- 习题1：某无限大板含中心裂纹$2a_0$，受$R = 0$的循环载荷作用，$K_c = 120\ \text{MPa}\cdot\text{m}^{1/2}$，裂纹扩展速率为$da/dN = 2\times10^{-12}(\Delta K)^3$ m/r。试对于$a_0 = 0.5$mm计算$\sigma_{max} = 200$ MPa时的寿命。

➢ 提示：临界裂纹长度

$$a_c = \frac{1}{\pi}\left(\frac{K_c}{\sigma_{\max}}\right)^2$$

- 习题2：某大尺寸钢板有一边裂纹$a_0 = 0.5$mm，受$R = 0$，$\sigma_{max} = 200$ MPa的循环载荷作用。已知材料的屈服极限$\sigma_s = 630$ MPa，强度极限$\sigma_b = 670$ MPa，弹性模量$E = 2.07\times105$ MPa，门槛应力强度因子幅度$\Delta K_{th} = 5.5\ \text{MPa}\cdot\text{m}^{1/2}$，断裂韧性$K_c = 104\ \text{MPa}\cdot\text{m}^{1/2}$，疲劳裂纹扩展速率为$da/dN = 6.9\times10^{-12}(\Delta K)^3$ m/r。试估算此裂纹板的寿命。

➢ 提示：对于边裂纹，$K_I = \alpha\sigma\sqrt{\pi a}$，几何修正因子$\alpha = 1.12$

习题1解 $a_0 = 0.5\text{mm}$时，

$$a_c = \frac{1}{\pi}\left(\frac{K_c}{\sigma_{\max}}\right)^2 = 114.6\text{mm}$$

$$N_c = \int_0^{N_c} \mathrm{d}N = \int_{a_0}^{a_c} \frac{\mathrm{d}a}{c\left(\Delta K_I\right)^n} = \int_{a_0}^{a_c} \frac{\mathrm{d}a}{2\times10^{-12}\left(\Delta K_I\right)^3}$$

$$= \frac{\mathrm{d}a}{2\times10^{-12}\pi^{\frac{3}{2}}\left(\Delta\sigma\right)^3}\int_{a_0}^{a_c}\frac{\mathrm{d}a}{a^{\frac{3}{2}}}$$

$$= \frac{1}{\left(1-\frac{3}{2}\right)2\times10^{-12}\pi^{\frac{3}{2}}\left(\Delta\sigma\right)^3}\left[a_c^{1-\frac{3}{2}} - a_0^{1-\frac{3}{2}}\right]$$

$= 937600$(次)

习题2解：

$$a_c = \frac{1}{\pi}\left(\frac{K_c}{\alpha\sigma_{\max}}\right)^2 = 68.6\text{mm}$$

$$N_c = \int_0^{N_c} \mathrm{d}N = \int_{a_0}^{a_c} \frac{\mathrm{d}a}{c\left(\Delta K_I\right)^n} = \int_{a_0}^{a_c} \frac{\mathrm{d}a}{2\times10^{-12}\left(\Delta K_I\right)^3}$$

$$= \frac{\mathrm{d}a}{2\times10^{-12}\pi^{\frac{3}{2}}\left(\alpha\Delta\sigma\right)^3}\int_{a_0}^{a_c}\frac{\mathrm{d}a}{a^{\frac{3}{2}}}$$

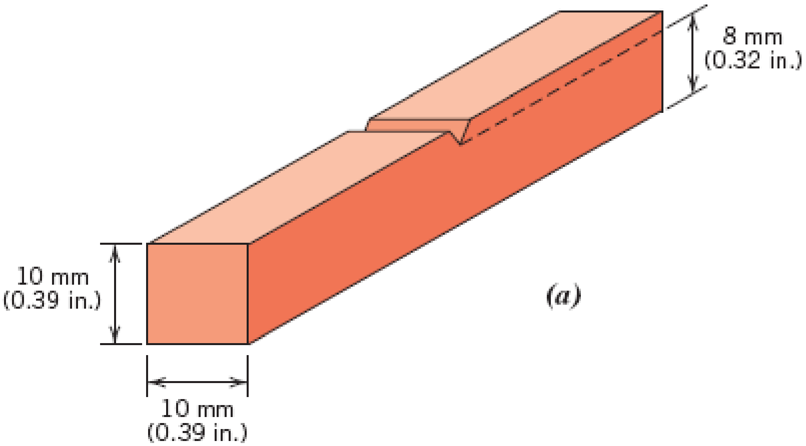
$$= \frac{1}{\left(1-\frac{3}{2}\right)2\times10^{-12}\pi^{\frac{3}{2}}\left(\alpha\Delta\sigma\right)^3}\left[a_c^{1-\frac{3}{2}} - a_0^{1-\frac{3}{2}}\right]$$

$$= 189579(\text{次})$$

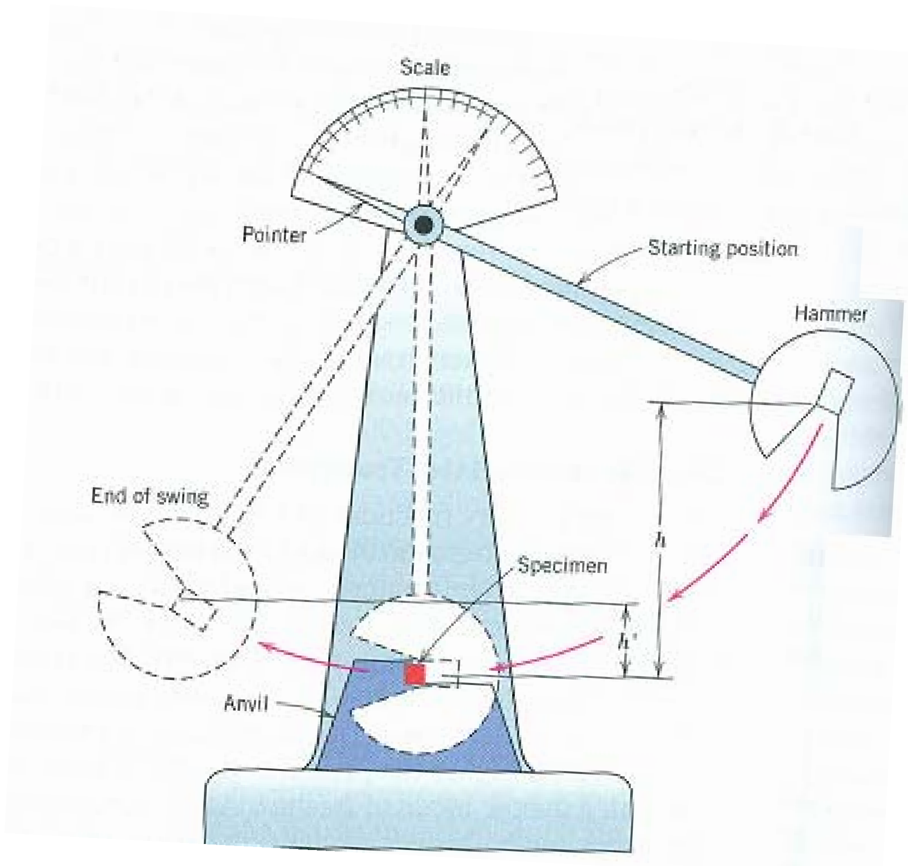
Structural metallic materials

5.5 Fracture Toughness TESTING

Impact testing techniques



(a)



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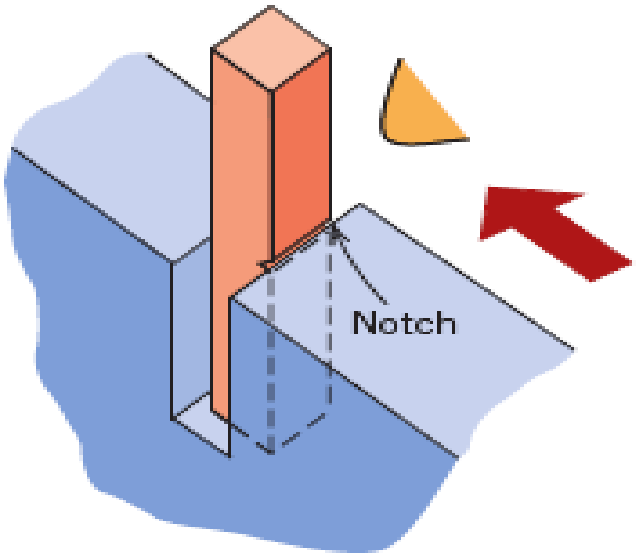
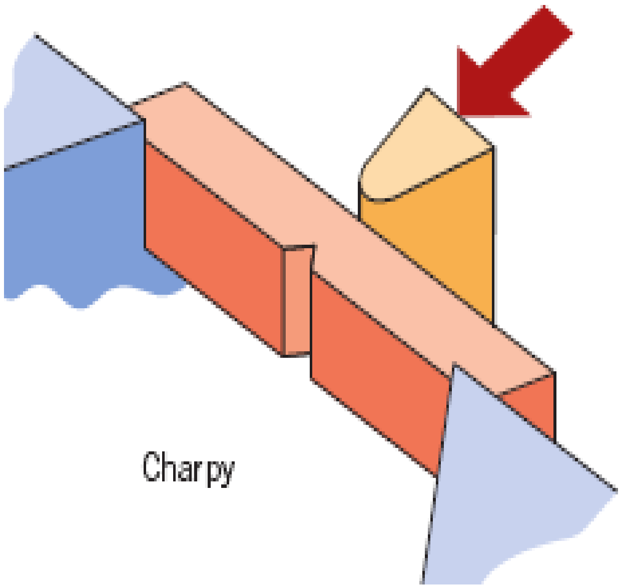
Structural metallic materials

5.5 Fracture Toughness TESTING

Impact testing techniques



Izod



Charpy

The charppy and Izod: the two standardized tests were designed to measure the impact energy.

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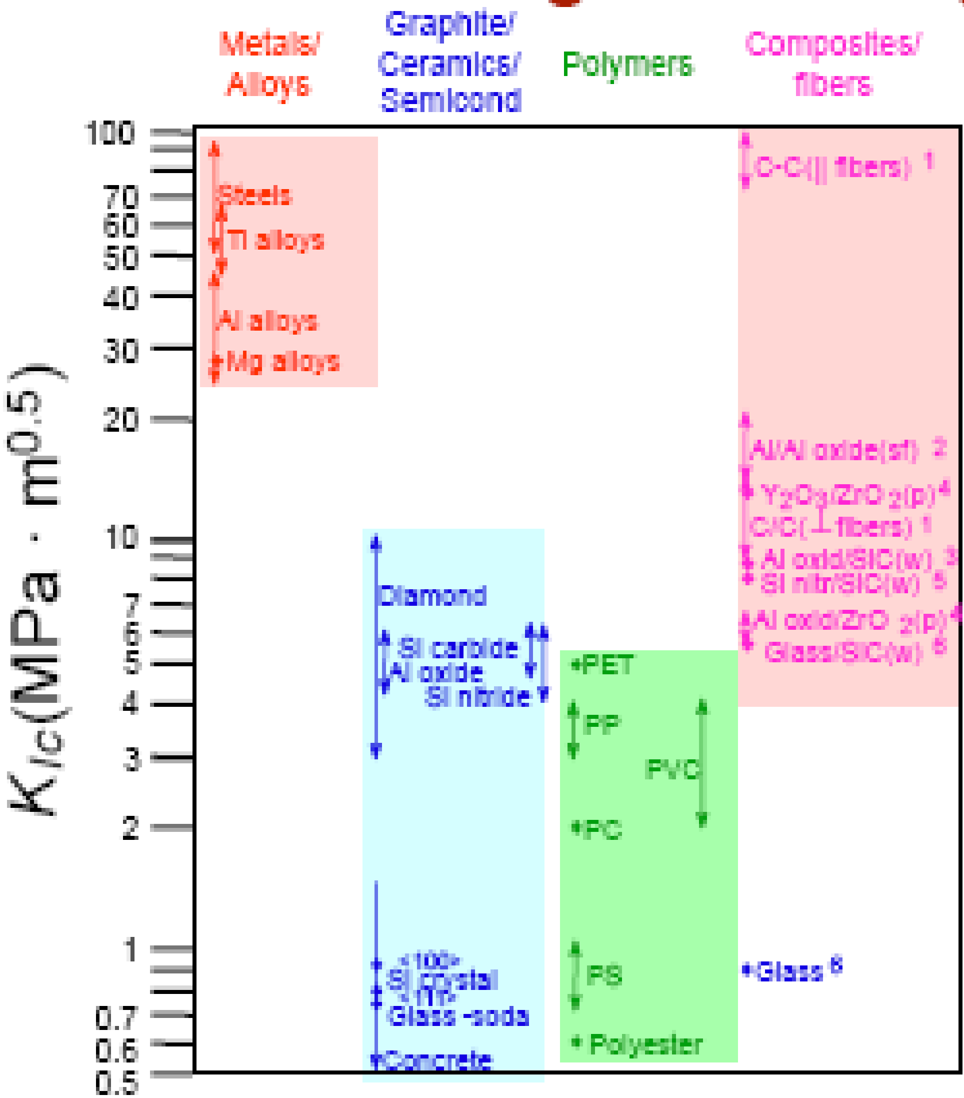
Fracture Toughness Ranges



Based on data in Table B.5, *Callister & Rethwisch 8e.*

Composite reinforcement geometry is: f = fibers; sf = short fibers; w = whiskers; p = particles. Addition data as noted (vol. fraction of reinforcement):

1. (55vol%) *ASM Handbook*, Vol. 21, ASM Int., Materials Park, OH (2001) p. 606.
2. (55 vol%) Courtesy J. Cornie, MMC, Inc., Waltham, MA.
3. (30 vol%) P.F. Becher et al., *Fracture Mechanics of Ceramics*, Vol. 7, Plenum Press (1986). pp. 61-73.
4. Courtesy CoorsTek, Golden, CO.
5. (30 vol%) S.T. Buljan et al., "Development of Ceramic Matrix Composites for Application in Technology for Advanced Engines Program", ORNL/Sub/85-22011/2, ORNL, 1992.
6. (20vol%) F.D. Gace et al., *Ceram. Eng. Sci. Proc.*, Vol. 7 (1986) pp. 978-82.

Structural metallic materials

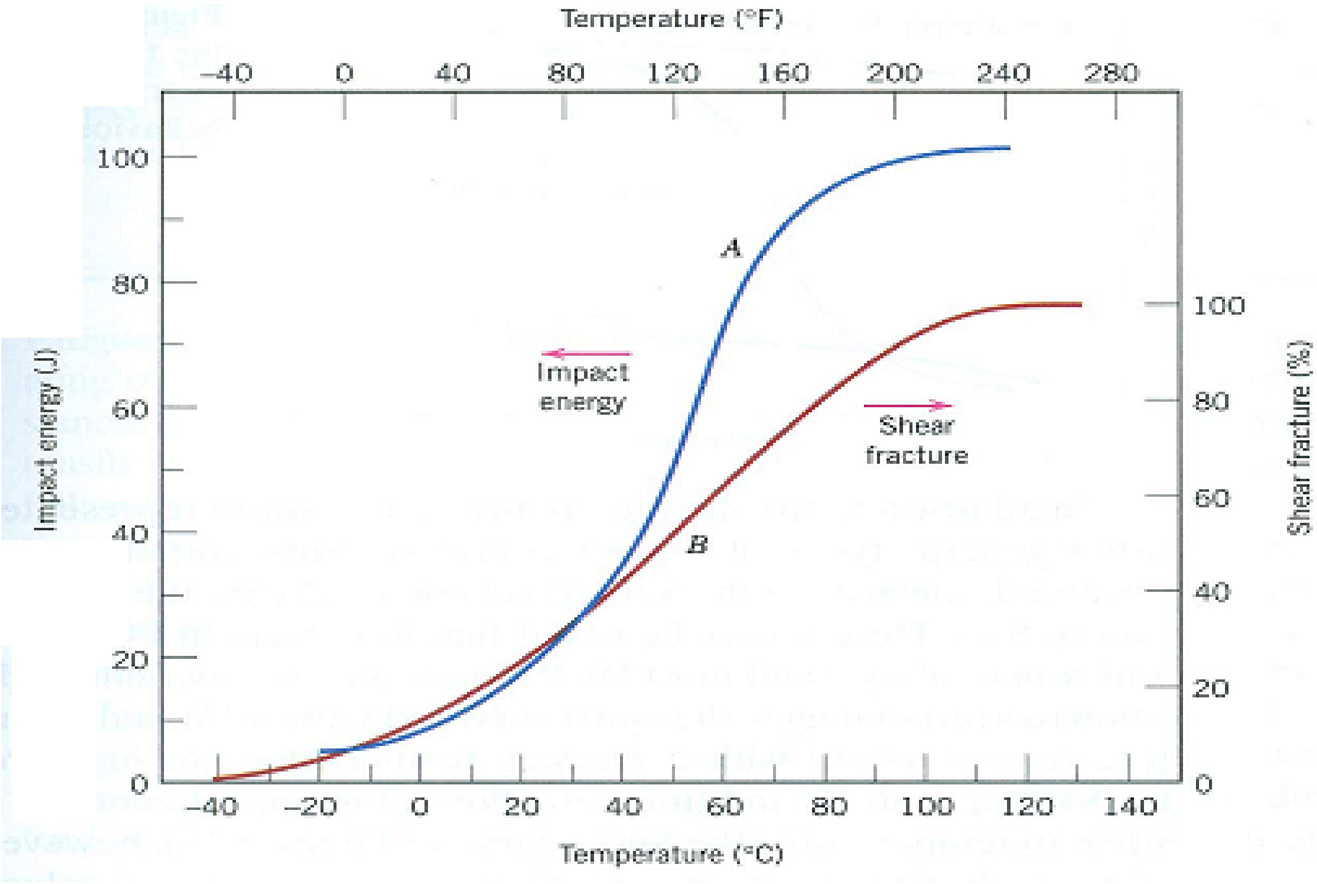
5.5 Fracture Toughness TESTING

Impact energy: A measure of the energy absorbed during the fracture of a specimen of standard dimensions and geometry when subjected to very rapid (impact) loading, which is important in assessing the ductile-to-brittle transition behavior of a material

ductile-to-brittle transition : the transition from ductile to brittle behavior with a decrease in temperature exhibited by some low-strength steel alloys; the temperature range over which the transition occurs is determined by Charpy and Izod impact tests

Structural metallic materials

5.5 Fracture Toughness TESTING



Temperature dependence of the Charpy V-notch impact energy (curve A) and percent shear fracture (curve B)

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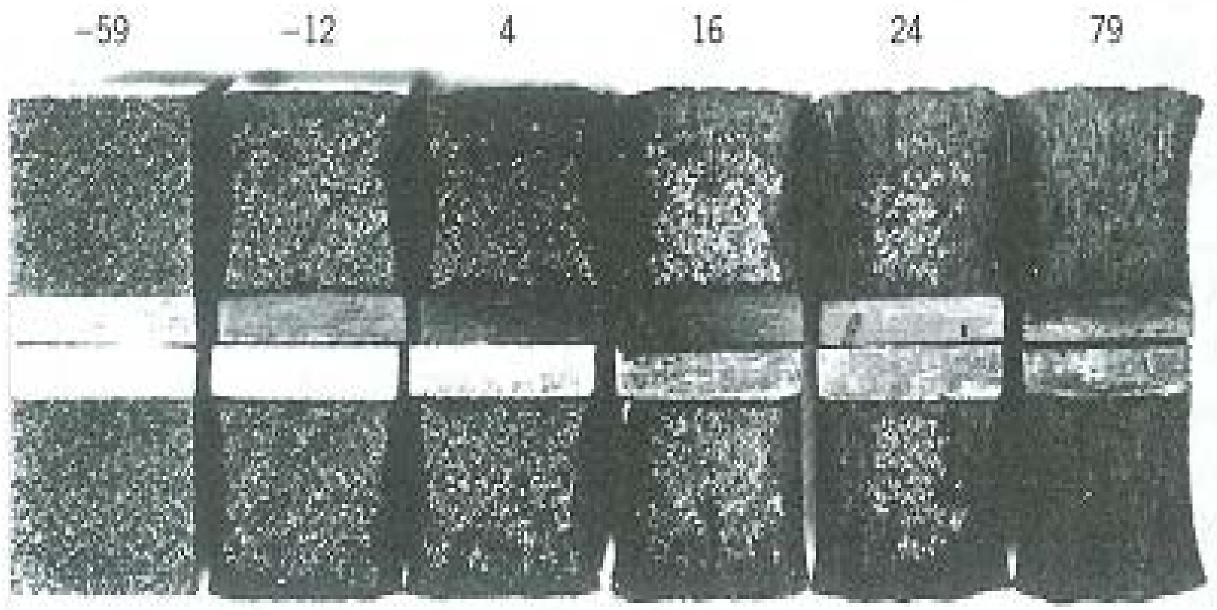
5.5 Fracture Toughness TESTING



Photograph of fracture surfaces of A36 steel Charpy V-notch specimens tested at indicated temperatures(℃)

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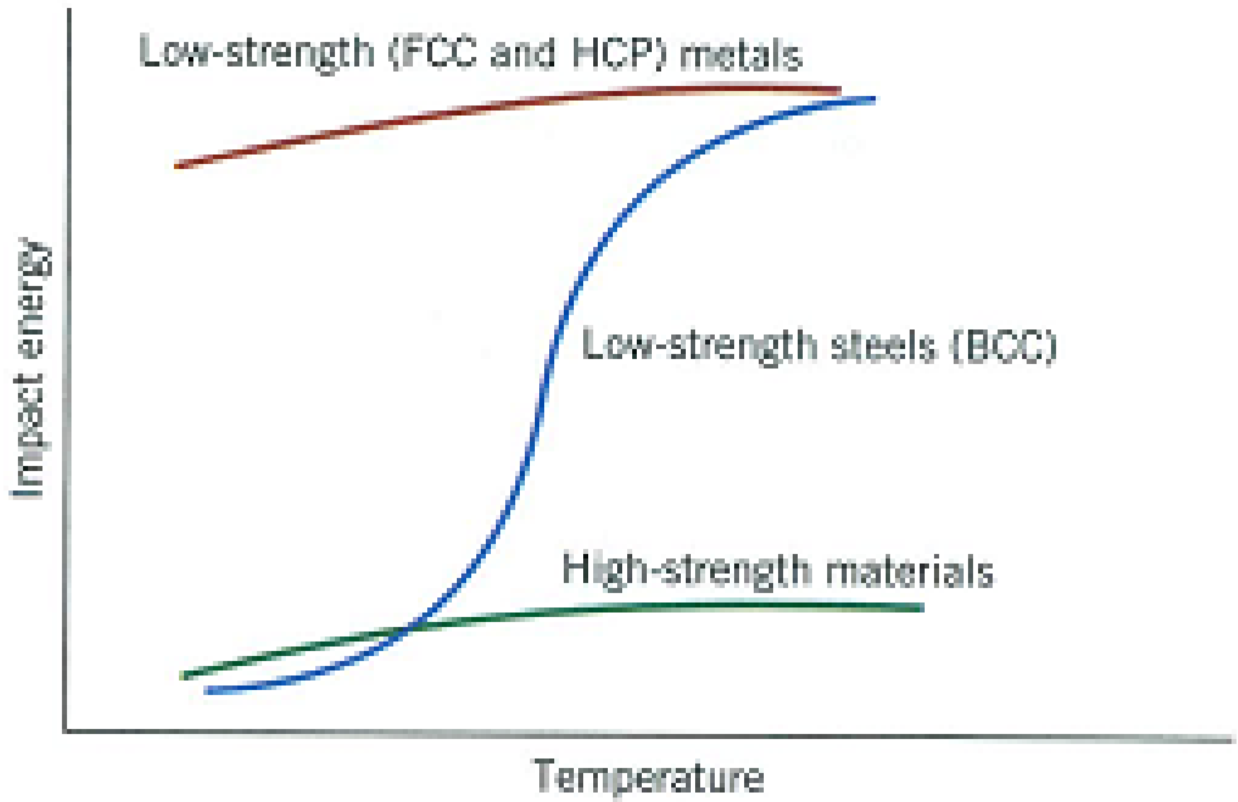
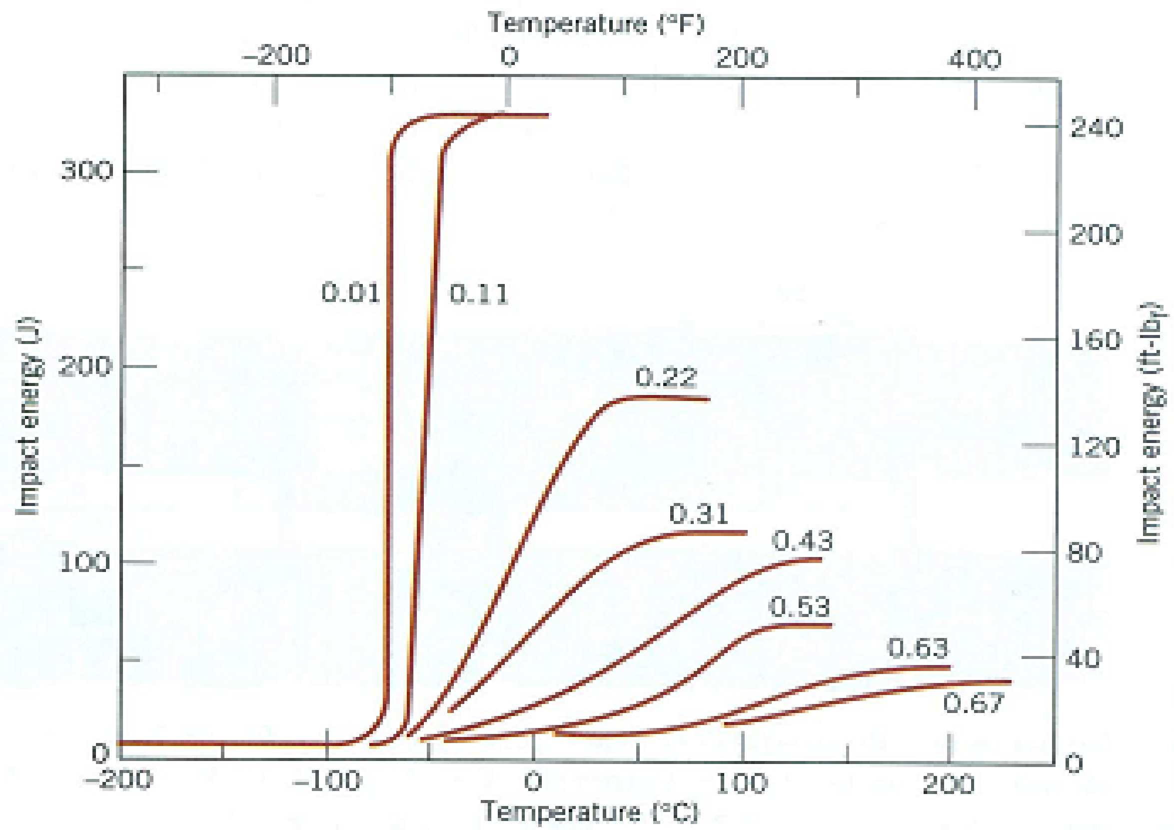
5.5 Fracture Toughness TESTING



Schematic curves for the three general types of impact energy-versus-temperature behavior

Structural metallic materials

5.5 Fracture Toughness TESTING



Influence of carbon content on the Charpy V-notch energy-versus-temperature behavior for steel

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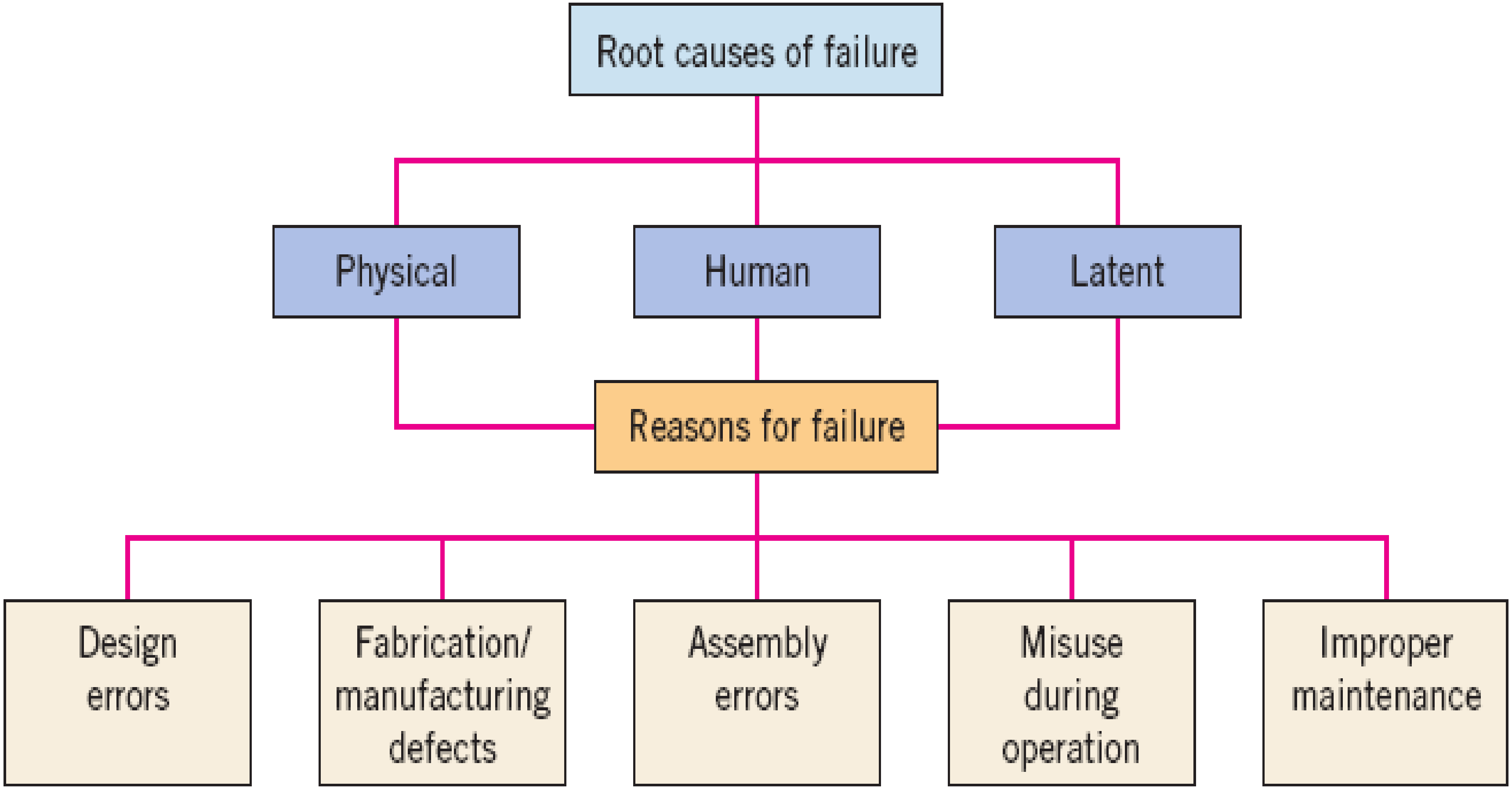
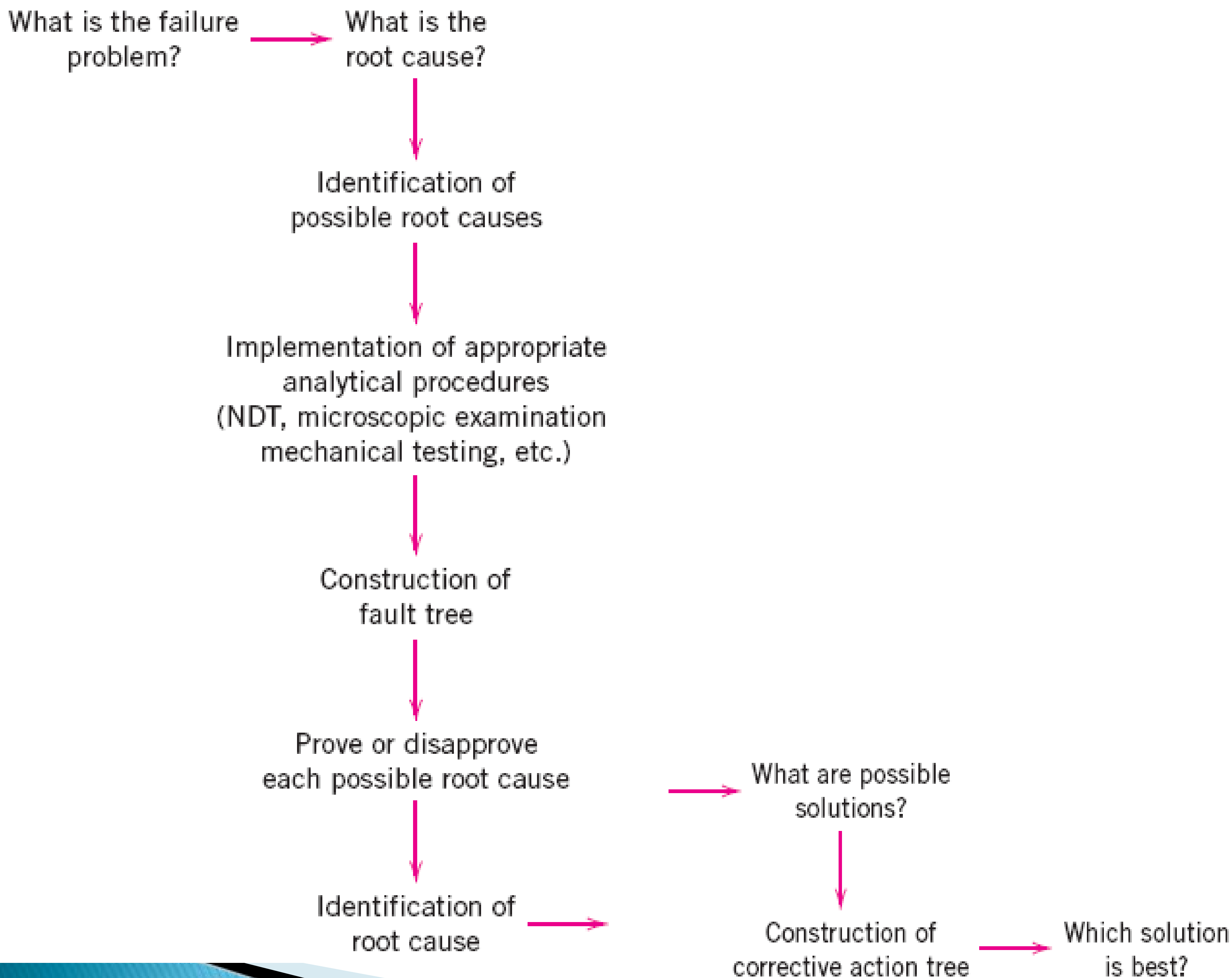
Investigation of Engineering Failures



The Failure Analysis

1. **What exactly is the failure problem?**
2. **What is the root cause of the failure problem?**
3. **What are possible solutions?**
4. **Which of these is the best solution?**


What is the failure problem?
What is the root cause?
Identification of possible root causes
Implementation of appropriate analytical procedures (NDT, microscopic examination mechanical testing, etc.)
Construction of fault tree
Prove or disapprove each possible root cause
Identification of root cause
What are possible solutions?
Construction of corrective action tree
Which solution is best?