2019 Fall

Introduction to Materials Science and Engineering

10. 31. 2019

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Summary of Chapter 9 (***Ds*** **& Strengthening mechanism**)

- Two primary methods of deformation in metals are **Slip** **and** **Twinning**.
- **Slip** occurs in close-packed direction (Slip direction) on highest-density planes (Slip plane) : **Slip system = Slip plane + Slip direction**

$$\tau_R = \sigma \cos\lambda \cos\phi \quad : \quad \underline{\tau_R(\max) = \tau_{CRSS}} \quad \Rightarrow \quad \tau_R > \tau_{CRSS}$$

- Importance of **twinning ~ crystallographic reorientations**

→ Additional slip process can take place

- **Strength** is increased by <u>making dislocation motion difficult</u>.
- Strength of metals may be increased by:
  - -- decreasing grain size
  - -- solid solution strengthening
  - -- precipitate hardening
  - -- cold working

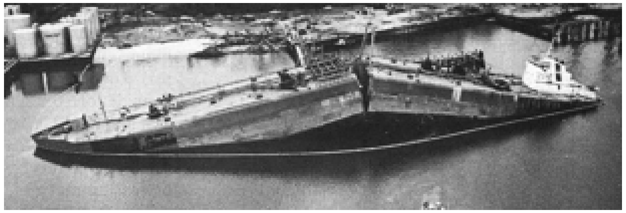
Four Strategies
for Strengthening

- A **cold-worked metal** that is **heat treated** may experience **recovery**, **recrystallization**, and **grain growth** – its properties will be altered.

Chapter 10: Failure

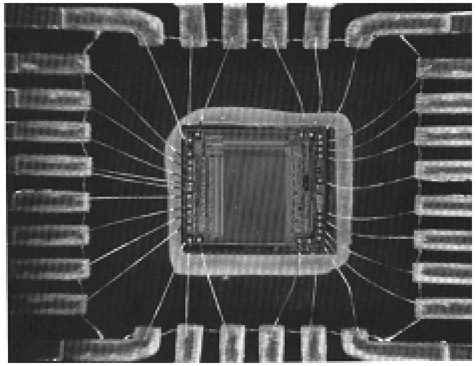
ISSUES TO ADDRESS...

- 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.*

Tacoma bridge, Washington USA

MAY 1940

From Youtube - https://www.youtube.com/watch?v=lXyG68_caV4

I. Fracture mechanisms

변형력으로 말미암아 물체나 물질이 둘 이상의 조각으로 분리되는 현상

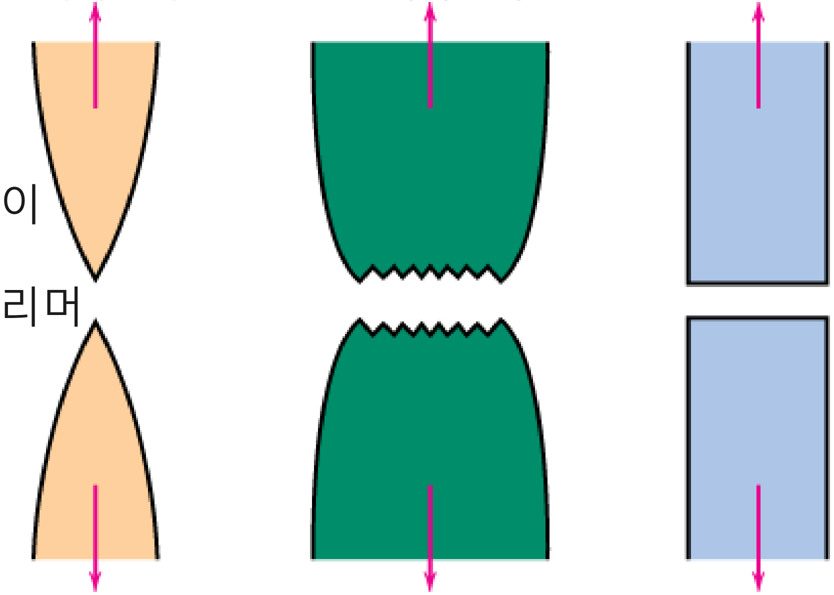
- Ductile fracture
  - Occurs with plastic deformation

- 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



상온: 순금이나 납과 같이
매우 연한 금속
고온: 다른 금속이나 폴리머
및 무기 유리
(inorganic glass)

- Ductile fracture is usually desirable!

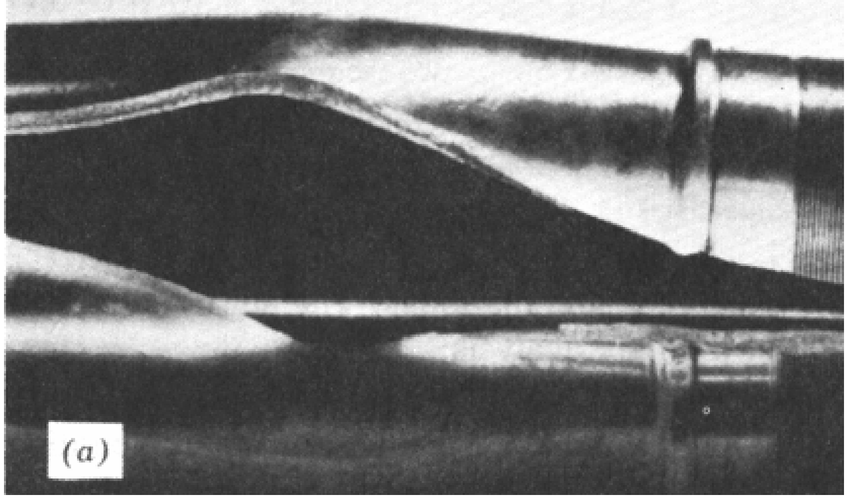
Ductile:
warning before
fracture

Brittle:
No
warning

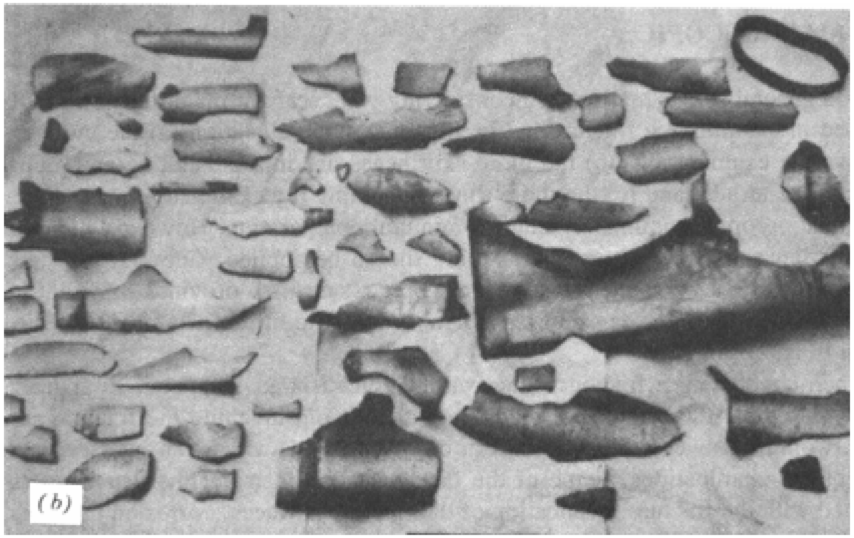
Adapted from Fig. 8.1, *Callister 7e.*

Example: Failure of a Pipe

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



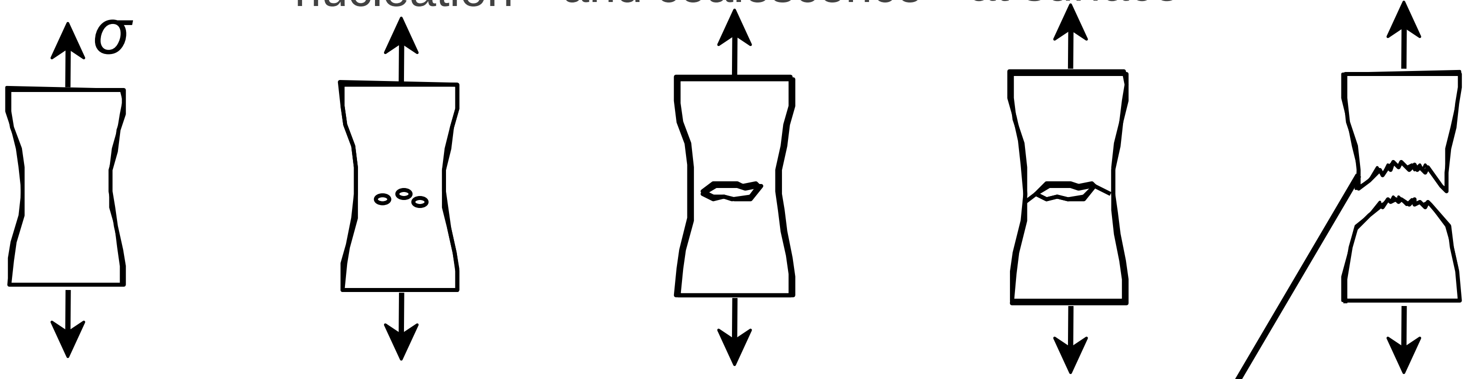
- **Brittle failure:**
  --many pieces
  --small deformation



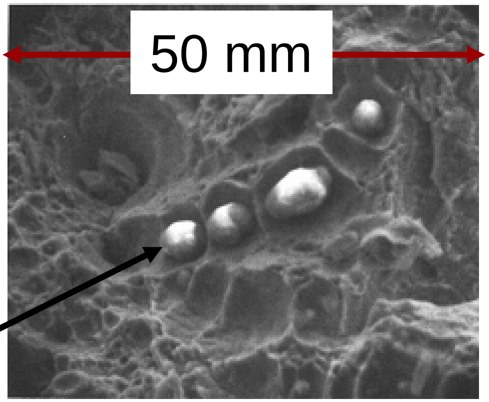
Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

(b) Moderately Ductile Failure

- Failure Stages:

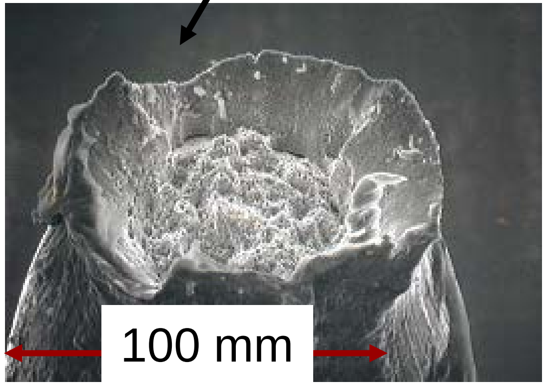


- Resulting fracture surfaces (steel)



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

소성변형이 일어난 흔적이 거의 없다

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

(c) Brittle Failure

취성 파괴면에서는 V자 모양의 ‘쉐브론’ 표시가 균열 시작점으로부터 시편의 중앙 부위를 따라 연속적으로 퍼져나간 것을 볼 수 있다. 또한 선이나 등선 모양이 균열 시작점에서부터 부채꼴로 퍼져나간 모습을 나타내기도 한다.

Arrows **indicate point** at which failure originated

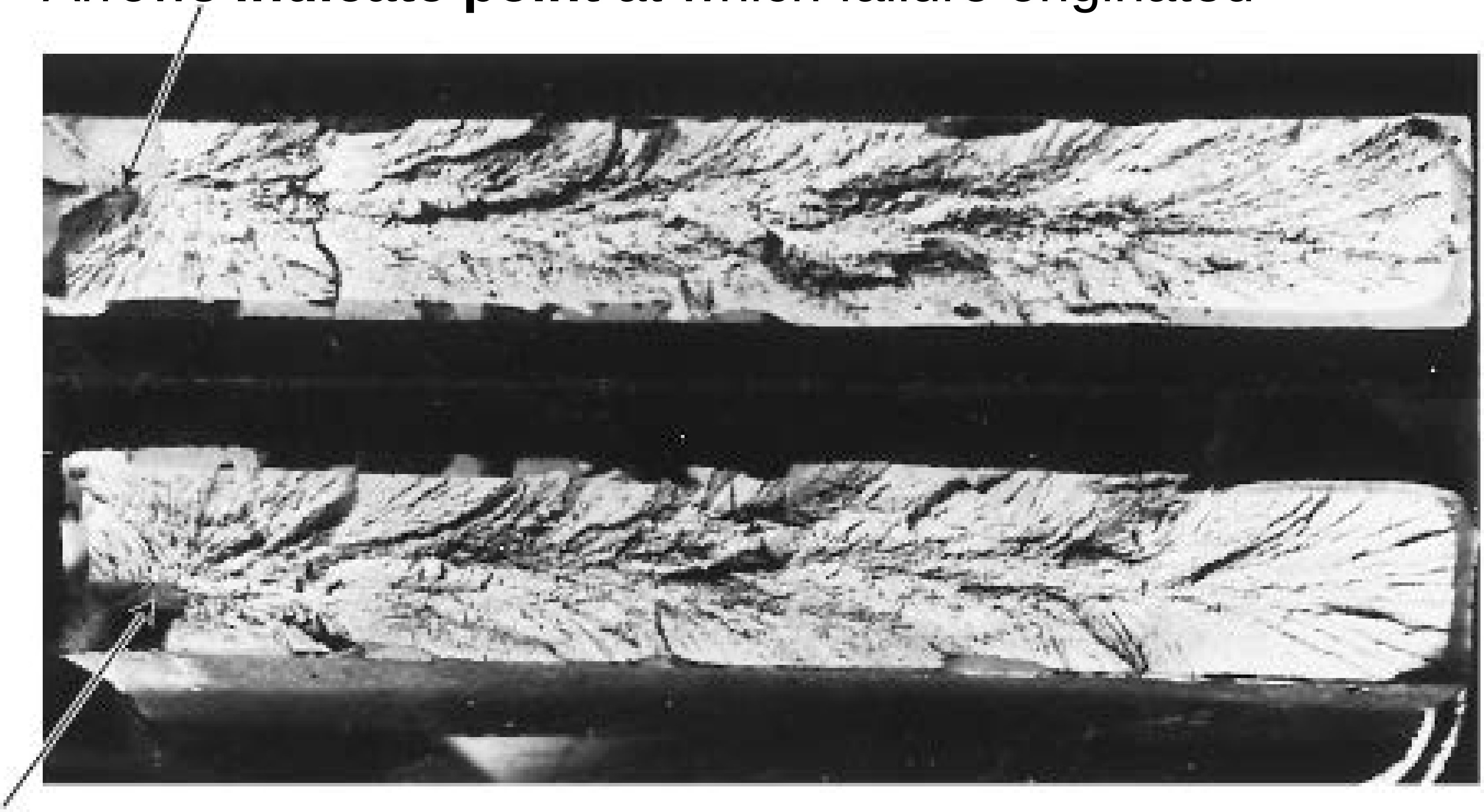
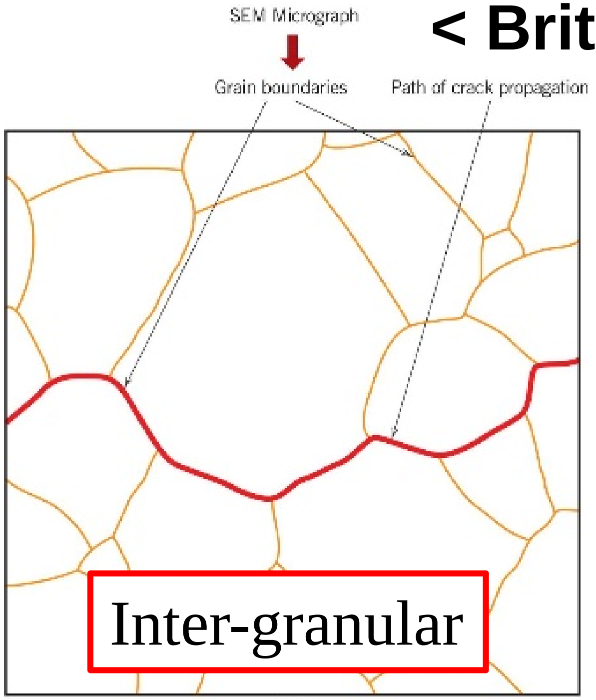


Fig. 10.5(a), *Callister & Rethwisch 9e.* [From R. W. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, 3rd edition. Copyright © 1989 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc. Photograph courtesy of Roger Slutter, Lehigh University.]

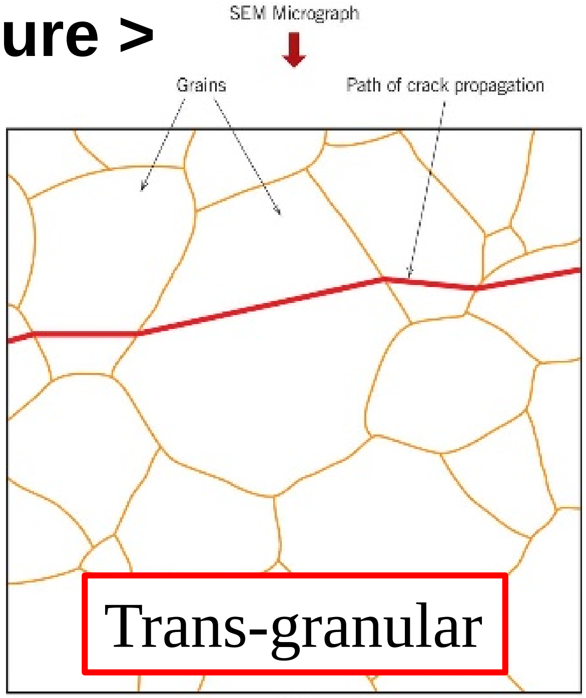
< Brittle Fracture >



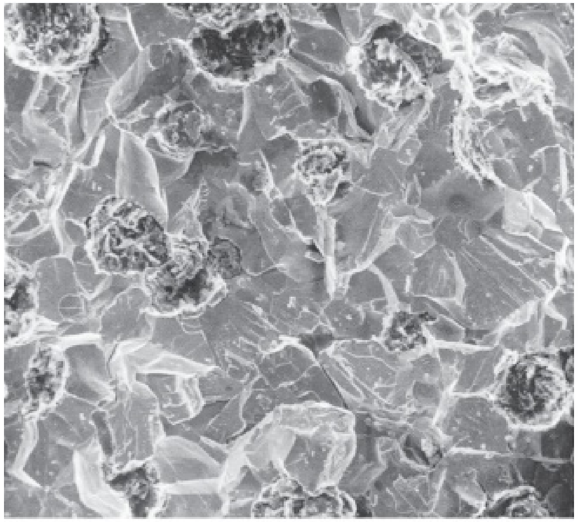
(b)

(b)

Figure (b) reproduced with permission from ASM Handbook, Vol. 12, Fractography, ASM International, Materials Park, OH, 1987.



(a)



(b)

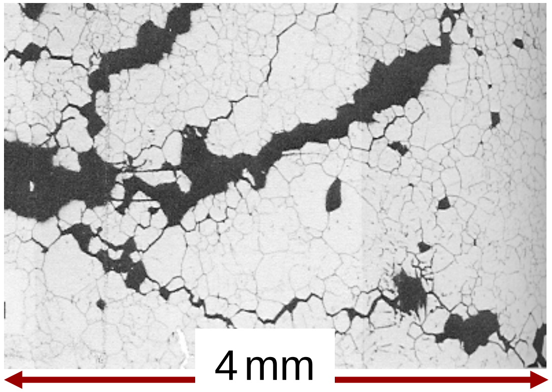
Figure (b) from V. J. Colangelo and F. A. Heiser, Analysis of Metallurgical Failures, 2nd edition. Copyright © 1987 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

Brittle Fracture Surfaces

- Intergranular
(between grains)

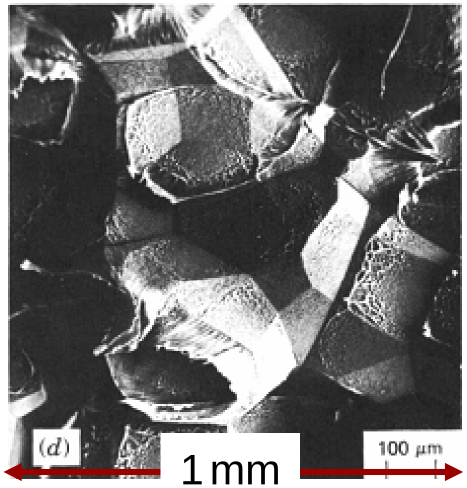
304 S. Steel (metal)

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.)



Polypropylene (polymer)

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

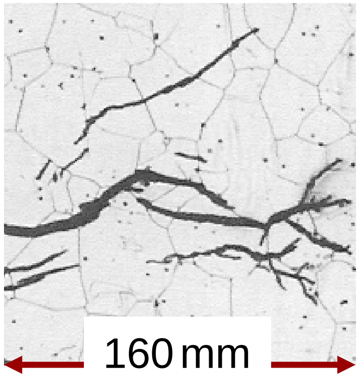


(Orig. source: K. Friedrick, *Fracture 1977*, Vol. 3, ICF4, Waterloo, CA, 1977, p. 1119.)

- Transgranular
(through grains)

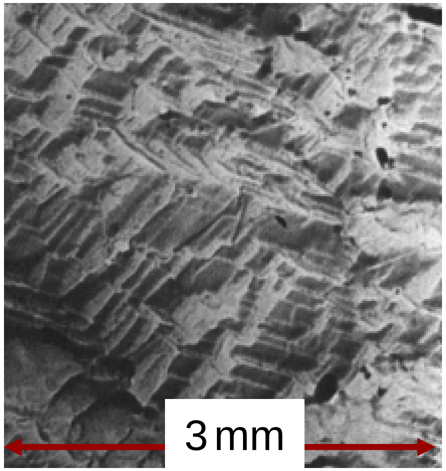
316 S. Steel (metal)

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.)



Al Oxide (ceramic)

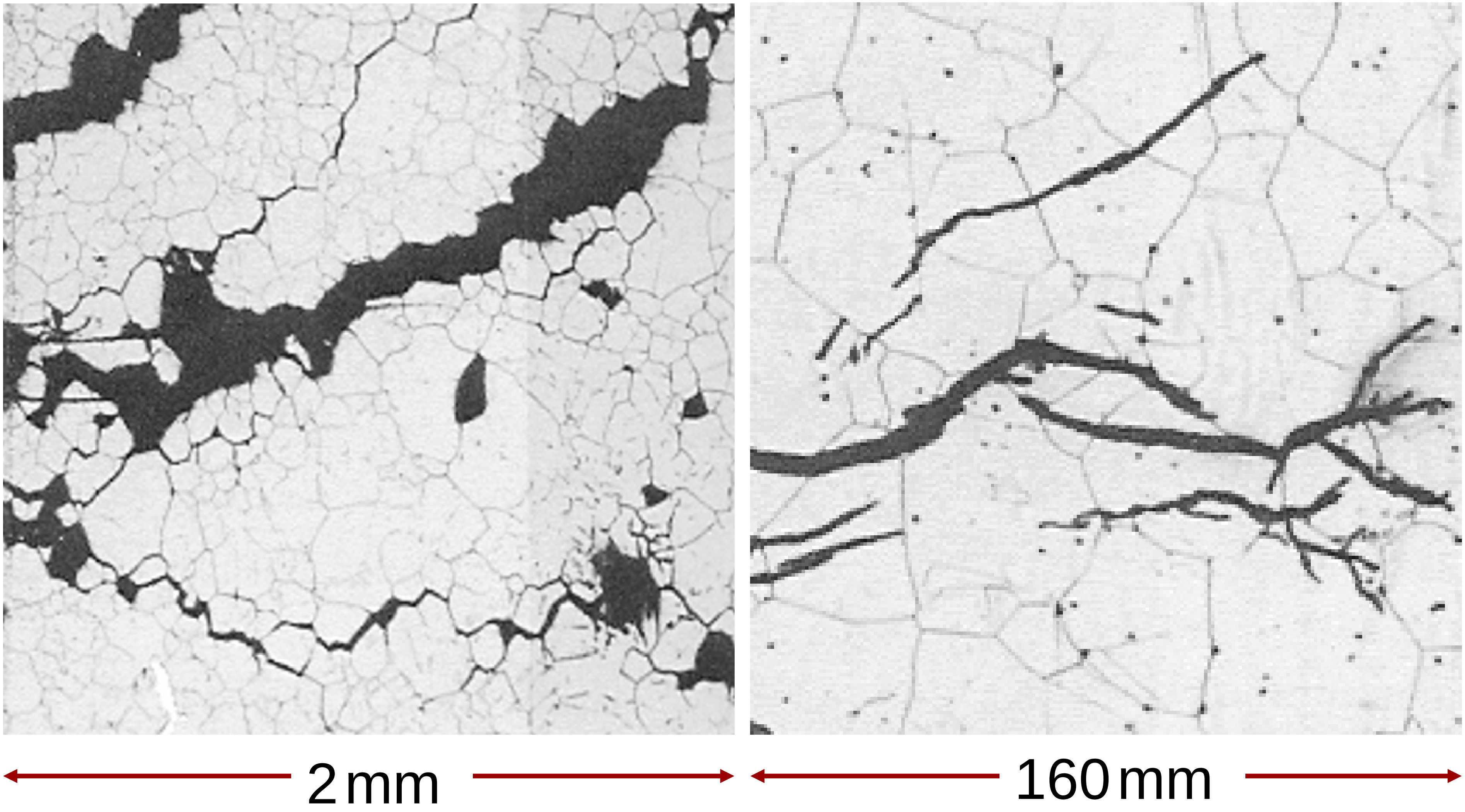
Reprinted w/ permission from "Failure Analysis of Brittle Materials", p. 78. Copyright 1990, The American Ceramic Society, Westerville, OH. (Micrograph by R.M. Gruver and H. Kirchner.)



Brittle Fracture Surfaces

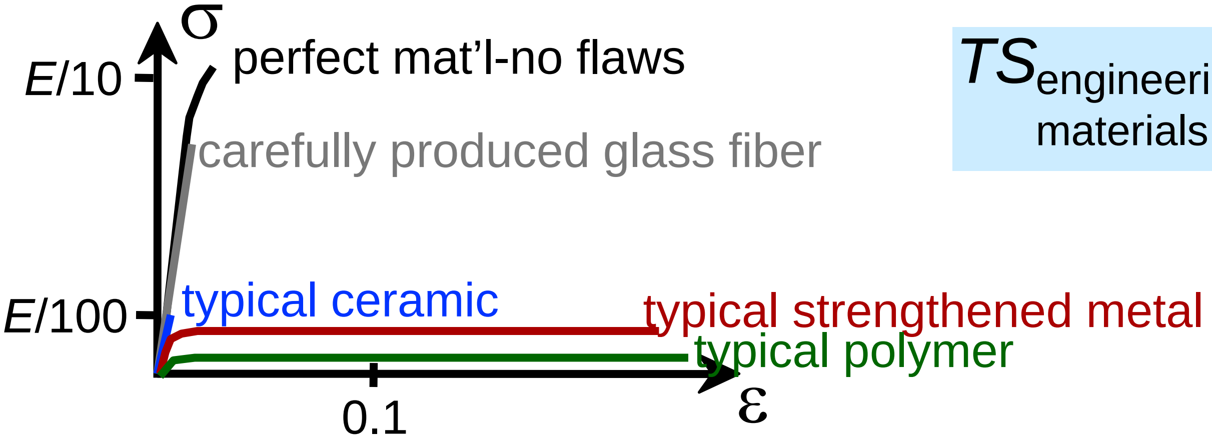
- Intergranular
(between grains)

- Transgranular
(through grains)



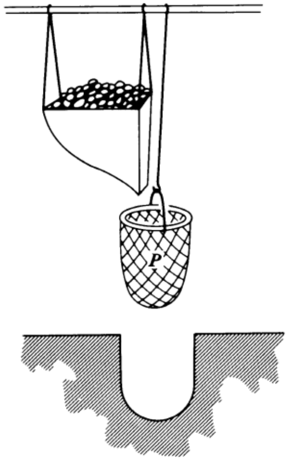
Ideal vs Real Materials

- Stress-strain behavior (Room *T*):



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

- DaVinci (500 yrs ago!) observed...
  -- the longer the wire, the smaller the load for failure.

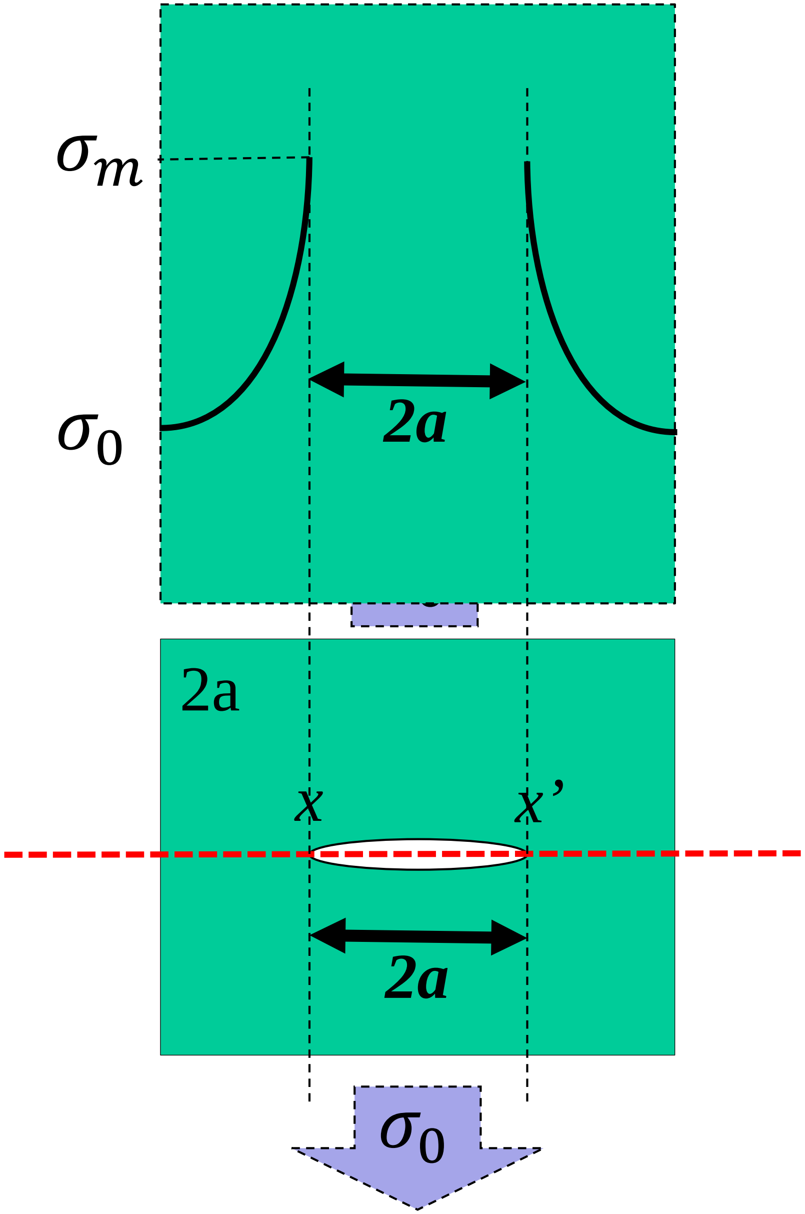


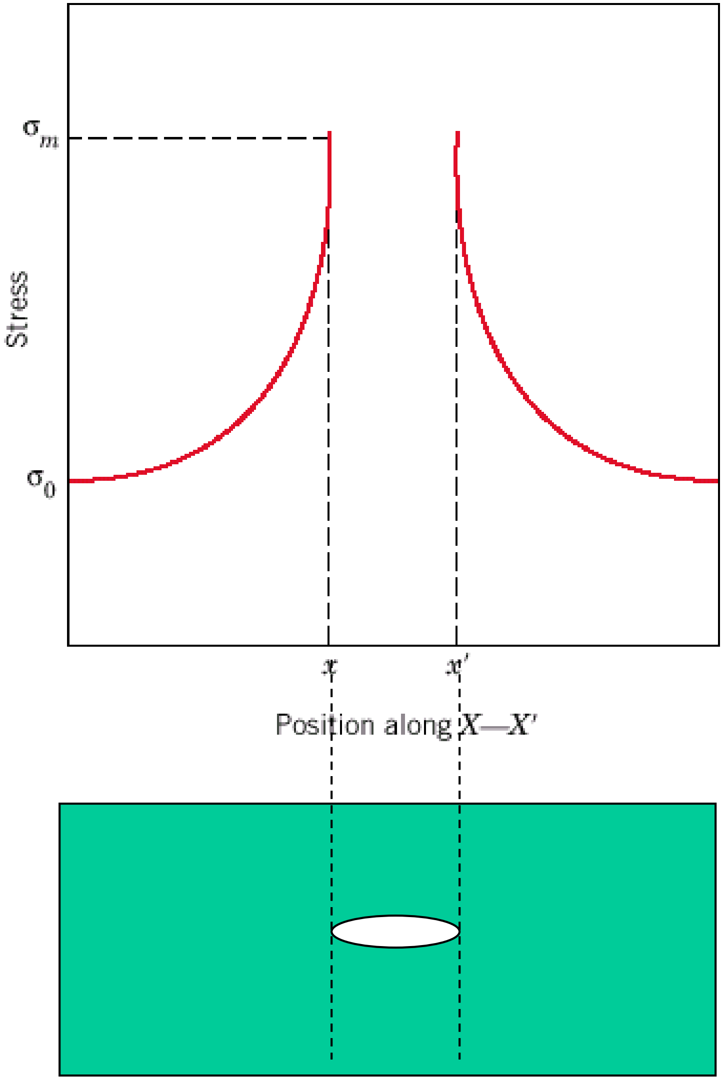
Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.4. John Wiley and Sons, Inc., 1996.

- Reasons:
  -- flaws cause premature failure.
  -- Larger samples contain more flaws!

II. Flaws are Stress Concentrators!

- Concentration of Stress at Crack Tip -



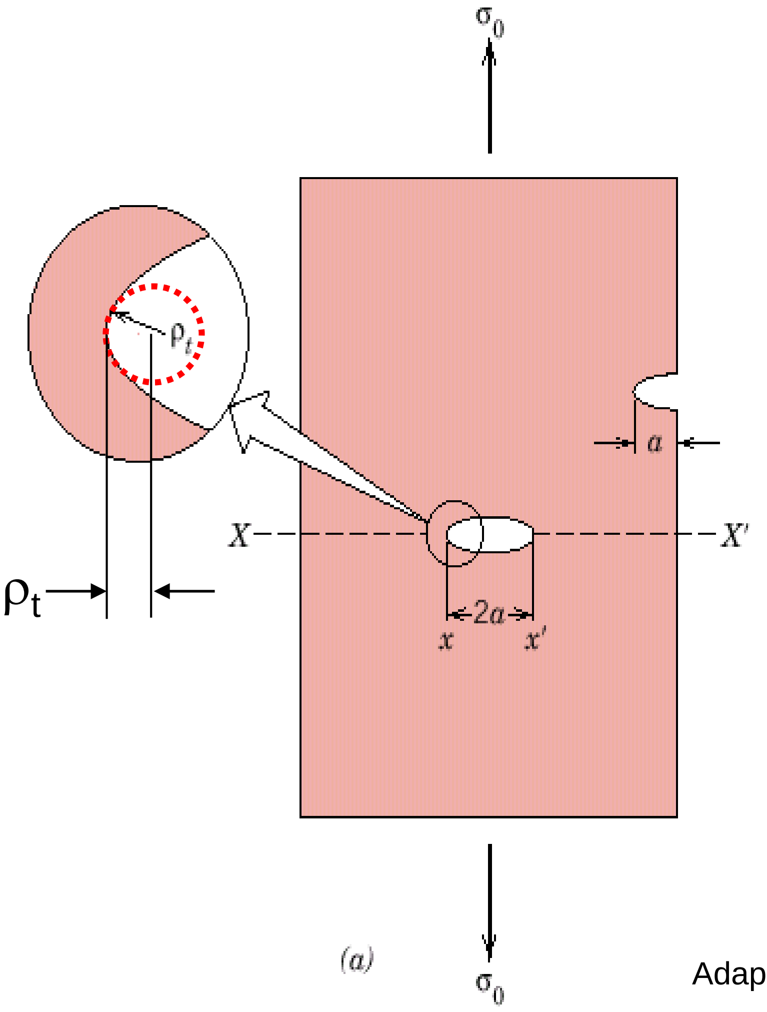


Adapted from Fig. 8.8(b), *Callister 7e.*

파괴 역학 (Fracture Mechanics)
재료 성질, 응력의 크기, 균열을 초래할 수 있는 결함의 존재 및 균열 전파 기구 사이의 관계를 정량화한 것

Flaws are Stress Concentrators!

균열이 타원형이고 균열 장축 방향이 작용 응력에 수직일 때 균열 첨단에서의 최대응력 σ_m



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

Results from crack propagation

- Griffith Crack σ_m은 σ_0에 비해 매우 큰 값

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

where

ρ_t = radius of curvature

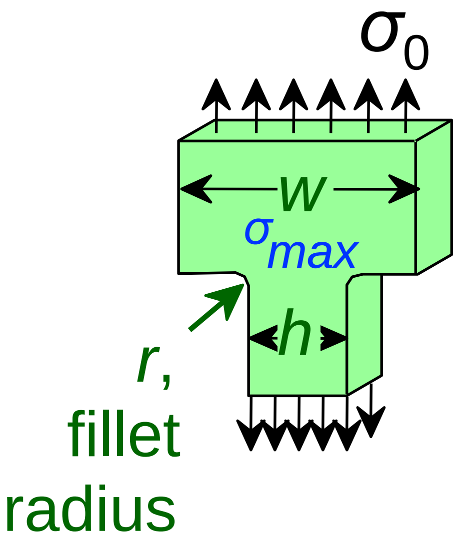
σ_o = applied stress

σ_m = stress at crack tip

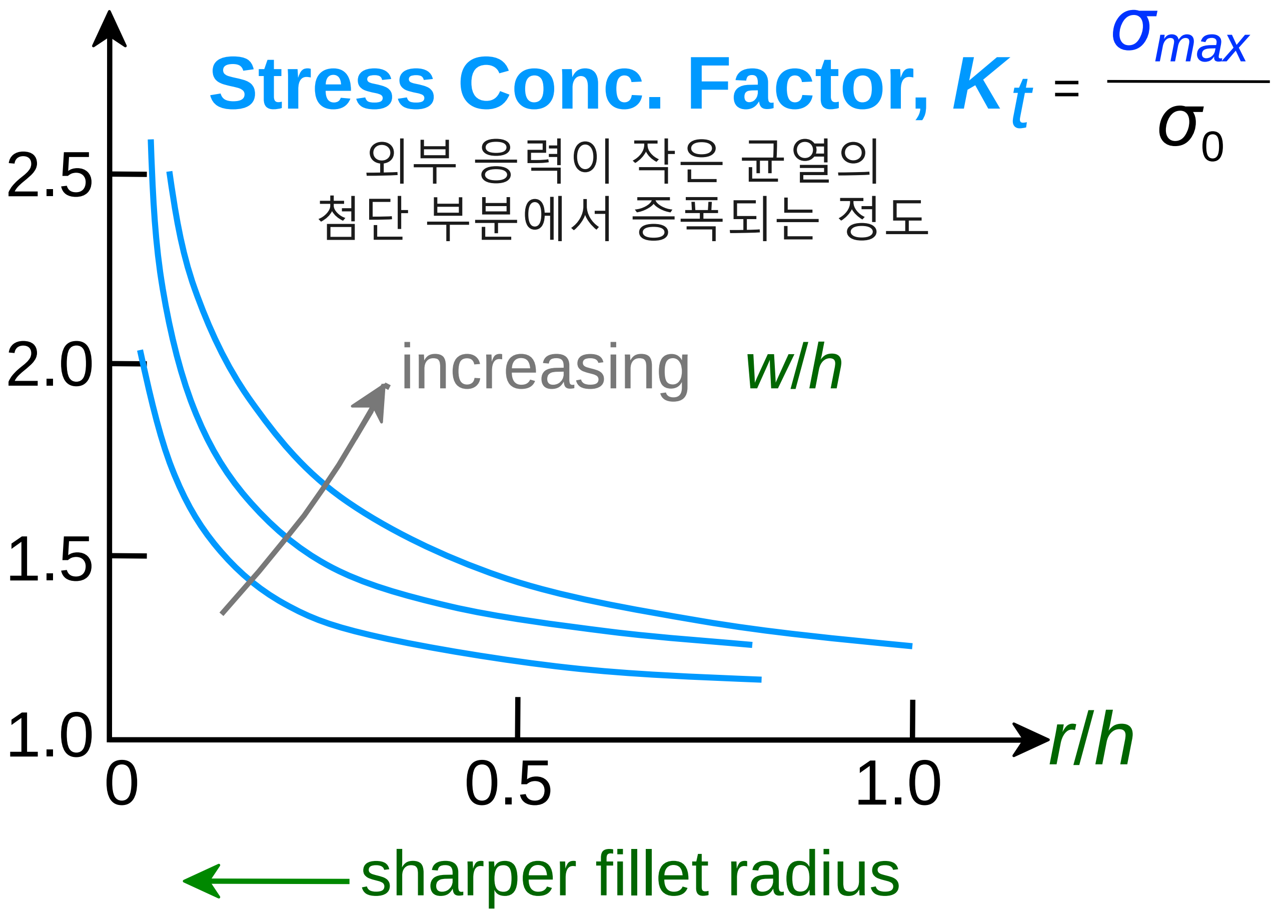
a = one half length of internal crack

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.)



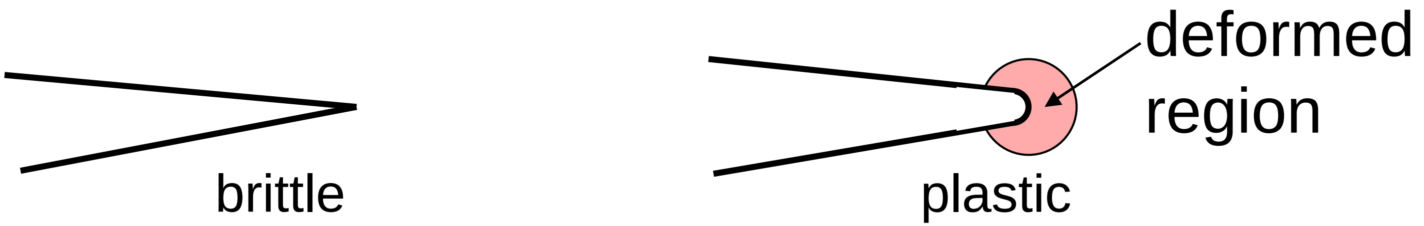
Stress Conc. Factor, $K_t = \dfrac{\sigma_{max}}{\sigma_0}$

외부 응력이 작은 균열의
첨단 부분에서 증폭되는 정도

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

III. When Does a Crack Propagate?

* Crack propagates if above critical stress

파괴역학의 기본 원리를 적용하면

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

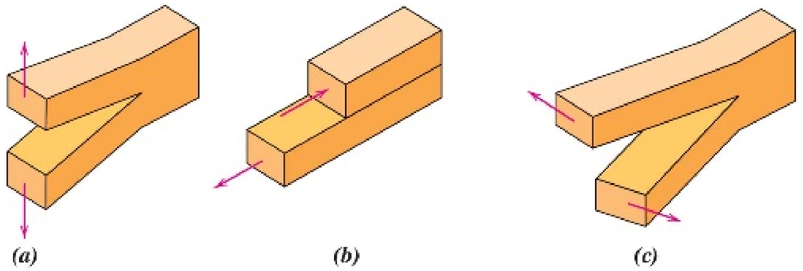
or $K_t > K_c$

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

where

- E = modulus of elasticity
- γ_s = specific surface energy
- a = one half length of internal crack
- $K_c = \sigma_c/\sigma_0$ = Fracture toughness

Fracture mode

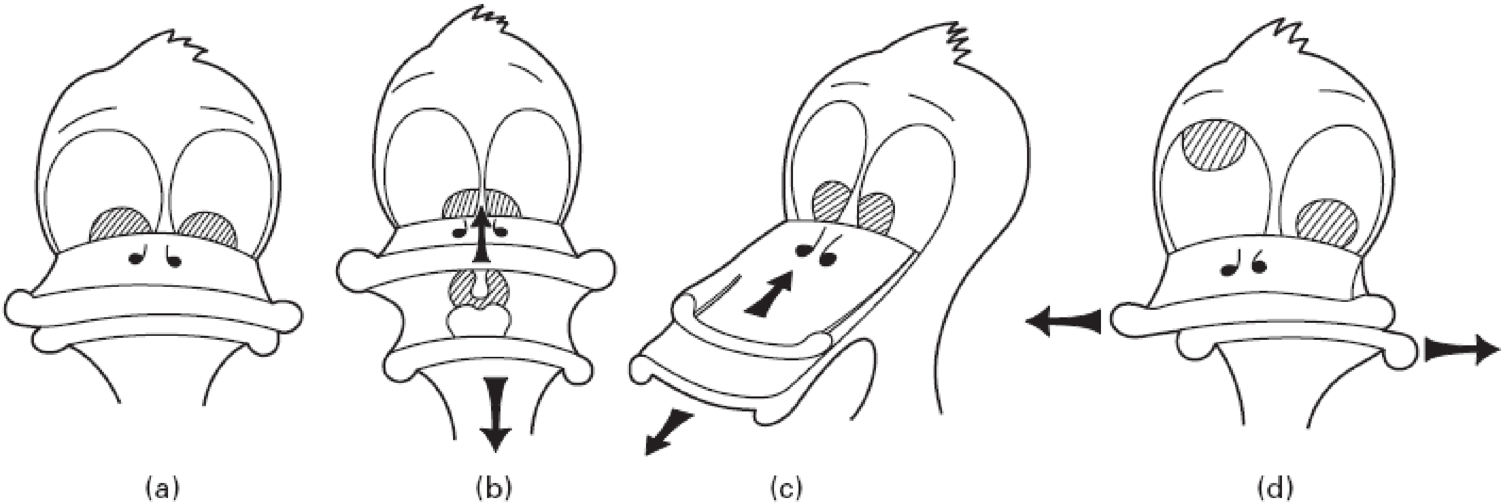


Mode I = opening mode Mode II = sliding mode Mode III = tearing mode

For ductile → replace γ_s by $\gamma_s + \gamma_p$

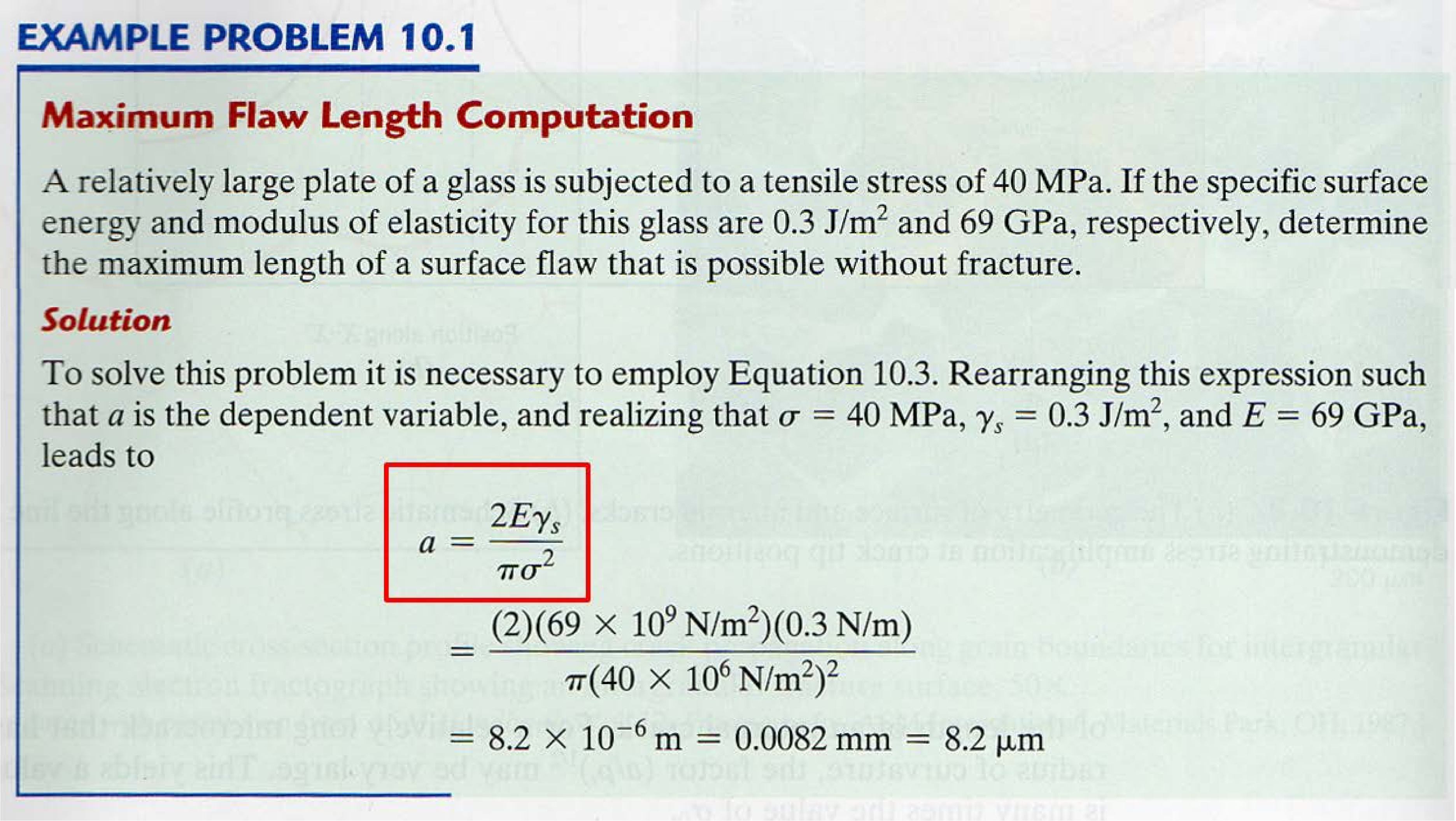
where γ_p is plastic deformation energy

Goofy Duck Analogy for Modes of Crack Loading



Type I Type II Type III

“Goofy duck” analog for three modes of crack loading. (a) Crack/beak closed. (b) Opening mode. (c) Sliding mode. (d) Tearing mode. (Courtesy of M. H. Meyers.)



EXAMPLE PROBLEM 10.1

Maximum Flaw Length Computation

A relatively large plate of a glass is subjected to a tensile stress of 40 MPa. If the specific surface energy and modulus of elasticity for this glass are 0.3 J/m^2 and 69 GPa, respectively, determine the maximum length of a surface flaw that is possible without fracture.

Solution

To solve this problem it is necessary to employ Equation 10.3. Rearranging this expression such that a is the dependent variable, and realizing that $\sigma = 40$ MPa, $\gamma_s = 0.3\ J/m^2$, and $E = 69$ GPa, leads to

$$\boxed{a = \frac{2E\gamma_s}{\pi\sigma^2}}$$

$$= \frac{(2)(69 \times 10^9\ N/m^2)(0.3\ N/m)}{\pi(40 \times 10^6\ N/m^2)^2}$$

$$= 8.2 \times 10^{-6}\ m = 0.0082\ mm = 8.2\ \mu m$$

Plane strain condition: in thick plate with relatively small crack

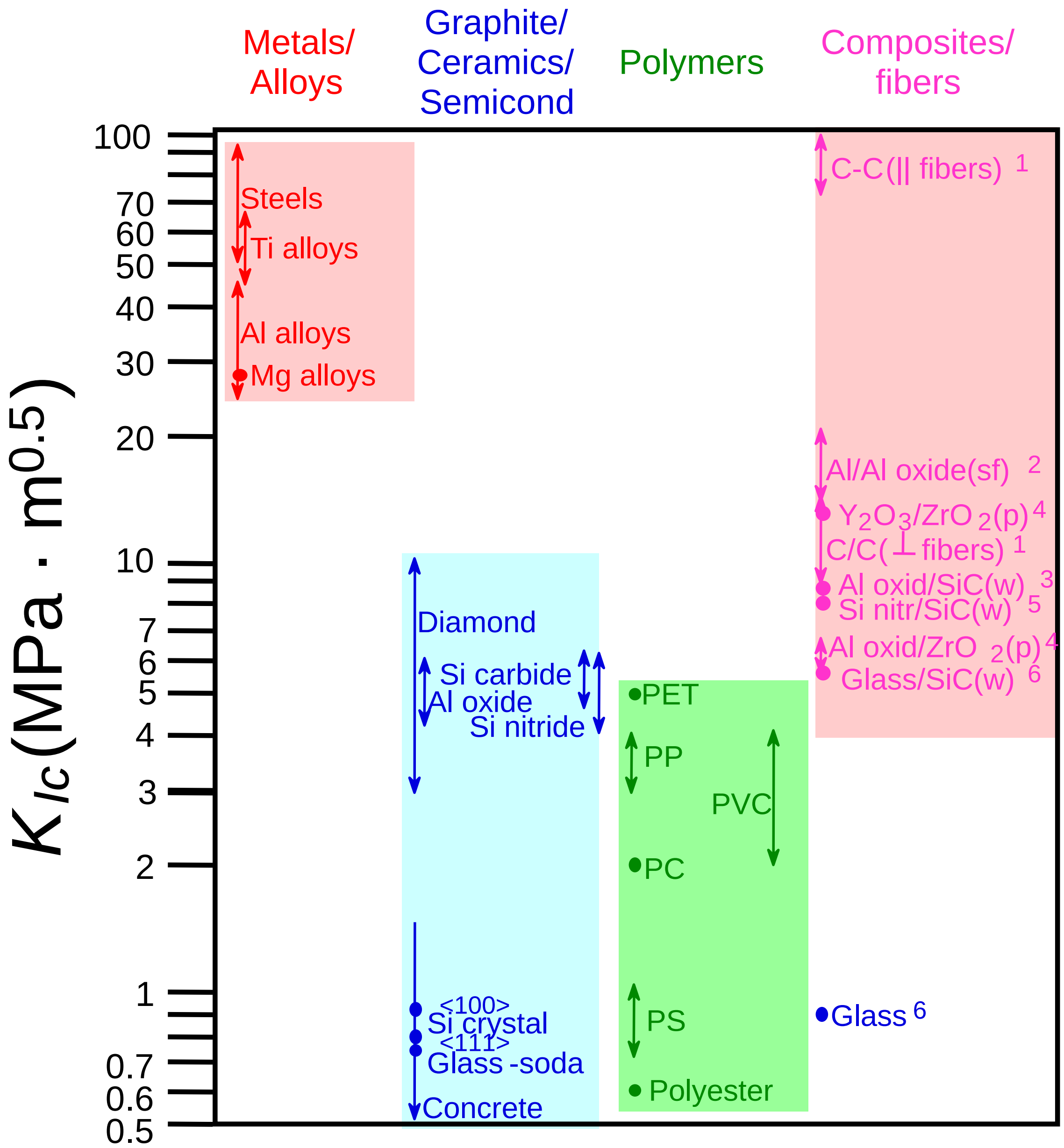
Plane stress condition?

Fracture Toughness

균열이 존재할 때 취성 파괴에 대한 재료의 저항 정도 나타냄

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

$$(= MPa\sqrt{m})$$



대체로 얇은 판에 있어 K_c값은 시편 두께에 따라 변한다. 시편의 두께가 균열 크기보다 매우 크면 K_c 값은 시편 두께의 영향을 받지 않으며, 이를 **평면 변형률(plane strain) 상태**라고 한다. 이러한 두꺼운 시편에서의 **K_c값을 평면 변형률 파괴 인성(plane strain fracture toughness) K_{Ic}**라 함.

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

Design Against Crack Growth

- Crack growth condition:

균열 전파에 대한 임계 응력(σ_c)과 균열 길이(a)의 관계

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

Y는 균열 크기, 시편의 크기 및 기하학적 형상과 하중 적용 방식에 따른 무차원 매개변수임. 시편의 폭보다 매우 짧은 균열을 포함하는 평면 시편의 경우에 Y는 약 1의 값을 갖는다.

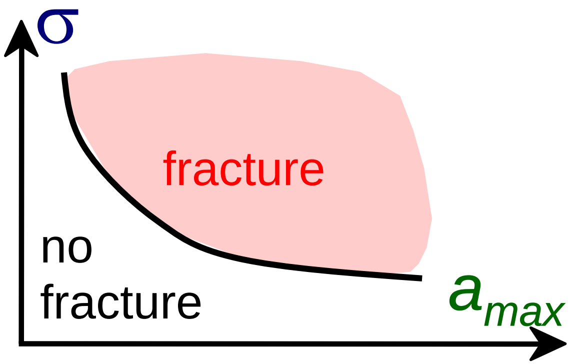
- Largest, most stressed cracks grow first!

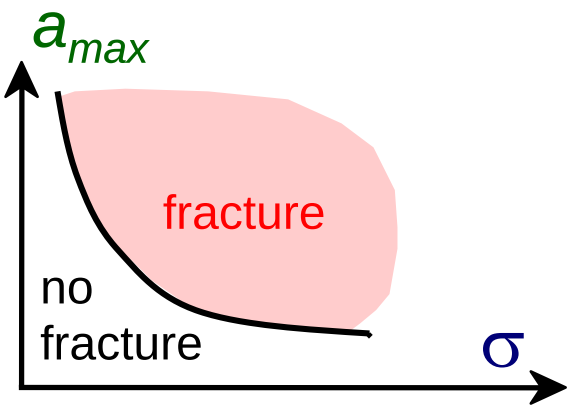
--Result 1: Max. flaw size dictates **design stress.**

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

--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...

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

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

--Result:

$$\left(\overset{112\text{ MPa}}{\sigma_c}\sqrt{\overset{9\text{ mm}}{a_{\max}}}\right)_A = \left(\sigma_c\sqrt{\overset{4\text{ mm}}{a_{\max}}}\right)_B$$

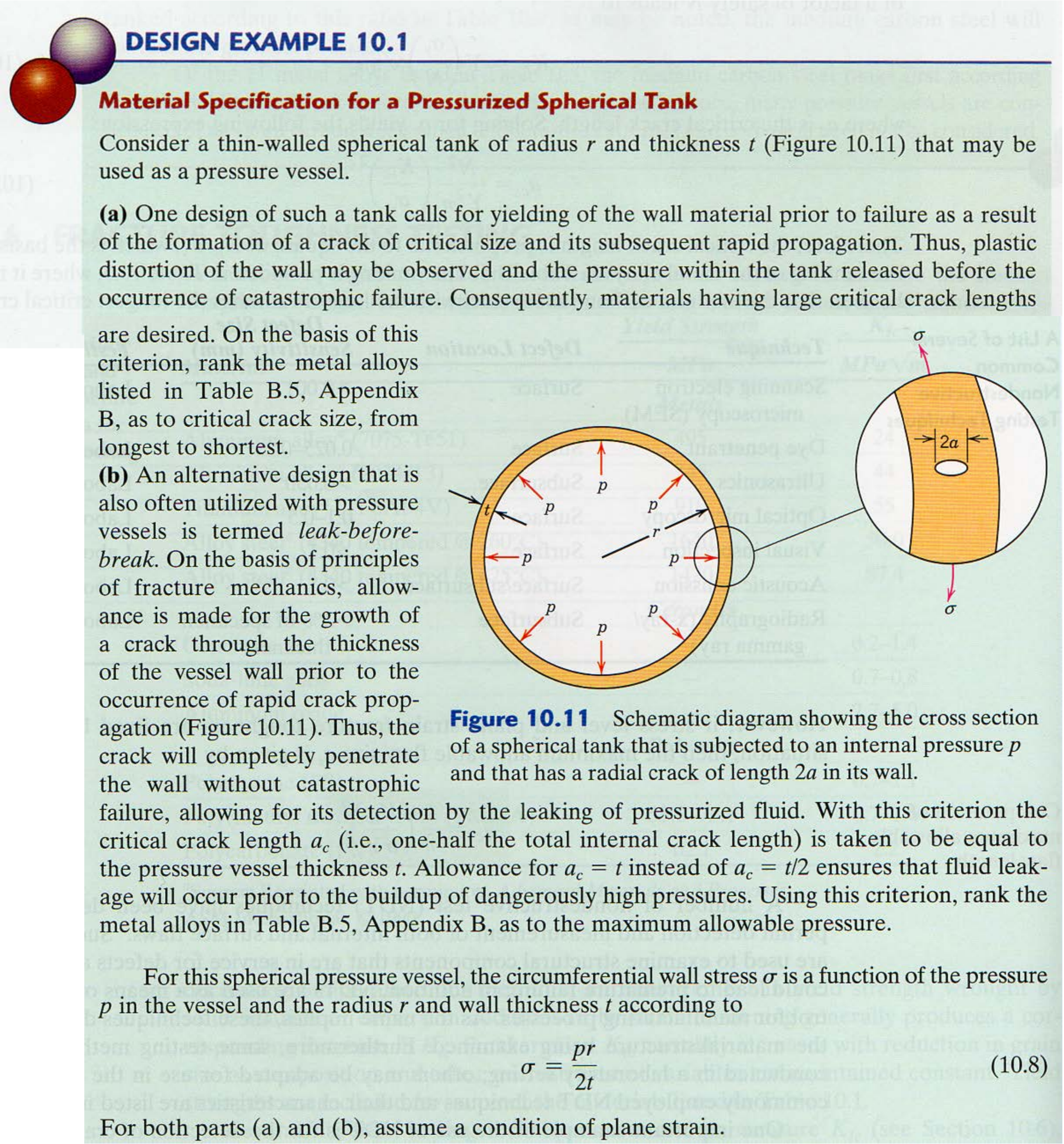
Answer: $(\sigma_c)_B = 168$ MPa

- Reducing flaw size pays off!

Design example 10.1

$$K_{IC} = Y\left(\frac{\sigma_Y}{N}\right)\sqrt{\pi a_c}$$

$$a_C = \frac{N^2}{Y^2\pi}\left(\frac{K_{IC}}{\sigma_y}\right)^2$$



DESIGN EXAMPLE 10.1

Material Specification for a Pressurized Spherical Tank

Consider a thin-walled spherical tank of radius r and thickness t (Figure 10.11) that may be used as a pressure vessel.

(a) One design of such a tank calls for yielding of the wall material prior to failure as a result of the formation of a crack of critical size and its subsequent rapid propagation. Thus, plastic distortion of the wall may be observed and the pressure within the tank released before the occurrence of catastrophic failure. Consequently, materials having large critical crack lengths are desired. On the basis of this criterion, rank the metal alloys listed in Table B.5, Appendix B, as to critical crack size, from longest to shortest.

(b) An alternative design that is also often utilized with pressure vessels is termed *leak-before-break*. On the basis of principles of fracture mechanics, allowance is made for the growth of a crack through the thickness of the vessel wall prior to the occurrence of rapid crack propagation (Figure 10.11). Thus, the crack will completely penetrate the wall without catastrophic failure, allowing for its detection by the leaking of pressurized fluid. With this criterion the critical crack length a_c (i.e., one-half the total internal crack length) is taken to be equal to the pressure vessel thickness t. Allowance for $a_c = t$ instead of $a_c = t/2$ ensures that fluid leakage will occur prior to the buildup of dangerously high pressures. Using this criterion, rank the metal alloys in Table B.5, Appendix B, as to the maximum allowable pressure.

Figure 10.11 Schematic diagram showing the cross section of a spherical tank that is subjected to an internal pressure p and that has a radial crack of length $2a$ in its wall.

For this spherical pressure vessel, the circumferential wall stress σ is a function of the pressure p in the vessel and the radius r and wall thickness t according to

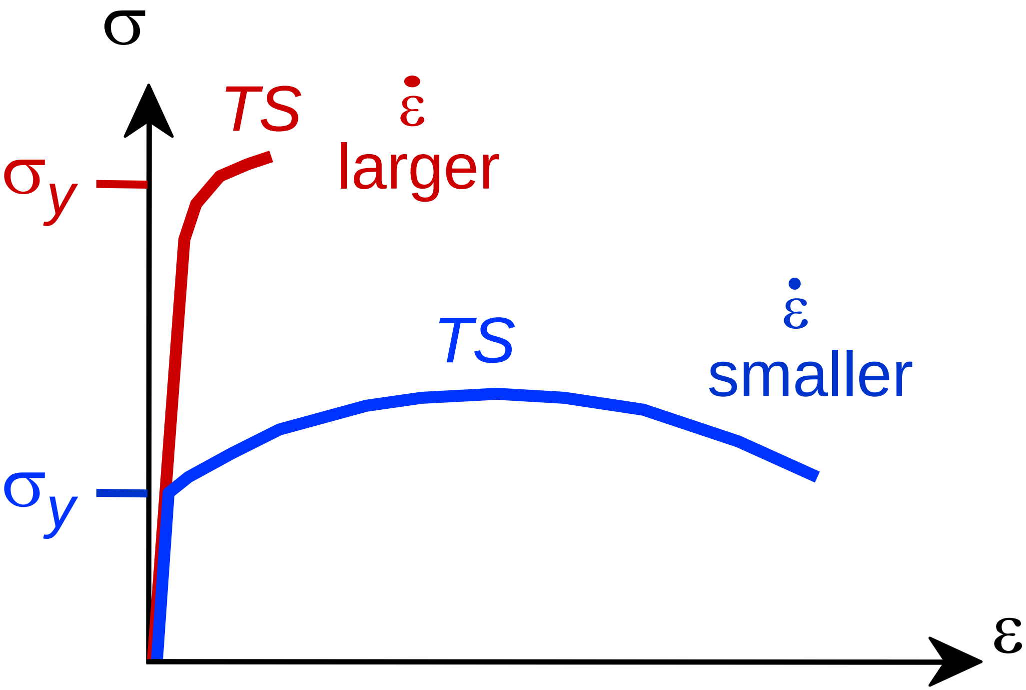
$$\sigma = \frac{pr}{2t} \qquad (10.8)$$

For both parts (a) and (b), assume a condition of plane strain.

IV. Effect of Loading Rate on σ-ε behavior

- Increased loading rate...
  -- increases σ_y and *TS*
  -- decreases %*EL*

- Why? An increased rate gives less time for dislocations to move past obstacles.



파괴인성 시험: 규정된 속도로 시편에 하중을 가하고, 하중값과 균열 변위값을 측정

a. Impact Testing

- Impact loading:
  - -- severe testing case
  - -- makes material more brittle
  - -- decreases toughness

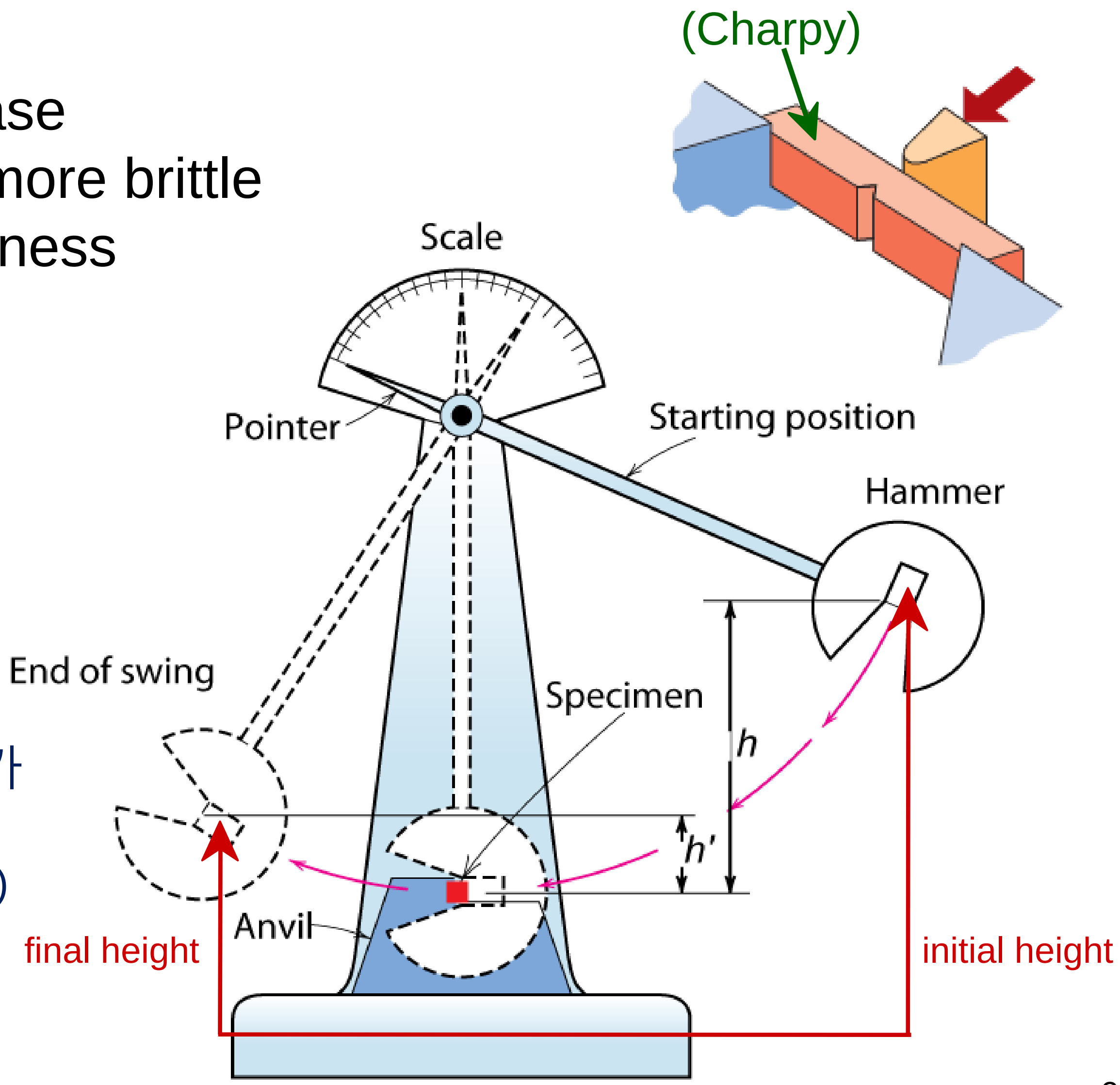


Fig. 10.12(b), *Callister & Rethwisch 9e.*
(Adapted from H.W. Hayden, W.G. Moffatt, and J. Wulff, *The Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, John Wiley and Sons, Inc. (1965) p. 13.)

샤르피 시험법과 아이조드 시험법의 주된 역할은 재료가 온도 감소에 따라 연성-취성 전이(ductile-to-brittle transition) 온도 범위를 결정하는 것

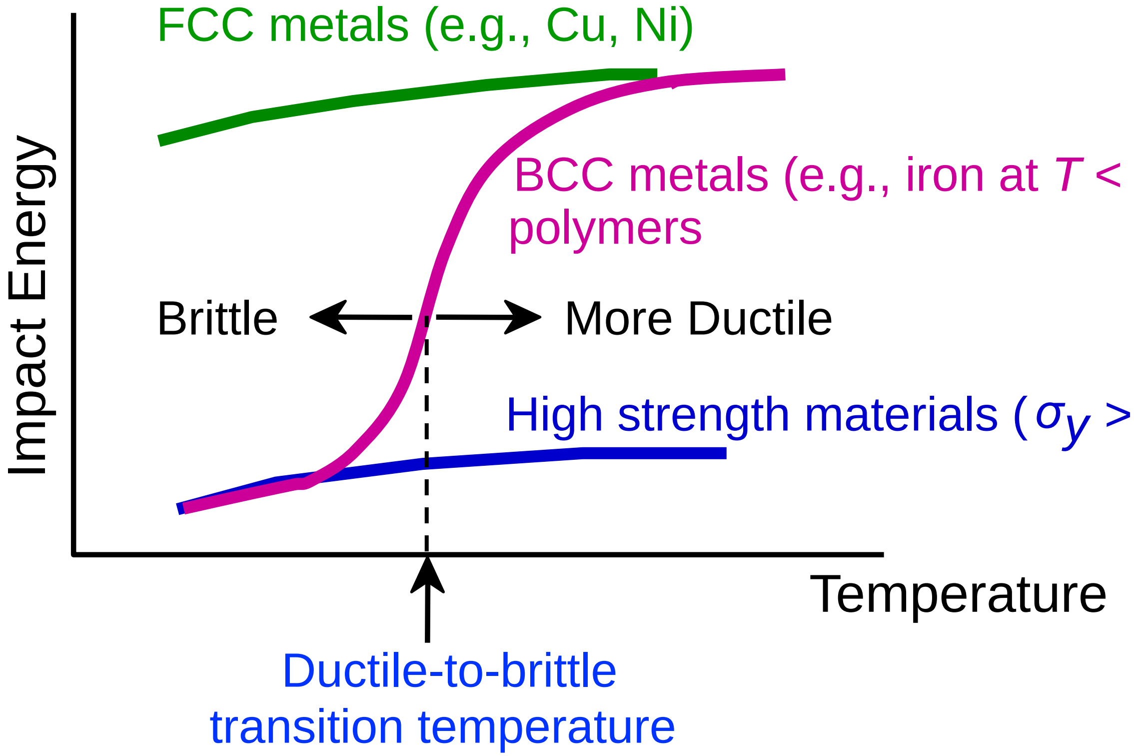
Influence of Temperature on Impact Energy

- **Increasing temperature...**

  --increases %*EL* and K_c

- **Ductile-to-Brittle Transition Temperature (DBTT)...**

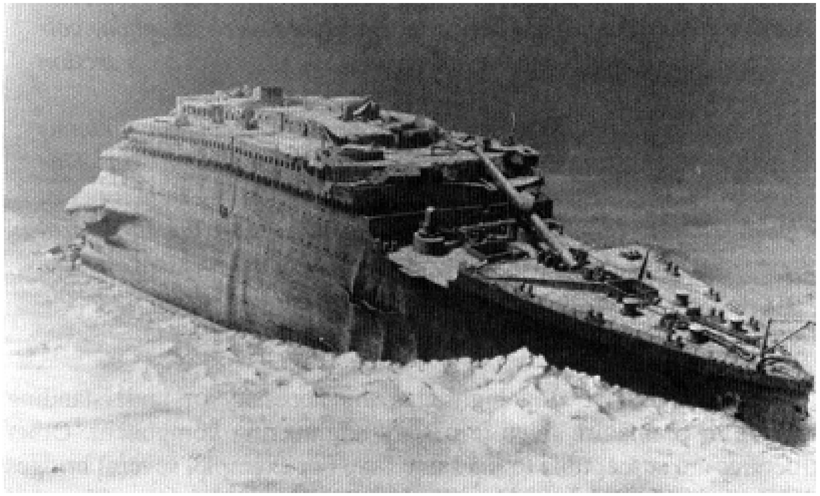
온도에 따른 충격 에너지 흡수량의 변화



Adapted from Fig. 10.15, *Callister & Rethwisch 9e.*

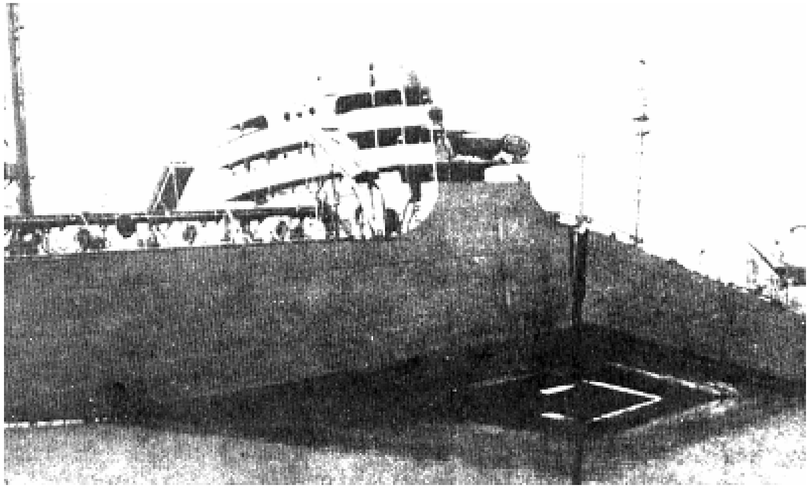
Design Strategy: Stay Above The DBTT!

- **Pre-WWII: The Titanic**



Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(a), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Dr. Robert D. Ballard, *The Discovery of the Titanic*.)

- **WWII: Liberty ships**

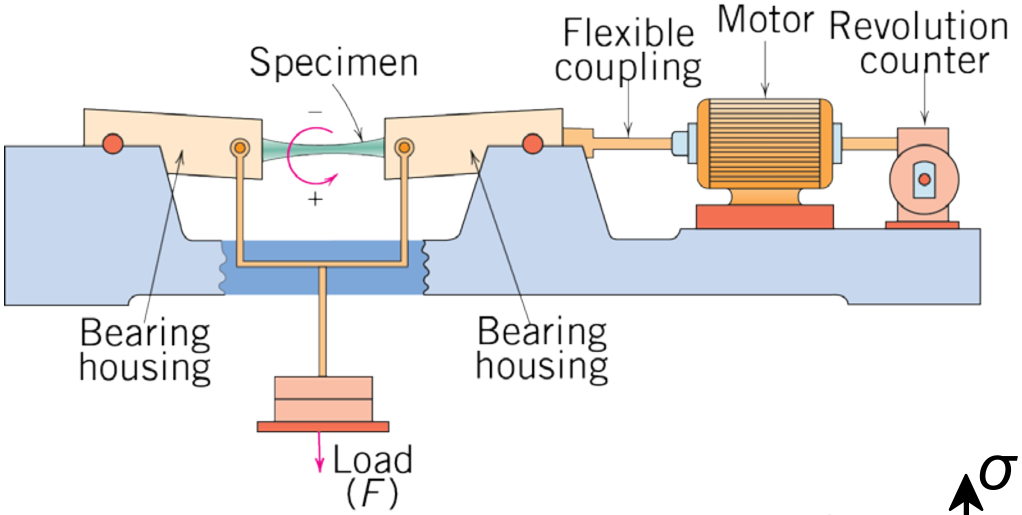


Reprinted w/ permission from R.W. Hertzberg, "Deformation and Fracture Mechanics of Engineering Materials", (4th ed.) Fig. 7.1(b), p. 262, John Wiley and Sons, Inc., 1996. (Orig. source: Earl R. Parker, "Behavior of Engineering Structures", Nat. Acad. Sci., Nat. Res. Council, John Wiley and Sons, Inc., NY, 1957.)

- Problem: Steels were used having DBTT's just below room temperature.

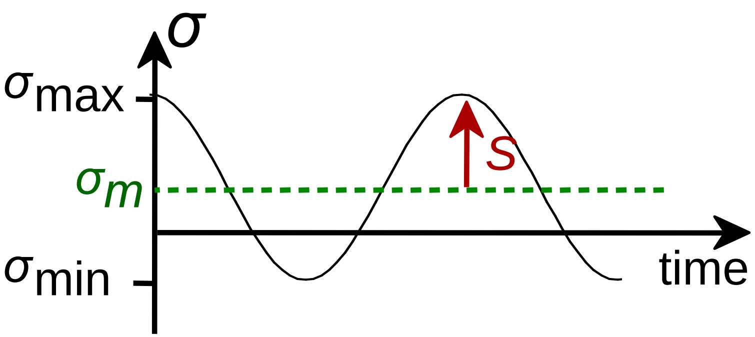
V. Fatigue

- Fatigue = failure under applied cyclic stress.



Adapted from Fig. 10.18(a), *Callister & Rethwisch 9e.*

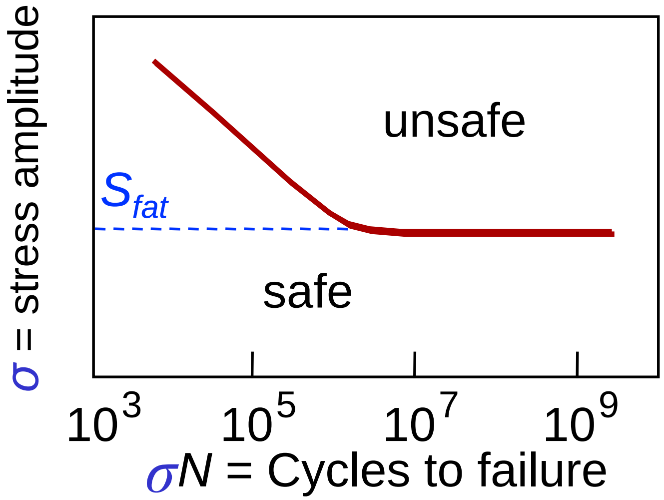
- Stress varies with time.
  -- key parameters are S, σ_m, and cycling frequency



- Key points: Fatigue...
  --can cause part failure, even though $\sigma_{max} < \sigma_y$.
  --responsible for ~ 90% of mechanical engineering failures.

Types of Fatigue Behavior

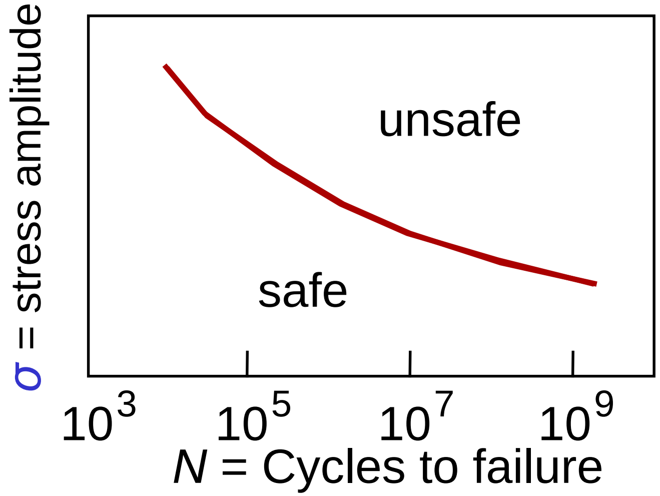
- Fatigue limit, σ_{fat}:
  --no fatigue if $\sigma < \sigma_{fat}$



case for
steel (typ.)

Adapted from Fig. 10.19(a), *Callister & Rethwisch 9e.*

- For some materials, there is no fatigue limit!



case for
Al (typ.)

Adapted from Fig. 10.19(b), *Callister & Rethwisch 9e.*

Rate of Fatigue Crack Growth

- Crack grows *incrementally*

$$\frac{da}{dN} = (\Delta K)^m$$

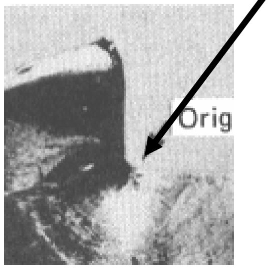
typ. 1 to 6

$$\sim \left(\Delta\sigma\right)\sqrt{a}$$

increase in crack length per loading cycle

- Failed rotating shaft
  - -- crack grew even though
    $K_{max} < K_c$
  - -- crack grows faster as
    - $\Delta\sigma$ increases
    - crack gets longer
    - loading freq. increases.

crack origin



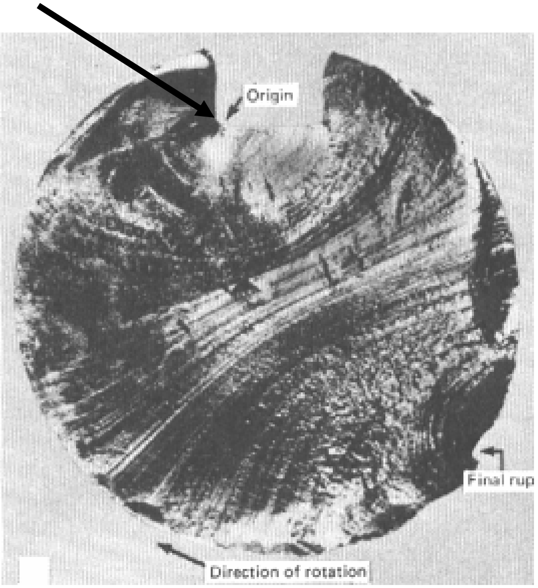
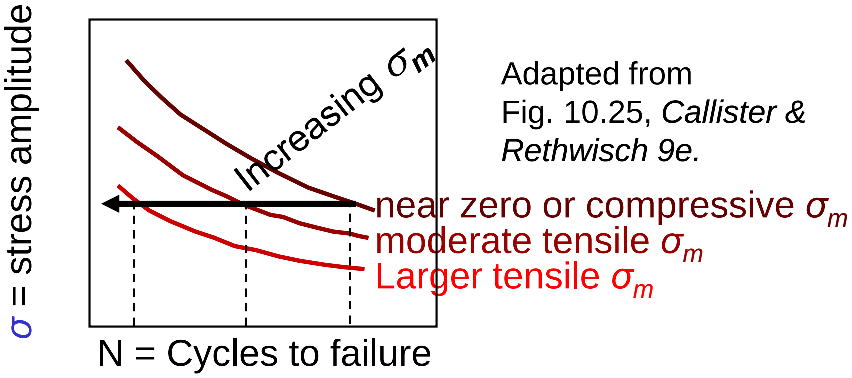


Fig. 10.22, *Callister & Rethwisch 9e.*
(From D. J. Wulpi, *Understanding How Components Fail*, 1985. Reproduced by permission of ASM International, Materials Park, OH.)

Improving Fatigue Life

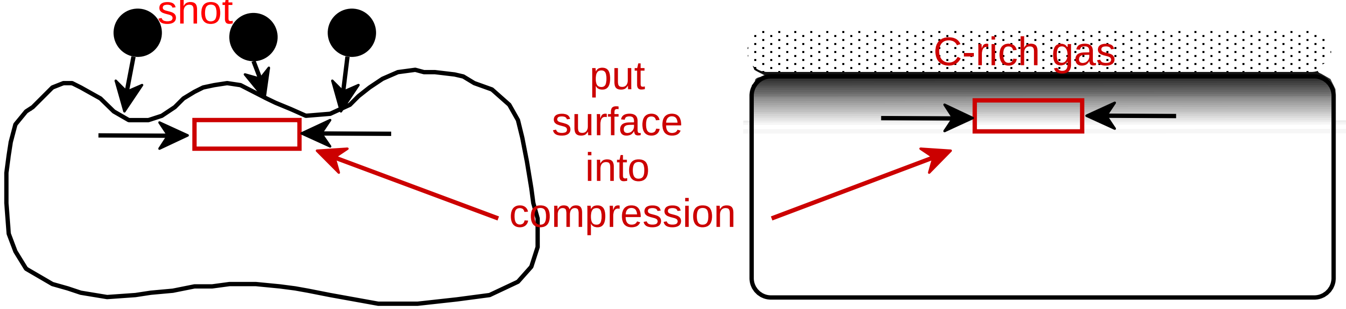
1. Impose compressive surface stresses (to suppress surface cracks from growing)



Adapted from Fig. 10.25, *Callister & Rethwisch 9e.*

--Method 1: shot peening

--Method 2: carburizing



2. Remove stress concentrators.

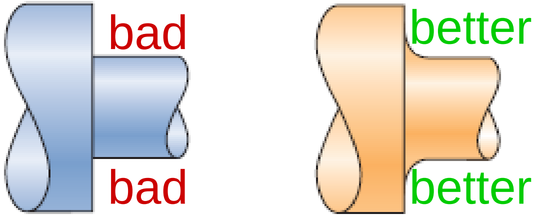
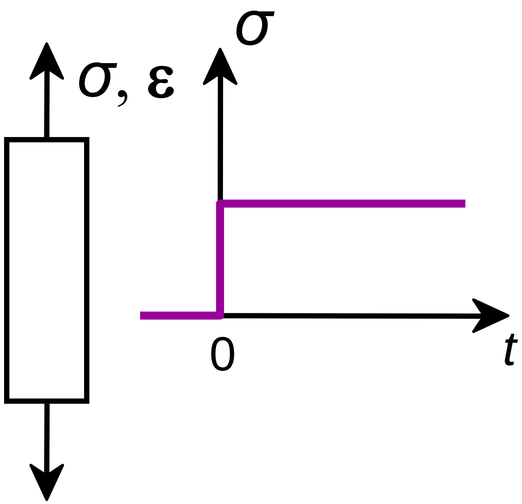
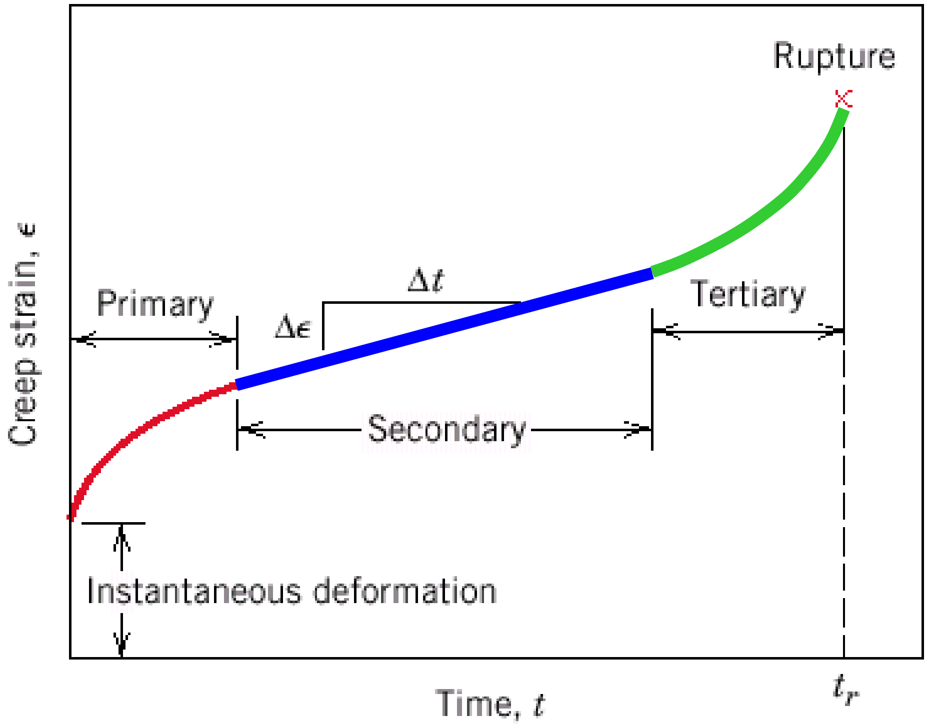


Fig. 10.26, *Callister & Rethwisch 9e.*

VI. Creep

Sample deformation at a constant stress (σ) vs. time





Adapted from
Fig. 10.29, *Callister & Rethwisch 9e.*

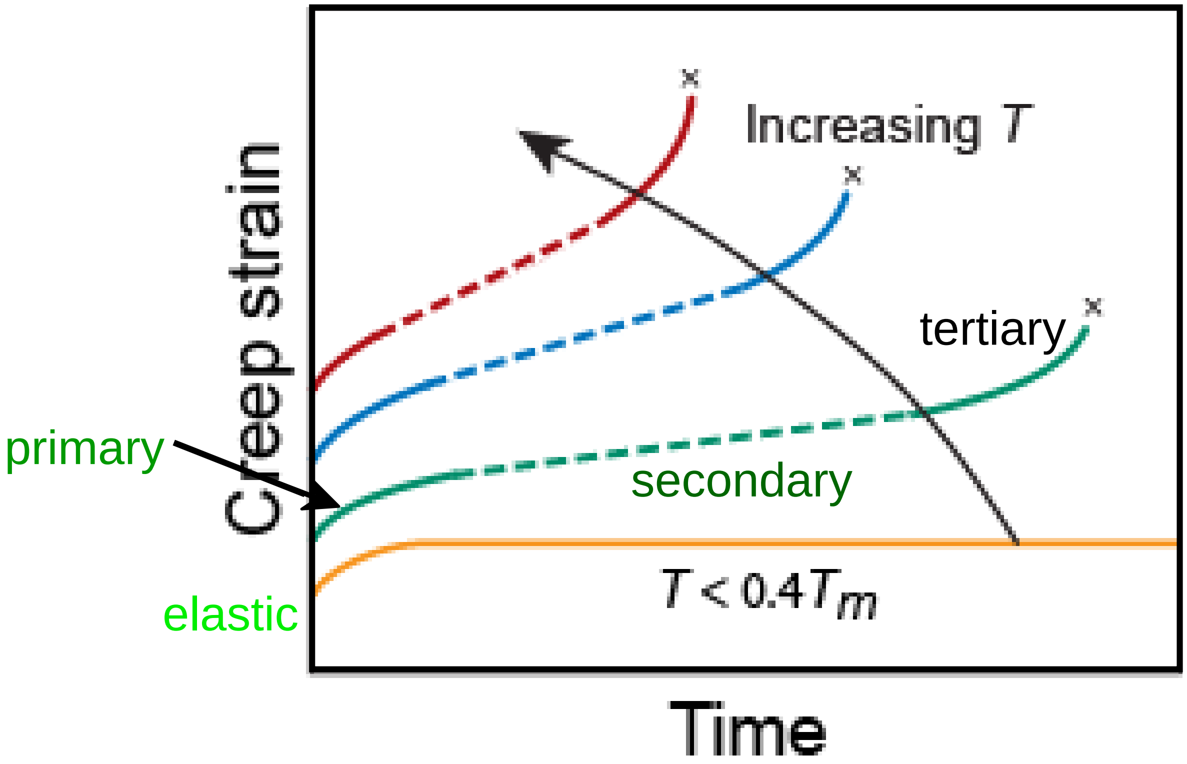
Primary Creep: slope (creep rate) decreases with time.

Secondary Creep: steady-state i.e., constant slope (Δ ε /Δ*t*).

Tertiary Creep: slope (creep rate) increases with time, i.e. acceleration of rate.

Creep: Temperature Dependence

- Occurs at elevated temperature, $T > 0.4\ T_m$ (in K)



Figs. 10.30, *Callister & Rethwisch 9e.*

Secondary Creep

- Strain rate is constant at a given T, σ
  - -- strain hardening is balanced by recovery

stress exponent (material parameter)

$$\dot{\varepsilon}_s = K_2\sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

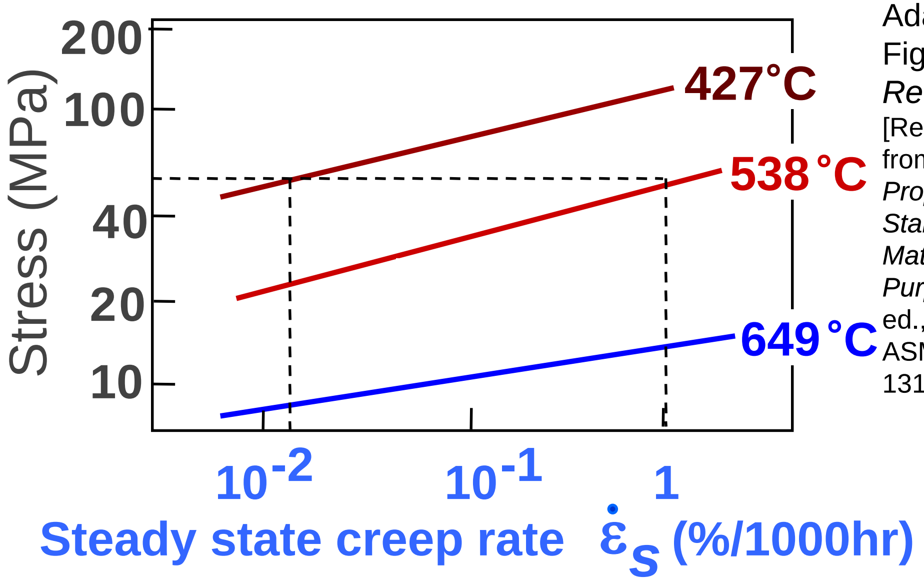
strain rate

material const.

applied stress

activation energy for creep (material parameter)

- Strain rate increases with increasing T, σ

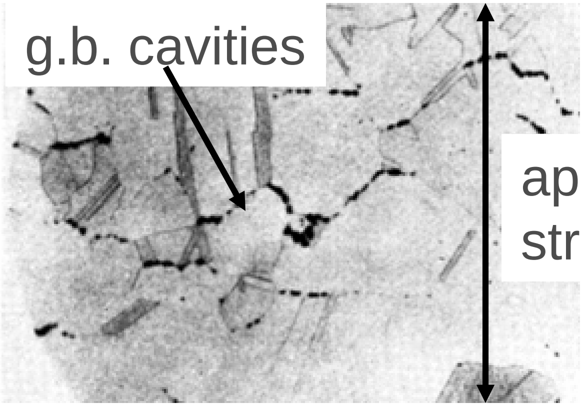


Adapted from Fig. 9.38, *Callister & Rethwisch 4e.* [Reprinted with permission from *Metals Handbook: Properties and Selection: Stainless Steels, Tool Materials, and Special Purpose Metals*, Vol. 3, 9th ed., D. Benjamin (Senior Ed.), ASM International, 1980, p. 131.]

Creep Failure

- Failure:

  along grain boundaries.



From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.32, p. 87, John Wiley and Sons, Inc., 1987. (Orig. source: Pergamon Press, Inc.)

- Time to rupture, t_r

$$T(20+\log t_r) = L$$

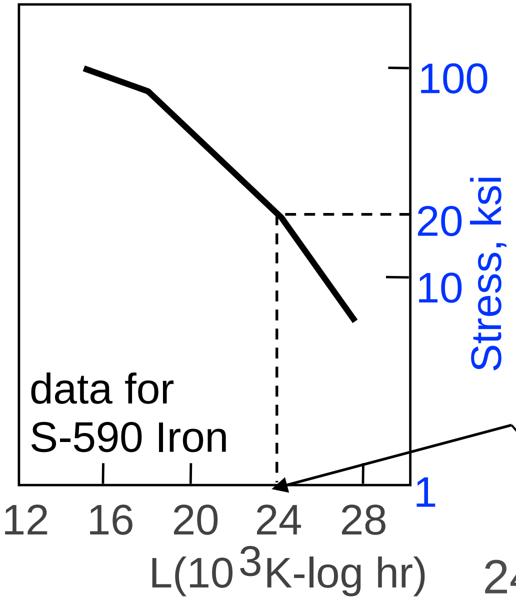
temperature

time to failure (rupture)

function of applied stress

- Estimate rupture time

  S-590 Iron, T = 800°C, σ = 20 ksi



Adapted from Fig. 8.32, *Callister 7e.* (Fig. 8.32 is from F.R. Larson and J. Miller, *Trans. ASME*, **74**, 765 (1952).)

24×10^3 K-log hr

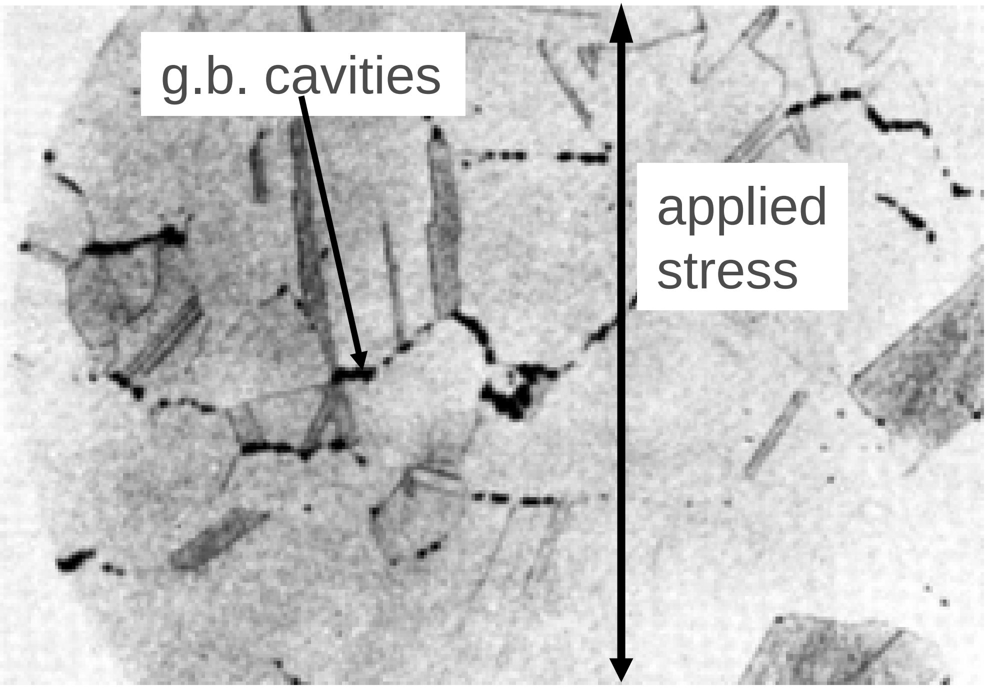
$$T(20+\log t_r) = L$$

1073K

Ans: t_r = 233 hr

Creep Failure

- Failure: along grain boundaries.

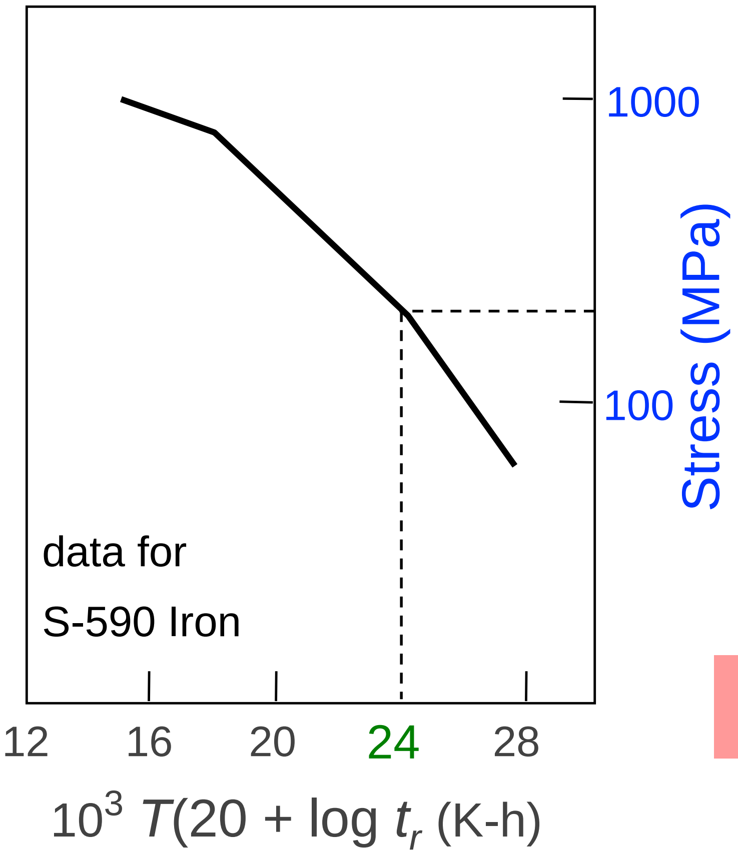


From V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.32, p. 87, John Wiley and Sons, Inc., 1987. (Orig. source: Pergamon Press, Inc.)

Prediction of Creep Rupture Lifetime

- Estimate rupture time

S-590 Iron, $T = 800°\text{ C}$, $\sigma = 140$ MPa



Adapted from Fig. 10.33, *Callister & Rethwisch 9e.* (From F.R. Larson and J. Miller, *Trans. ASME*, **74**, 765 (1952). Reprinted by permission of ASME)

Time to rupture, t_r

$$T(20 + \log t_r) = L$$

temperature

function of applied stress

time to failure (rupture)

$$(1073\text{ K})(20 + \log t_r) = 24\text{x}10^3$$

Ans: $t_r = 233$ hr

SUMMARY

- Engineering materials not as strong as predicted by theory
- Flaws act as stress concentrators that cause failure at stresses lower than theoretical values.
- **Sharp corners** produce large stress concentrations and premature failure.
- Failure type depends on T and σ :

-**For simple fracture** (noncyclic σ and $T < 0.4T_m$), failure stress decreases with:

  - increased maximum flaw size,
  - decreased T,
  - increased rate of loading.

- **For fatigue** (cyclic σ):

  - cycles to fail decreases as $\Delta\sigma$ increases.

- **For creep** ($T > 0.4T_m$):

  - time to rupture decreases as σ or T increases.