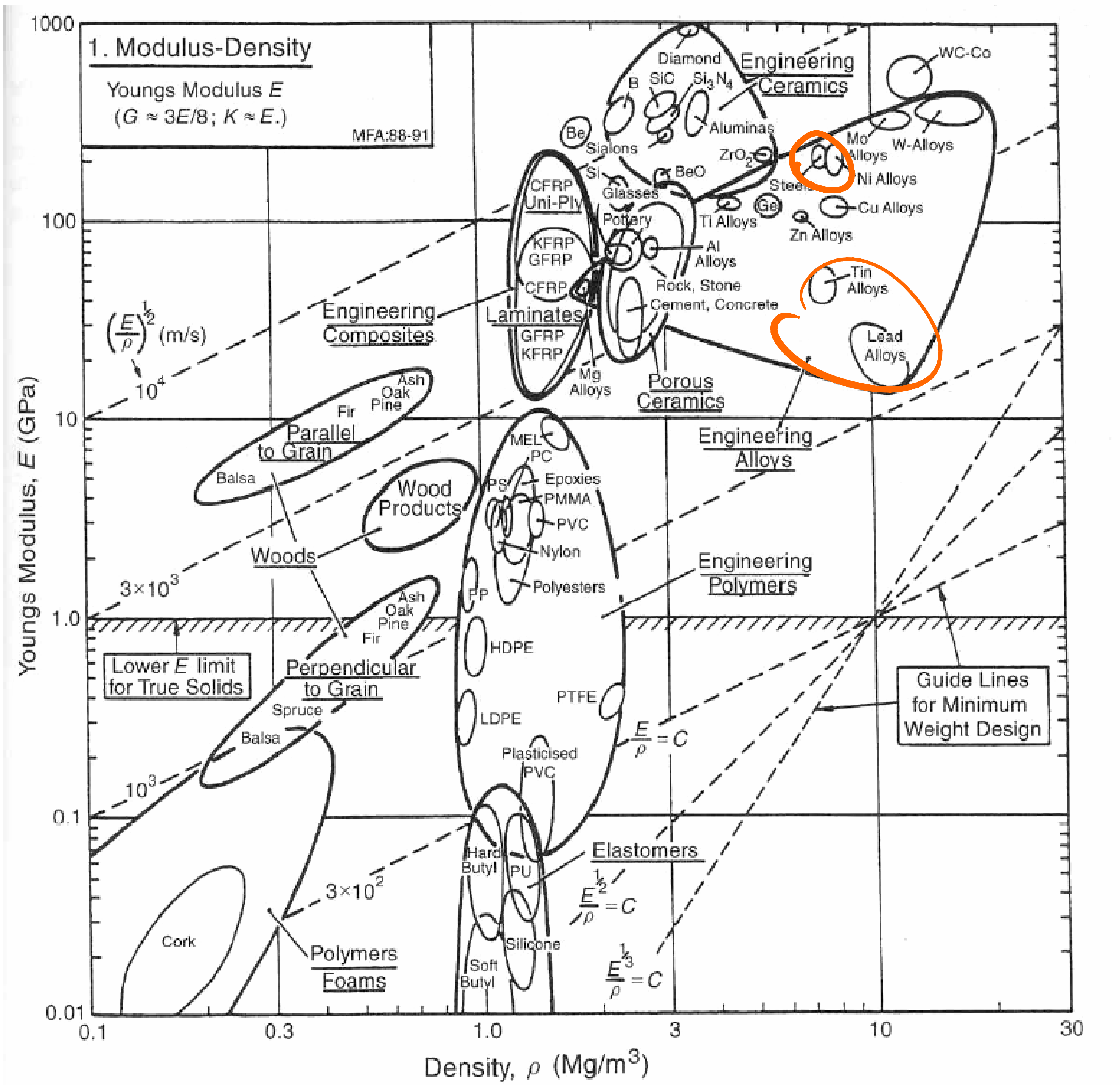
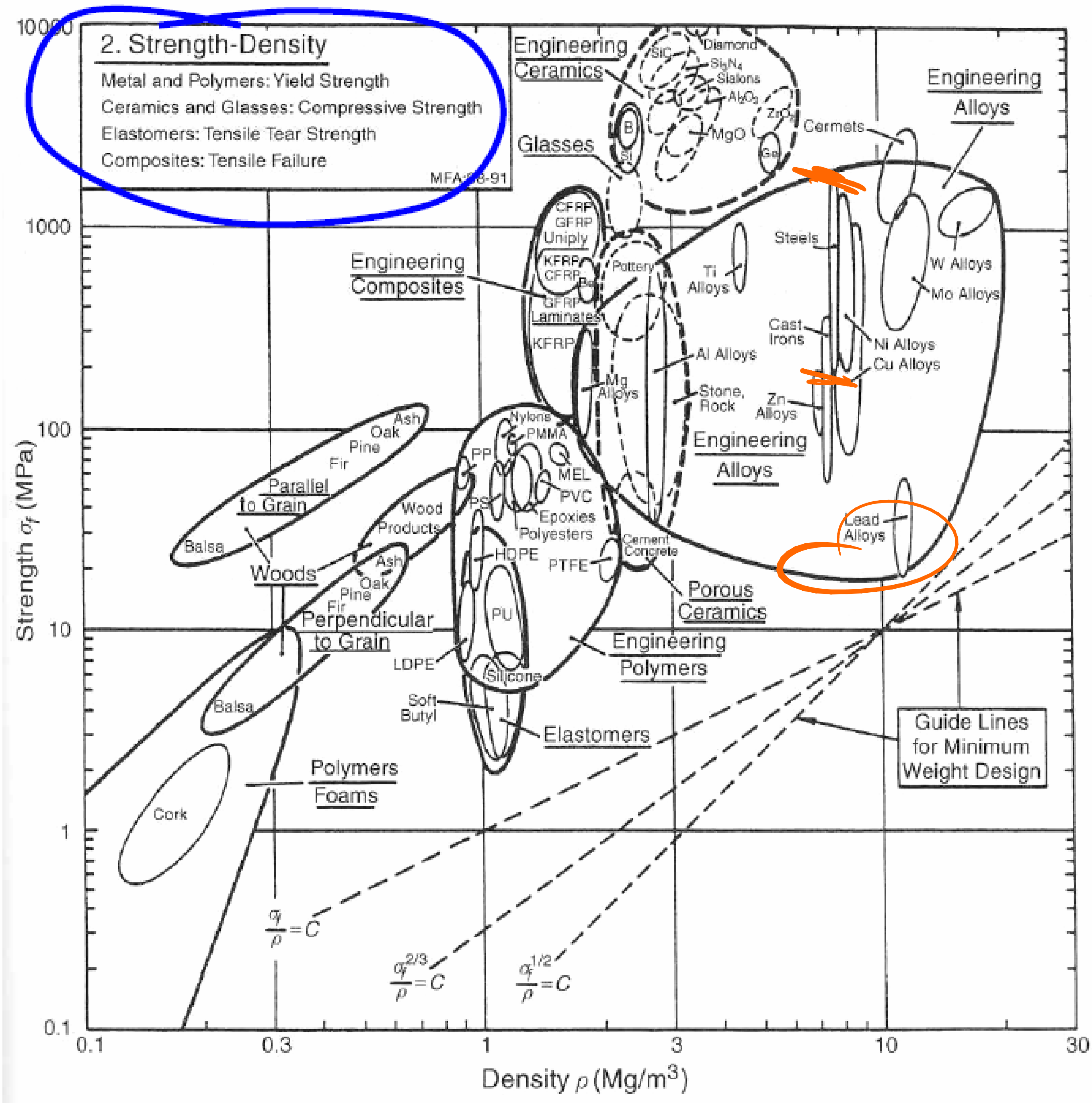
REVIEW

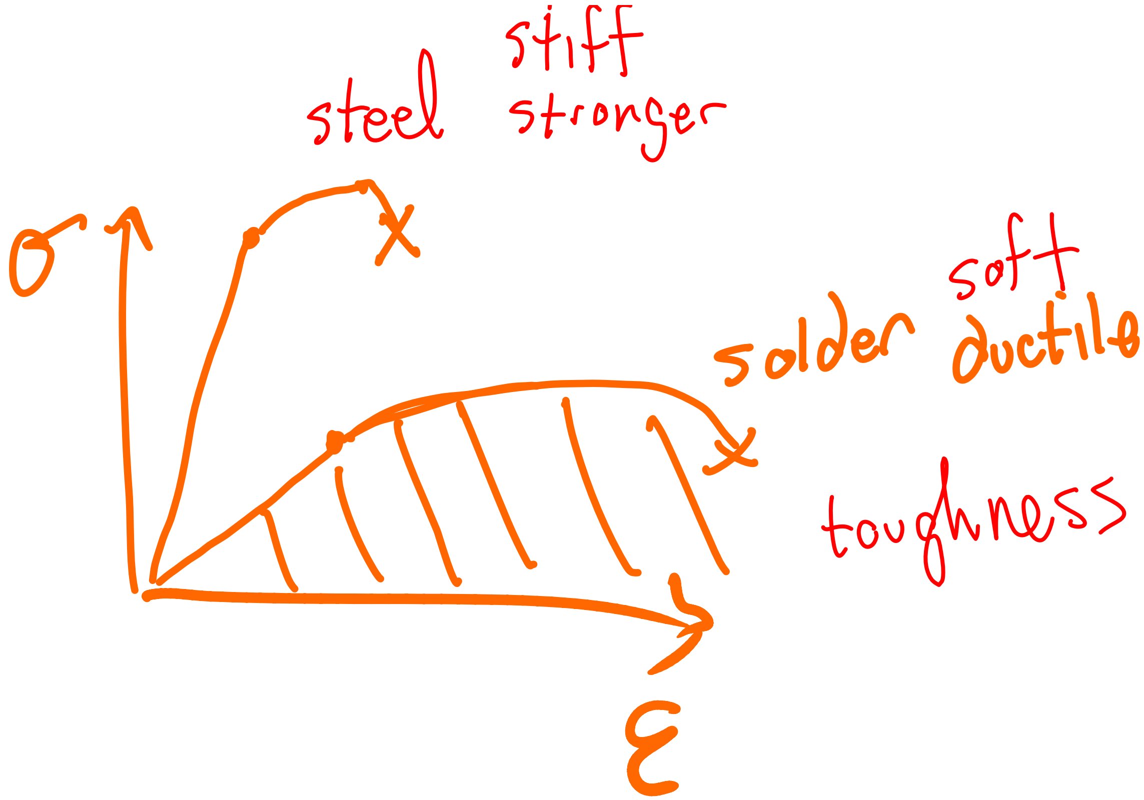
- **A solder joint provides an electrical connection for integrated circuits. However, it is also a component that supports a varying mechanical load. Why are we successful in using solder for microelectronics applications, such as a ball-grid array (BGA), when the soft solder often experiences stresses past its yield point?**



1. Modulus-Density
Youngs Modulus E
(G ≈ 3E/8; K ≈ E.)
MFA:88-91
Youngs Modulus, E (GPa)
Density, ρ (Mg/m3)
Engineering Ceramics
Diamond
B
SiC
Si3N4
Be
Sialons
Aluminas
ZrO2
BeO
Si
Glasses
Pottery
Ge
Steels
WC-Co
Mo Alloys
W-Alloys
Ni Alloys
Cu Alloys
Ti Alloys
Zn Alloys
Al Alloys
Tin Alloys
Lead Alloys
Rock, Stone
Cement, Concrete
Porous Ceramics
Engineering Alloys
CFRP
Uni-Ply
KFRP
GFRP
Laminates
Mg Alloys
Engineering Composites
Ash
Oak
Pine
Fir
Parallel to Grain
Balsa
Wood Products
Woods
Perpendicular to Grain
Spruce
Lower E limit for True Solids
MEL
PC
PS
Epoxies
PMMA
PVC
Nylon
Polyesters
PP
HDPE
PTFE
LDPE
Plasticised PVC
Engineering Polymers
Hard Butyl
PU
Silicone
Soft Butyl
Elastomers
Cork
Polymers Foams
Guide Lines for Minimum Weight Design
E/ρ = C
E^1/2/ρ = C
E^1/3/ρ = C
(E/ρ)^1/2 (m/s)
10^4
3×10^3
10^3
3×10^2

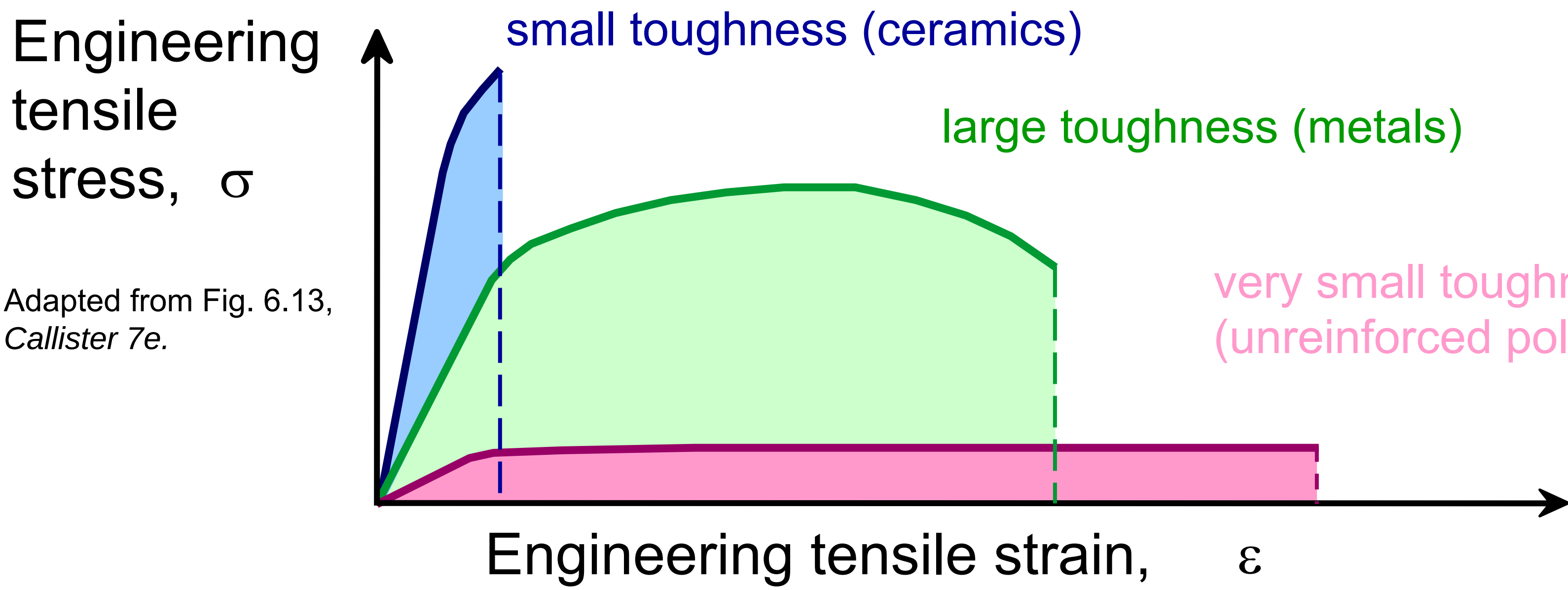


2. Strength-Density
Metal and Polymers: Yield Strength
Ceramics and Glasses: Compressive Strength
Elastomers: Tensile Tear Strength
Composites: Tensile Failure
MFA:88-91
Engineering Ceramics
Diamond
SiC
Glasses
Cermets
Engineering Alloys
Engineering Composites
Steels
Ti Alloys
W Alloys
Mo Alloys
Cast Irons
Ni Alloys
Cu Alloys
Al Alloys
Mg Alloys
Stone, Rock
Zn Alloys
Pottery
Lead Alloys
Woods
Parallel to Grain
Perpendicular to Grain
Balsa
Cork
Polymers Foams
Engineering Polymers
Elastomers
Porous Ceramics
Cement Concrete
Nylons
PMMA
PP
MEL
PVC
PS
Epoxies
Polyesters
HDPE
PTFE
PU
LDPE
Silicone
Soft Butyl
Guide Lines for Minimum Weight Design
Strength σ_f (MPa)
Density ρ (Mg/m^3)


stiff
steel
stronger
σ
solder
soft
ductile
toughness
ε

Toughness

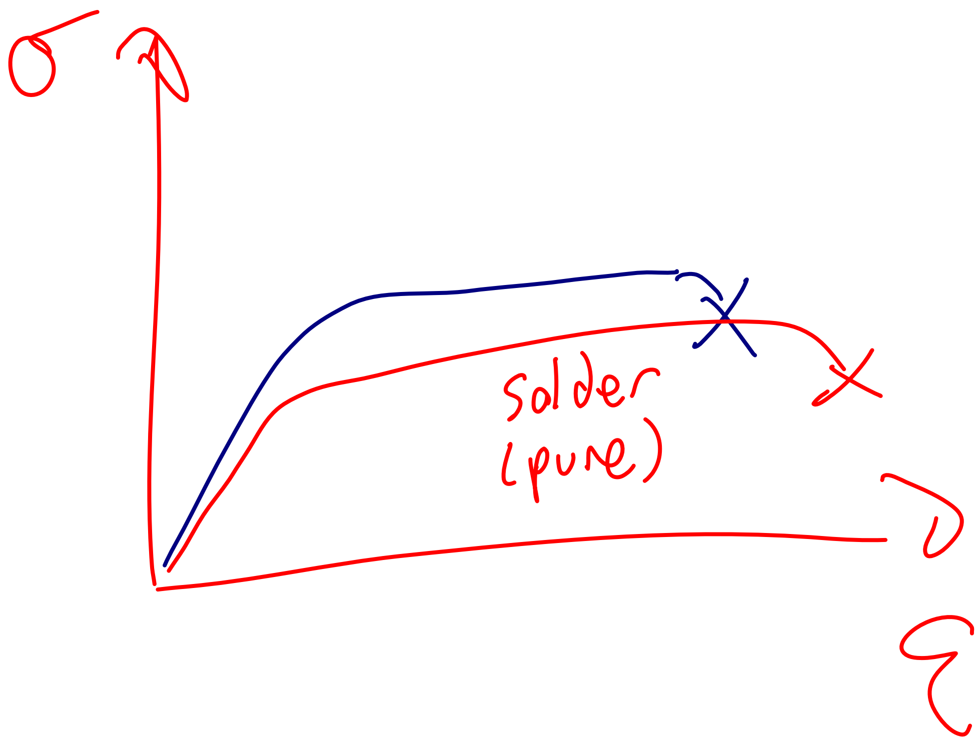
- Energy to break a unit volume of material
- Approximate by the area under the stress-strain curve.

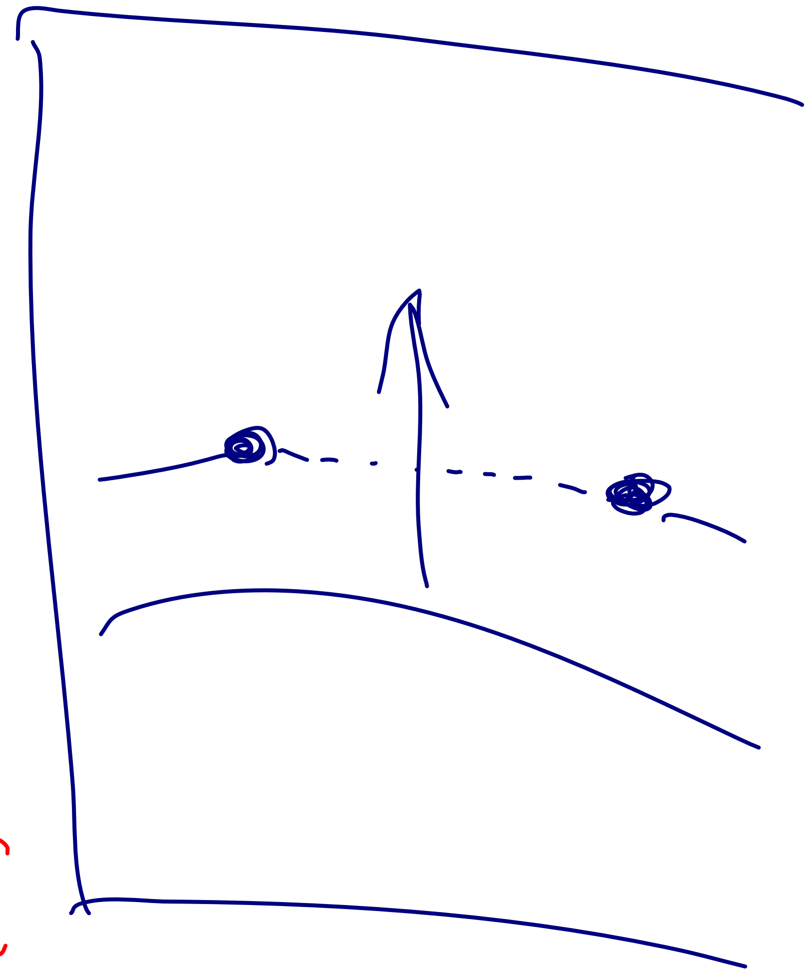


Adapted from Fig. 6.13, *Callister 7e.*

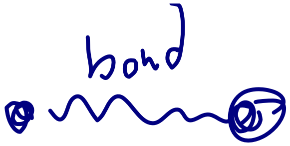
Brittle fracture: elastic energy
Ductile fracture: elastic + plastic energy

2) hard particles





3) opinion



Chapters 6 & 7

- **Stress vs. strain curves**
- **Elastic vs. plastic behavior**
- **Adjectives to describe mechanical behavior**
- **Strengthening mechanisms**
- **Materials**

Chapter 8

- **Failure!**
- **Engineers don’t like cracks.**
- **People don’t like it when engineers don’t design properly and things break!**

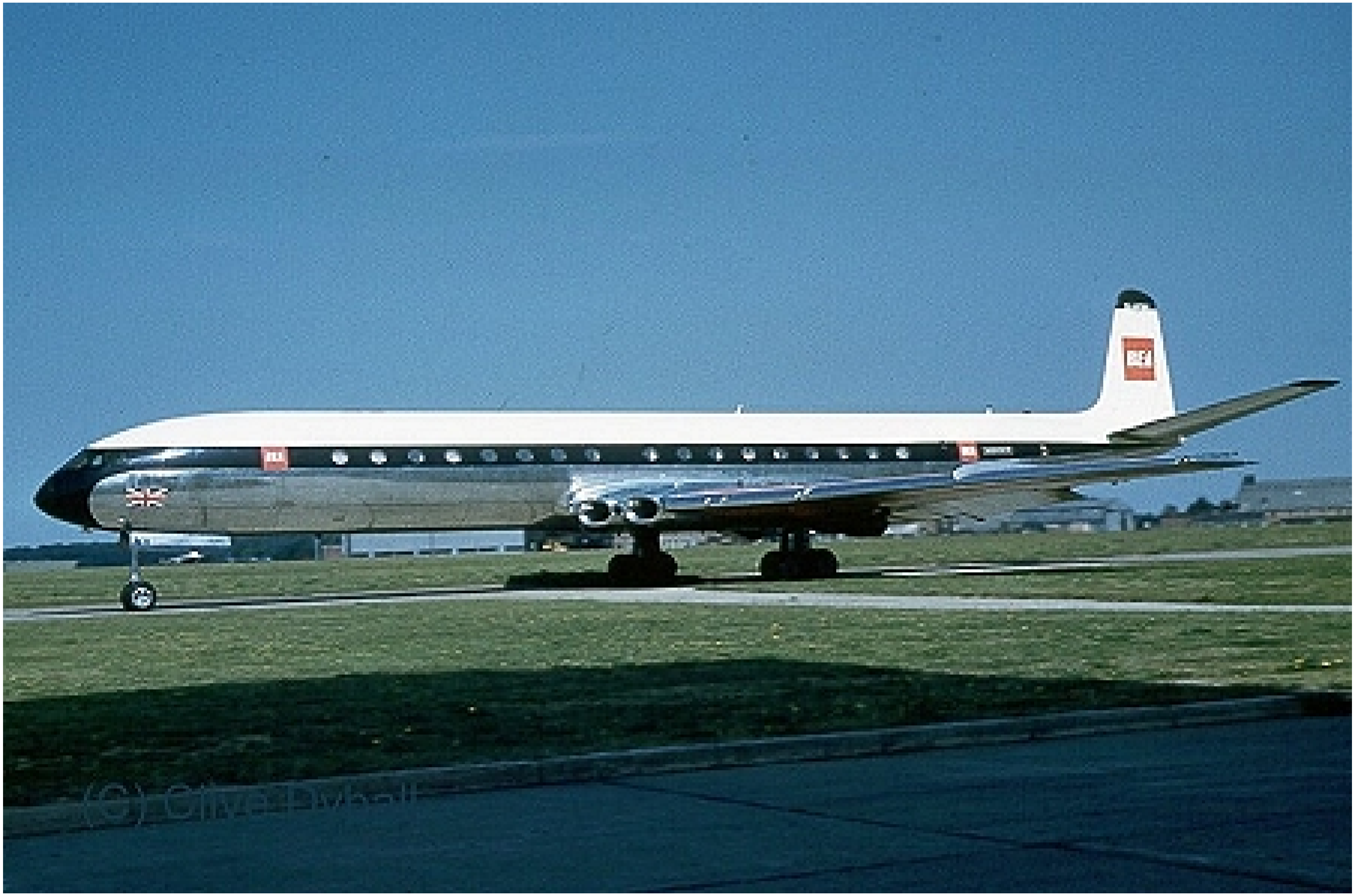
<u>G-ALYY / 6011 crash in Stromboli (Crew 7/7 & Passengers 14/14)</u>

YY G-ALYY was leased from B.O.A.C. to South African Airways. Flight SA201 was on its way from London to Johannesburg. After a fuel stop in Rome the plane took-off, but only 36 minutes later the radio-contact was interrupted in the area of Stromboli.

The next morning remains were found in the sea. Since the sea was at this place as deep as 1000 meters, no parts of the aircraft could be inspected. Only four days after the crash the Comet flights were again suspended, one of the reasons being the similarities to the YP crash. G-ALYY had only performed 2704 flighthours. A very intensive flight test program was performed in order to find out the reason of the YY and YP crashes, with no special conclusion.

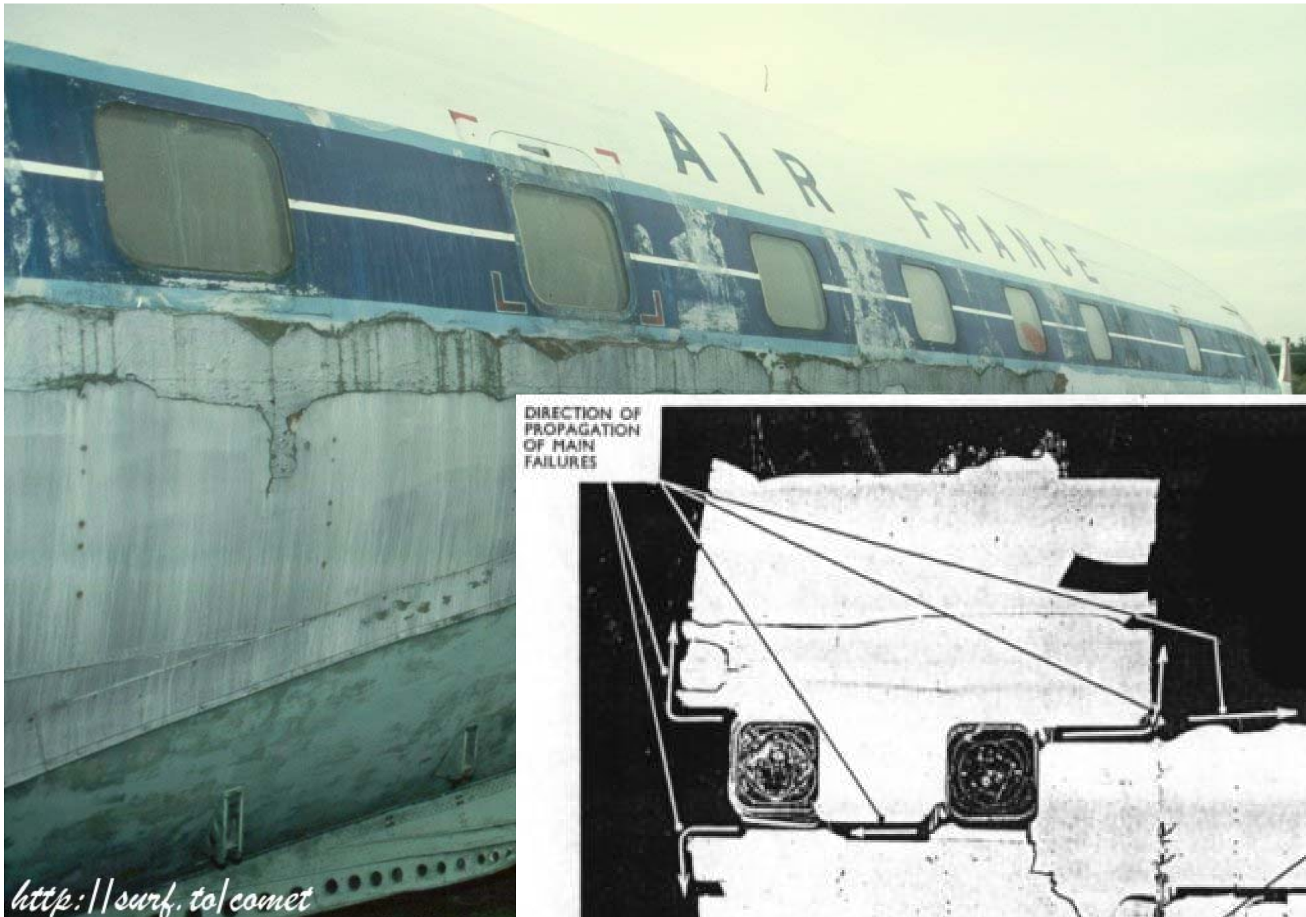
Only after a *very long expensive investigations*, which included the assembly of the remains of

Cause of the accident: design fault


© Clive Dyball


DE HAVILLAND COMET
B.O.A.C.
G-ALVG


http://surf.to/comet
Photo credit: Aeroplane Montly



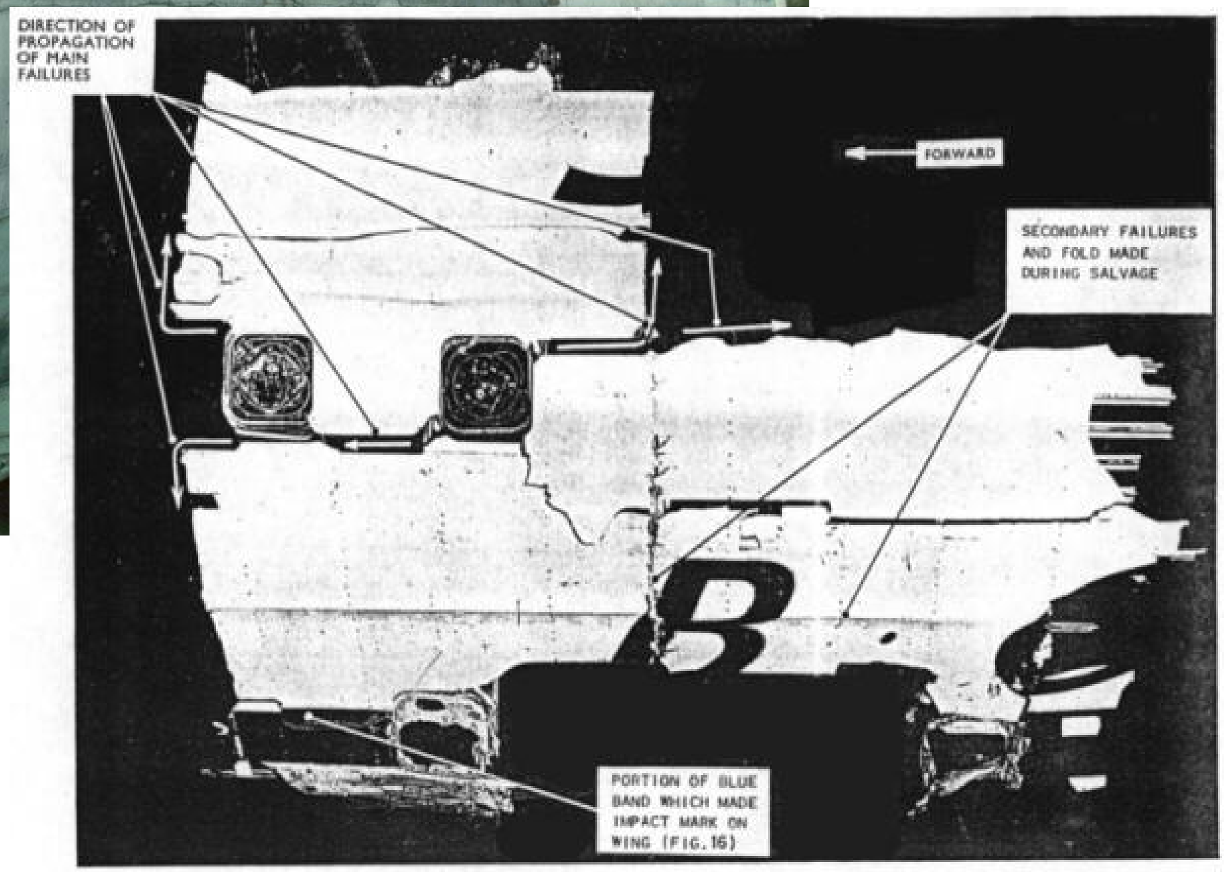


FIG. 12. PHOTOGRAPH OF WRECKAGE AROUND ADF AERIAL WINDOWS—G-ALYP.

<u>G-ALYY / 6011 crash in Stromboli (Crew 7/7 & Passengers 14/14)</u>

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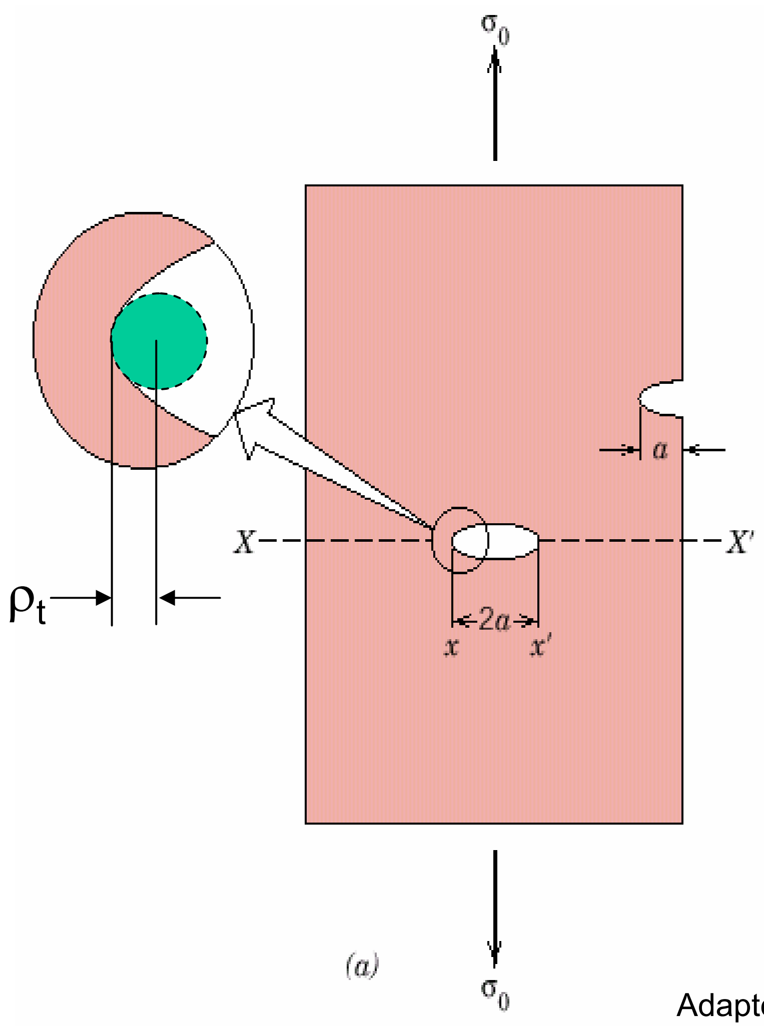
The next morning remains were found in the sea. Since the sea was at this place as deep as 1000 meters, no parts of the aircraft could be inspected. Only four days after the crash the Comet flights were again suspended, one of the reasons being the similarities to the YP crash. G-ALYY had only performed 2704 flighthours. A very intensive flight test program was performed in order to find out the reason of the YY and YP crashes, with no special conclusion.

Only after a *very long expensive investigations*, which included the assembly of the remains of the crashed YP and the underwater stress test of the YU Comet which came from B.O.A.C. Finally the fuselage of YU broke up on a sharp edge of the forward escape-hatch. After that this rupture was repaired the tests were restarted, but only shortly afterwards the fuselage broke up. *<u>This time the rupture started at the upper edge of a window and was three meters long.</u>*

The YP and YY crashes were due to metal fatigue, which took place because of the crystalline changes in the fuselage skin. They were amplified by the high speed and altitude the Comets were operated. The metal fatigue resulted in ruptures of the fuselage, this had as a consequence a terrible decompression at 33Kft, tearing up the plane with all known consequences.

Cause of the accident: design fault

Flaws are Stress Concentrators!



Results from crack propagation

- Griffith Crack

$$\sigma_m = 2\sigma_o \left(\frac{a}{\rho_t}\right)^{1/2} = K_t \sigma_o$$

where

ρ_t = radius of curvature

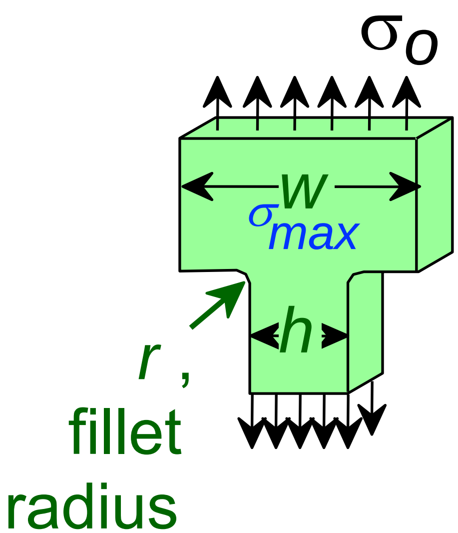
σ_o = applied stress

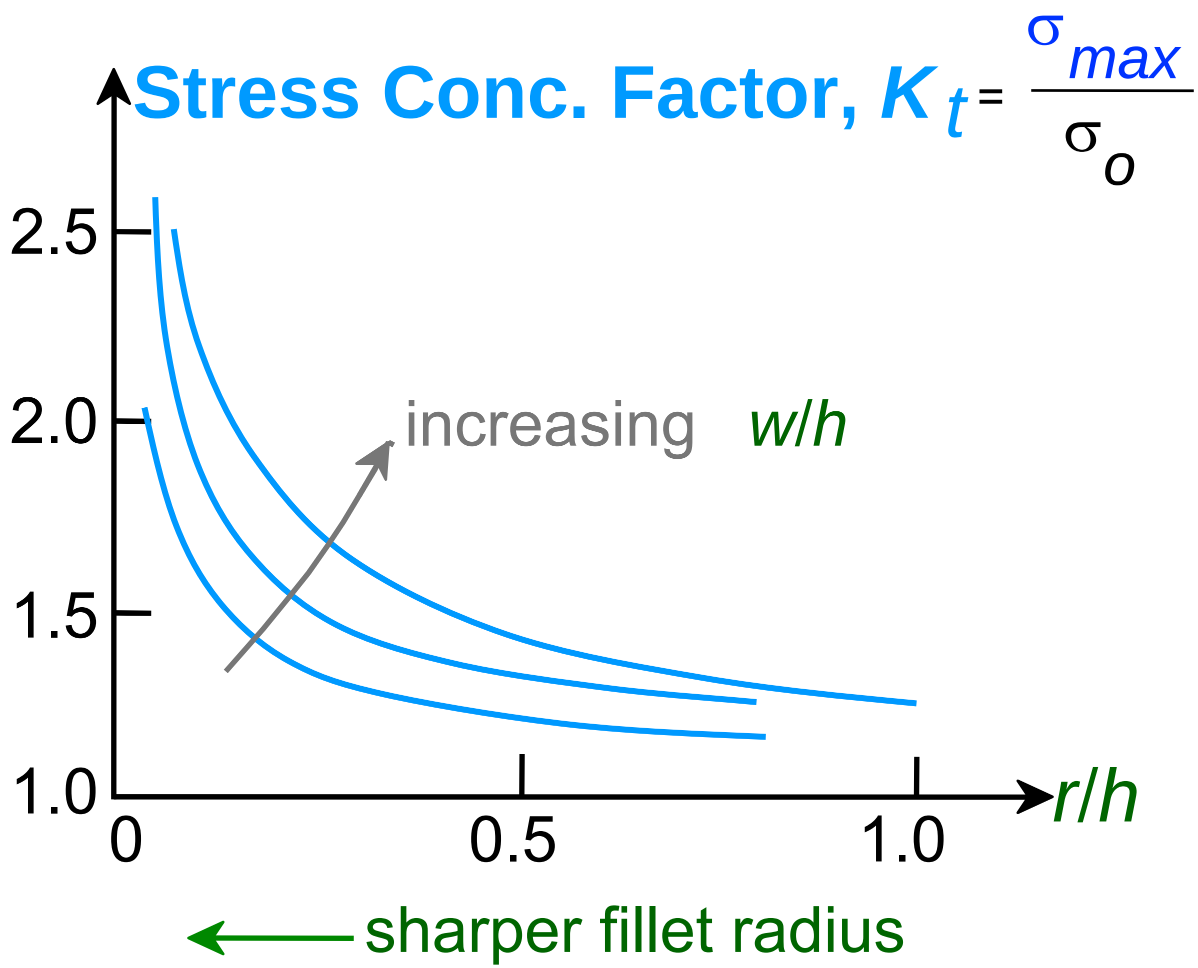
σ_m = stress at crack tip

Adapted from Fig. 8.8(a), *Callister 7e.*

Engineering Fracture Design

- **Avoid sharp corners!**



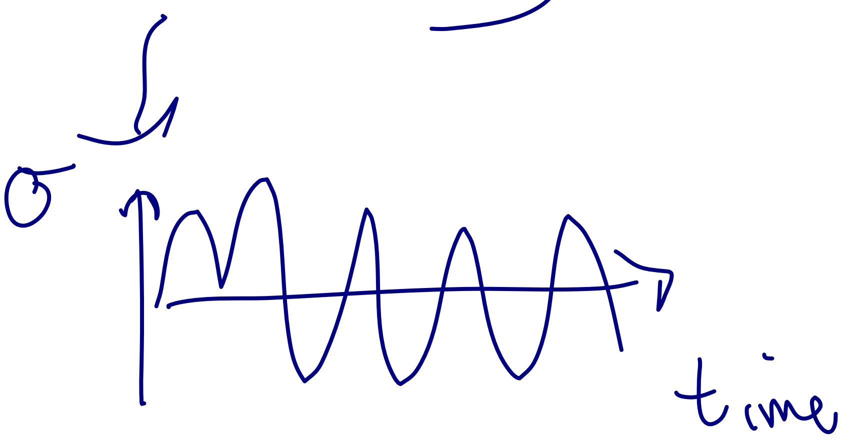


Adapted from Fig. 8.2W(c), *Callister 6e.* (Fig. 8.2W(c) is from G.H. Neugebauer, *Prod. Eng.* (NY), Vol. 14, pp. 82-87 1943.)

Fortunately…

- **Engineers design things well these days.**
- **Most things fail by two methods that result in slow accumulation of damage and eventual fracture**
  - **Creep** → constant stress
  - **Fatigue**

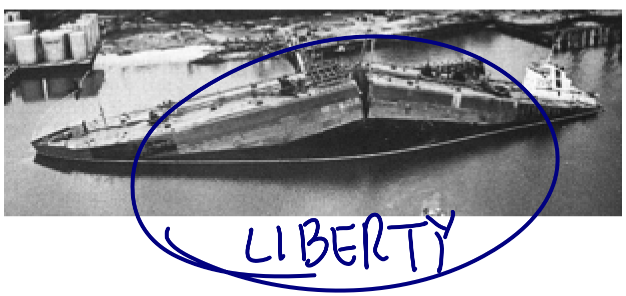
next



Chapter 8: Mechanical Failure

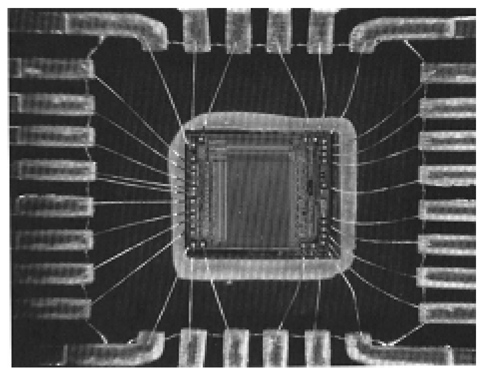
ISSUES TO ADDRESS...

- How do flaws in a material initiate failure?
- How is fracture resistance quantified; how do different material classes compare?
- How do we estimate the stress to fracture?
- How do loading rate, loading history, and temperature affect the failure stress?



Ship-cyclic loading from waves.

Adapted from chapter-opening photograph, Chapter 8, *Callister 7e.* (by Neil Boenzi, *The New York Times*.)



Computer chip-cyclic thermal loading.

Adapted from Fig. 22.30(b), *Callister 7e.* (Fig. 22.30(b) is courtesy of National Semiconductor Corporation.)

Hip implant-cyclic loading from walking.

Adapted from Fig. 22.26(b), *Callister 7e.*

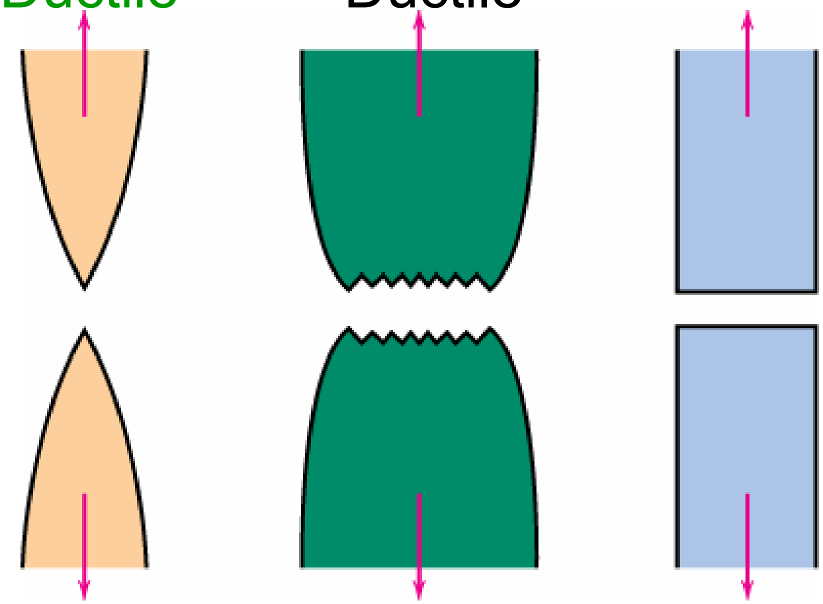
Fracture mechanisms

- Ductile fracture
  - Occurs with plastic deformation
- Brittle fracture
  - Little or no plastic deformation
  - Catastrophic

Ductile vs Brittle Failure

- Classification:

Fracture behavior:	Very Ductile	Moderately Ductile	Brittle
%*AR* or %*EL*	Large	Moderate	Small



Adapted from Fig. 8.1, *Callister 7e.*

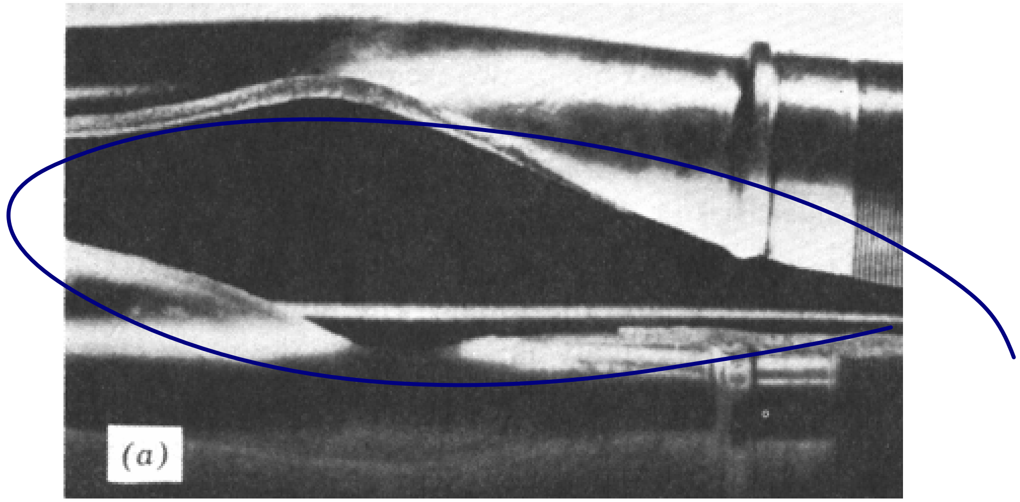
- Ductile fracture is usually desirable!

Ductile: warning before fracture

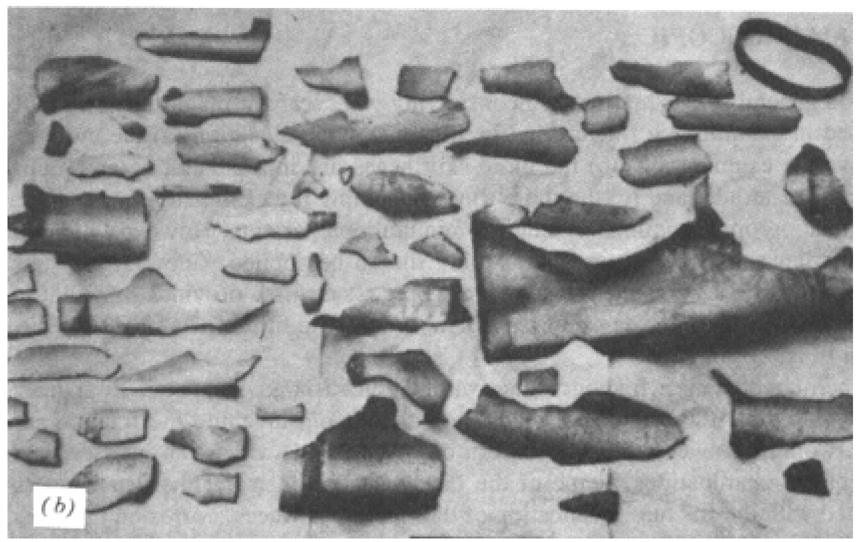
Brittle: No warning

Example: Failure of a Pipe

- **Ductile failure:**
  --one piece
  --large deformation



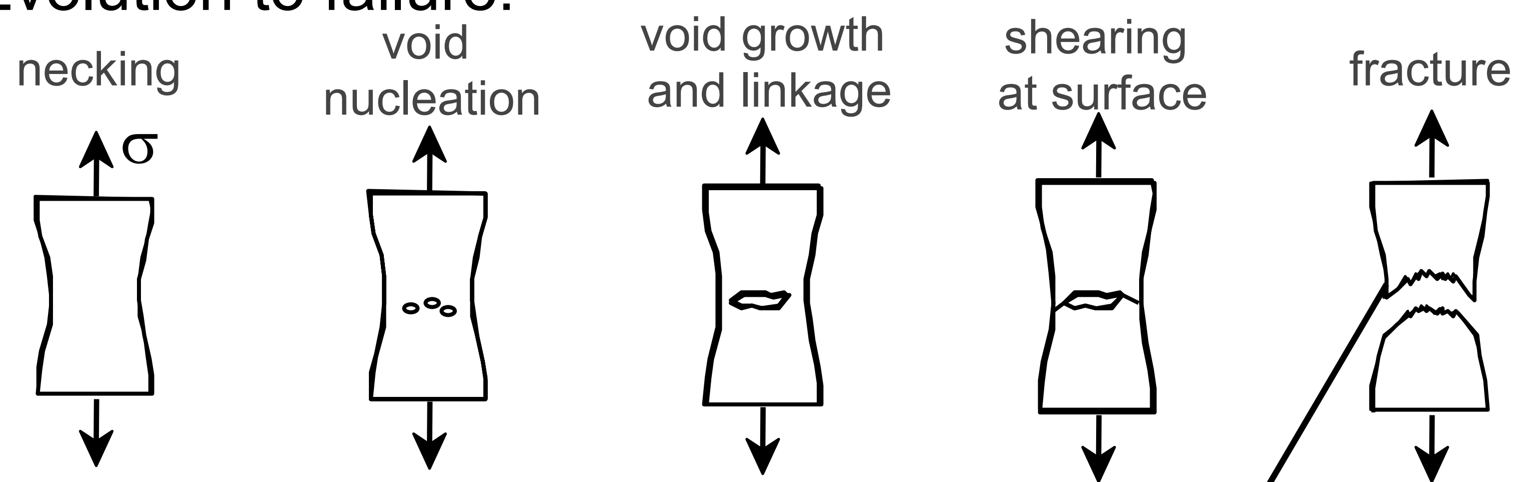
- **Brittle failure:**
  --many pieces
  --small deformation



Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

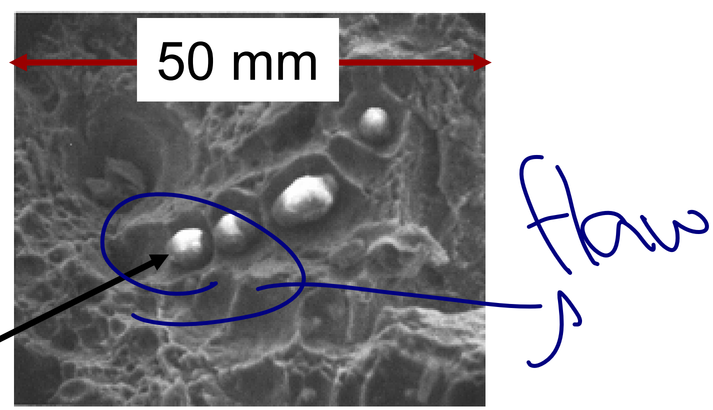
Moderately Ductile Failure

• Evolution to failure:

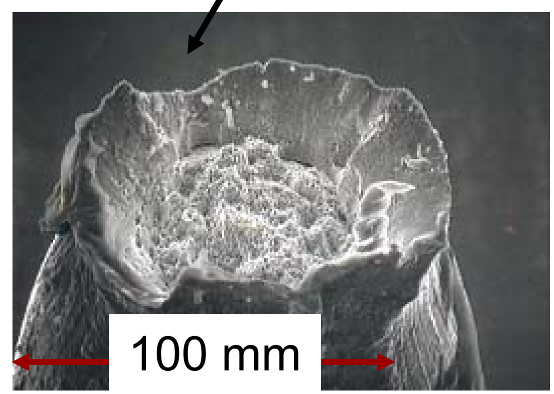


• Resulting fracture surfaces (steel)

particles serve as void nucleation sites.



From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 11.28, p. 294, John Wiley and Sons, Inc., 1987. (Orig. source: P. Thornton, *J. Mater. Sci.*, Vol. 6, 1971, pp. 347-56.)



Fracture surface of tire cord wire loaded in tension. Courtesy of F. Roehrig, CC Technologies, Dublin, OH. Used with permission.

Ductile vs. Brittle Failure

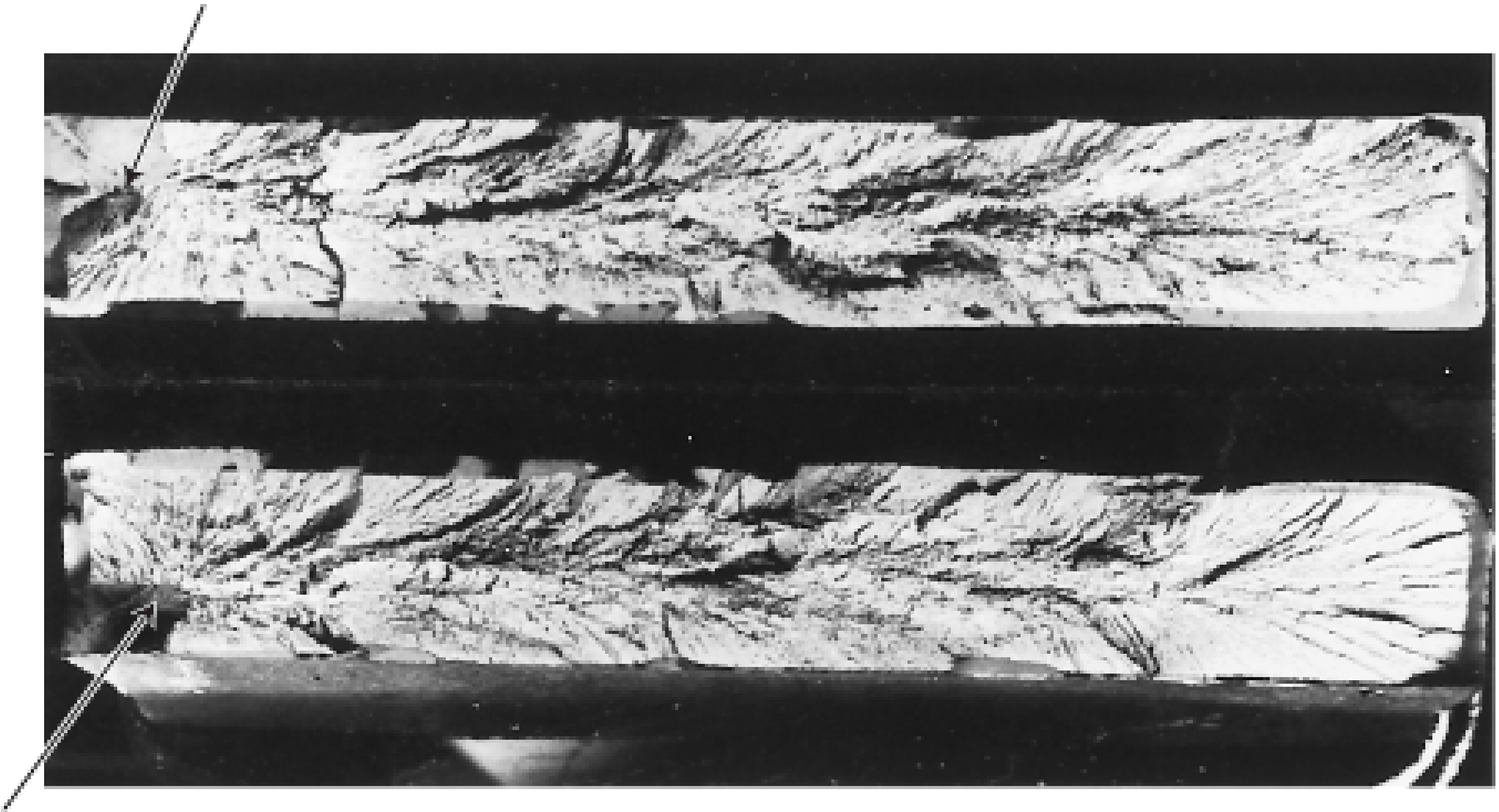
cup-and-cone fracture

brittle fracture

Adapted from Fig. 8.3, *Callister 7e.*

Brittle Failure

Arrows indicate pt at which failure originated

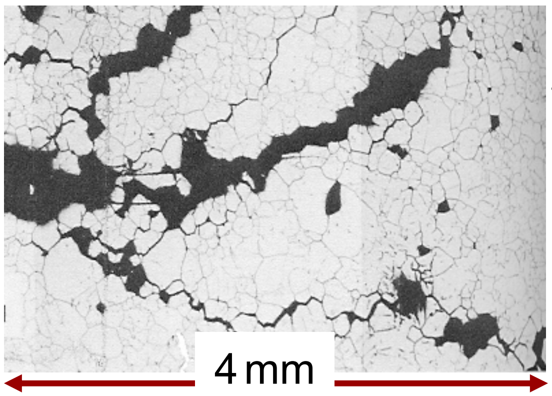


Adapted from Fig. 8.5(a), *Callister 7e.*

Brittle Fracture Surfaces

- Intergranular (between grains)

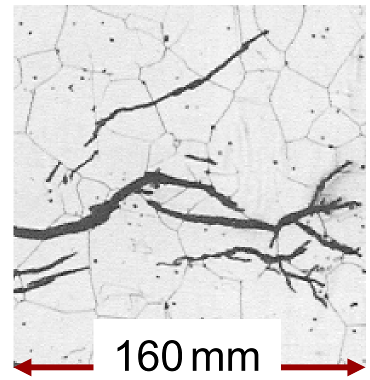
304 S. Steel (metal)



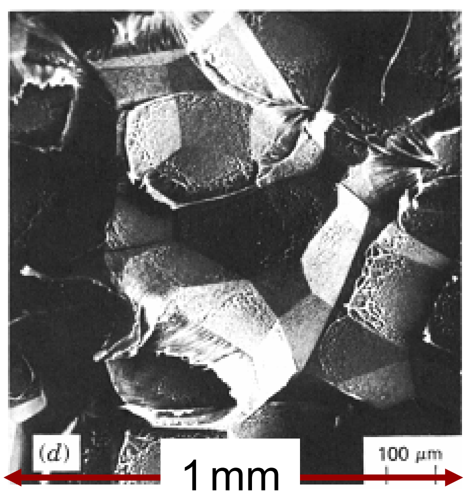
Reprinted w/permission from "Metals Handbook", 9th ed, Fig. 633, p. 650. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by J.R. Keiser and A.R. Olsen, Oak Ridge National Lab.)

- Intragranular (within grains)

316 S. Steel (metal)



Reprinted w/ permission from "Metals Handbook", 9th ed, Fig. 650, p. 357. Copyright 1985, ASM International, Materials Park, OH. (Micrograph by D.R. Diercks, Argonne National Lab.)



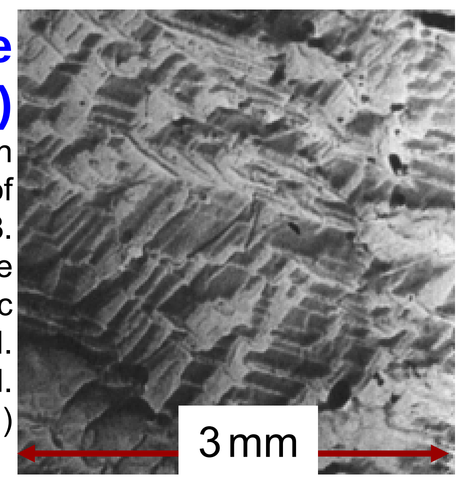
Polypropylene (polymer)

Reprinted w/ permission from R.W. Hertzberg, "Defor-mation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.35(d), p. 303, John Wiley and Sons, Inc., 1996.

(Orig. source: K. Friedrick, *Fracture 1977*, Vol. 3, ICF4, Waterloo, CA, 1977, p. 1119.)

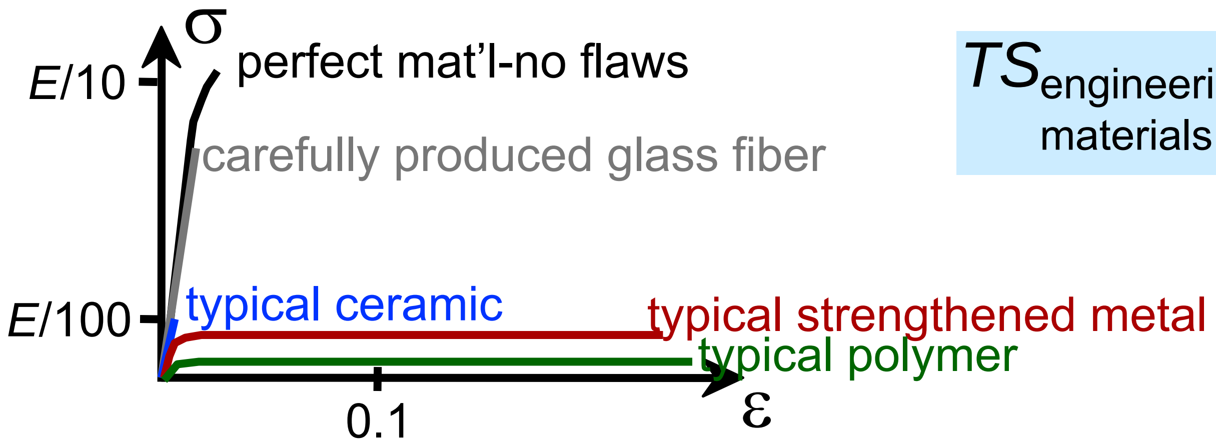
Al Oxide (ceramic)

Reprinted w/ permission from "Failure Analysis of Brittle Materials", p. 78. Copyright 1990, The American Ceramic Society, Westerville, OH. (Micrograph by R.M. Gruver and H. Kirchner.)



Ideal vs Real Materials

• Stress-strain behavior (Room *T*):



$TS_{\text{engineering materials}} << TS_{\text{perfect materials}}$

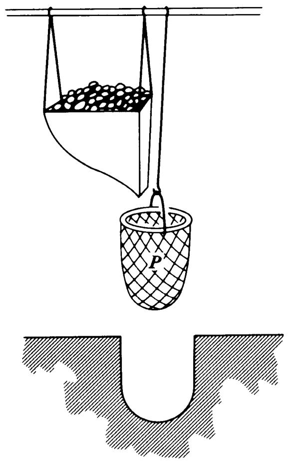
• DaVinci (500 yrs ago!) observed...

-- the longer the wire, the smaller the load for failure.

• Reasons:

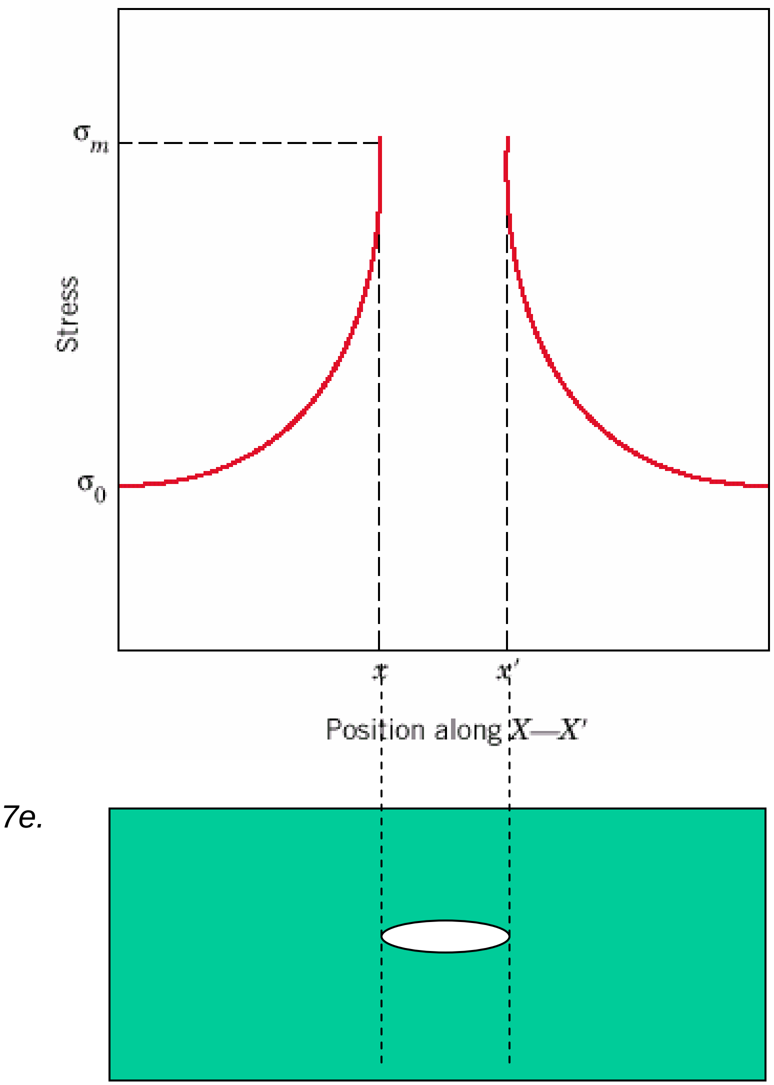
-- flaws cause premature failure.

-- Larger samples contain more flaws!



Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.4. John Wiley and Sons, Inc., 1996.

Concentration of Stress at Crack Tip

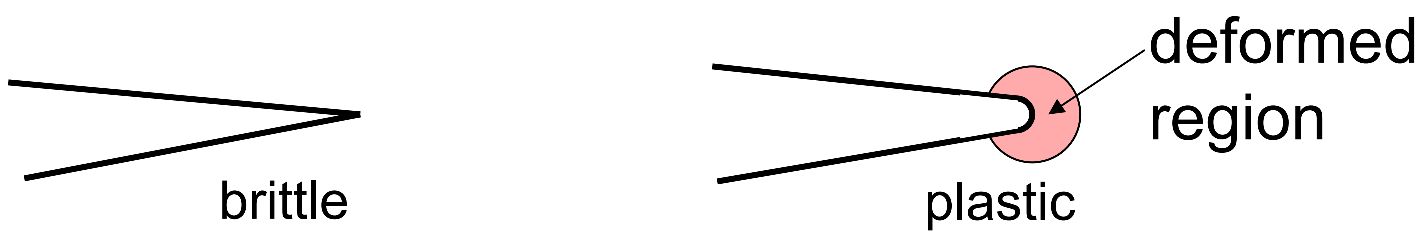


Adapted from Fig. 8.8(b), *Callister 7e.*

Crack Propagation

Cracks propagate due to sharpness of crack tip

- A plastic material deforms at the tip, “blunting” the crack.



Energy balance on the crack

- Elastic strain energy-
  - energy stored in material as it is elastically deformed
  - this energy is released when the crack propagates
  - creation of new surfaces requires energy

Metals Ceramic Polymers Composites

When Does a Crack Propagate?

Crack propagates if above critical stress Griffith

i.e., $\sigma_m > \sigma_c$

or $K_t > K_c$

$$\sigma_c = \left(\frac{2E\gamma_s}{\pi a}\right)^{1/2}$$

geometrical parameter

Fracture Toughness

$K_c = Y\sigma_c\sqrt{\pi a}$

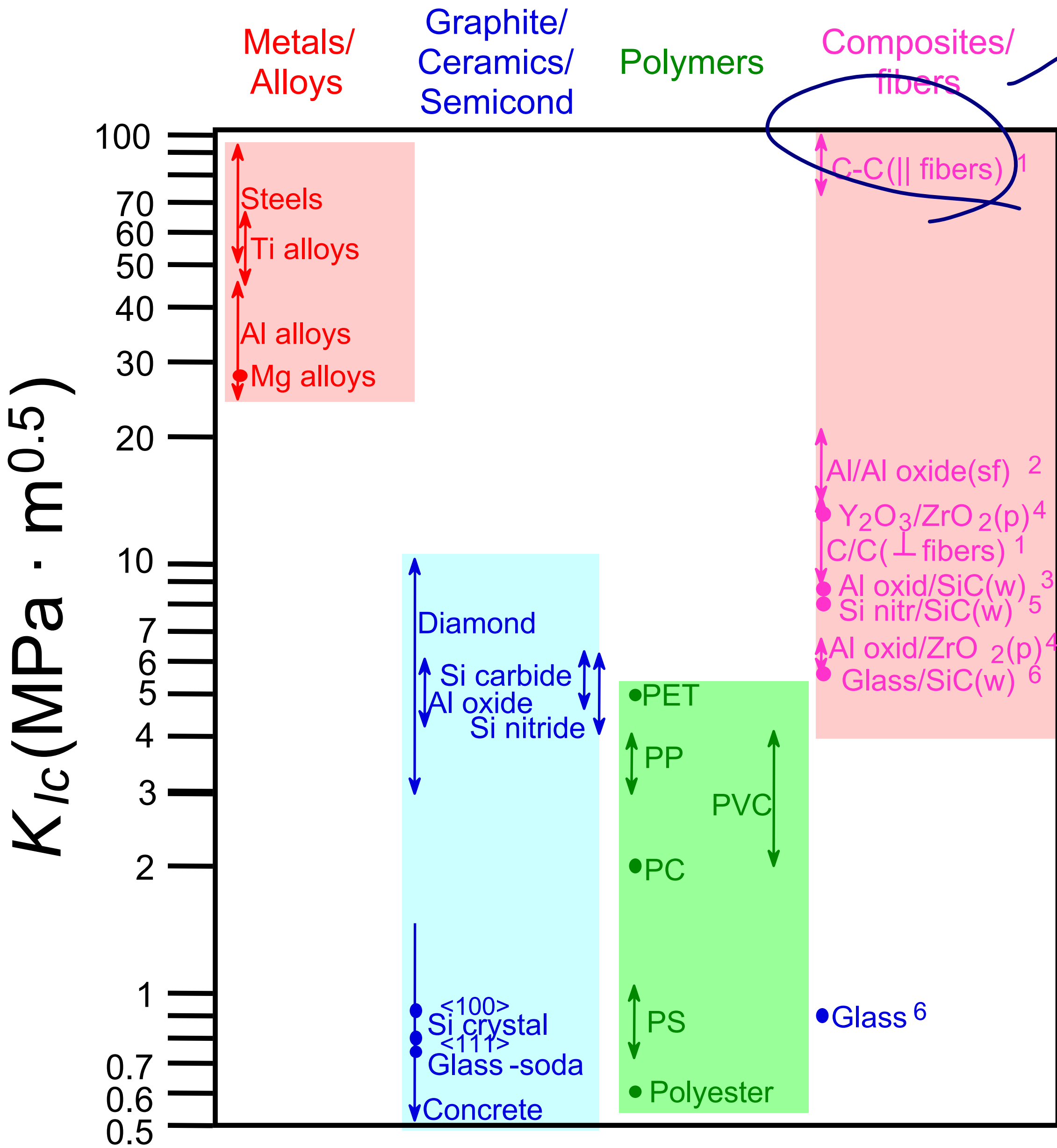
where

- E = modulus of elasticity
- γ_s = specific surface energy
- a = one half length of internal crack

For ductile => replace γ_s by $\gamma_s + \gamma_p$

where γ_p is plastic deformation energy

Fracture Toughness



space shuttle

Based on data in Table B5, *Callister 7e*.

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.

Design Against Crack Growth

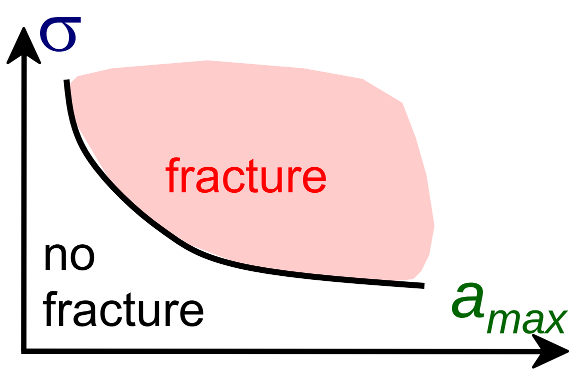
- Crack growth condition:

$$K \geq K_c = Y\sigma\sqrt{\pi a}$$

- Largest, most stressed cracks grow first!

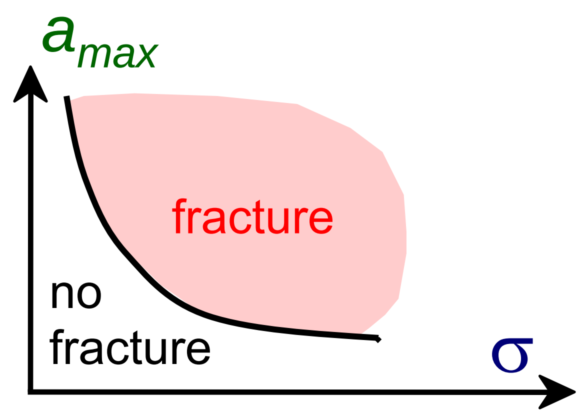
--Result 1: Max. flaw size dictates design stress.

$$\sigma_{design} < \frac{K_c}{Y\sqrt{\pi a_{max}}}$$



--Result 2: Design stress dictates max. flaw size.

$$a_{max} < \frac{1}{\pi}\left(\frac{K_c}{Y\sigma_{design}}\right)^2$$



Design Example: Aircraft Wing

- Material has K_c = 26 MPa-m$^{0.5}$
- Two designs to consider...

Design A
--largest flaw is 9 mm
--failure stress = 112 MPa

Design B
--use same material
--largest flaw is 4 mm
--failure stress = ?

- Use...

$$\sigma_c = \frac{K_c}{Y\sqrt{\pi a_{max}}}$$

fract toughness
max flaw size

- Key point: Y and K_c are the same in both designs.

--Result:

112 MPa   9 mm   4 mm

$$\left(\sigma_c \sqrt{a_{max}}\right)_A = \left(\sigma_c \sqrt{a_{max}}\right)_B$$

Answer: $(\sigma_c)_B = 168\text{ MPa}$

- Reducing flaw size pays off!

Engineering Design

- Great, we can design to prevent brittle behavior
- Things still fail
  - Creep
  - Fatigue
- Next time!

Ch 8