

# Chapter4

# Failure

강의명: 기계재료공학 (MFA9009)

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# Recap

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- Learned mechanical properties
- Uniaxial tension tests provides
  - Yield strength
  - Elastic modulus
  - Ultimate tensile strength
  - Ductility
  - **Toughness**
    - Area under the stress-strain curve
    - Energy required to break a material into two separate pieces.

# Objectives and outlines

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- Failure: occurs by three main mechanisms
  - Fracture
  - Fatigue
  - Creep
- Fractography
- Fracture (파고)
  - Brittle fracture
  - Ductile fracture
  - DBTT
  - Basic Fracture mechanics and application to design problems
- Fatigue (피로)
  - Failure under stress far below YS, TS; Cyclic loading
- Creep (크리프)
  - Time dependent permanent deformation

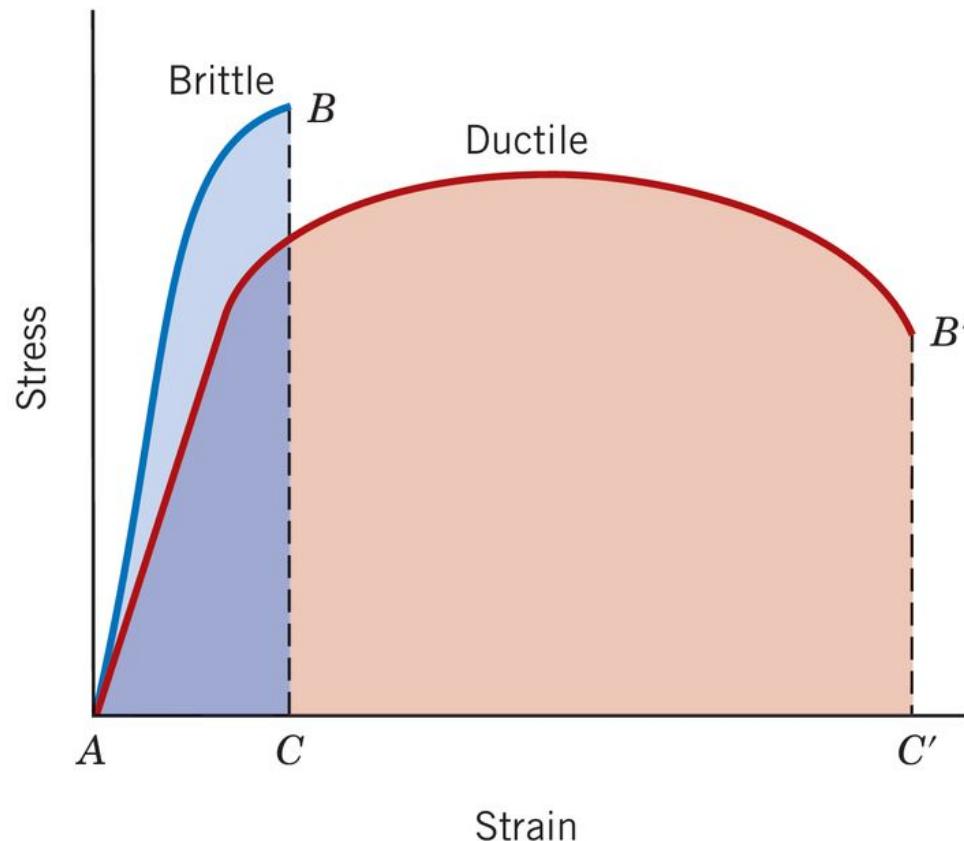
# Fundamentals of Fracture

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- Simple fracture is the separation of a body into two (or more) pieces; 정적인 힘이 가해져 발생하거나 혹은
  - Fatigue
  - Creep 에 의해서도 발생
  - Tensile, shear, 혹은 compression 모두 파괴로 이어질 수 있지만, 우리는 일축 인장에 한정하여 다루도록 한다.
- Two case of fracture
  - Ductile (연성 파괴)
  - Brittle (취성 파괴)
  - 재료의 '소성 가공성' 즉 얼마나 많은량의 소성 변형을 일으킬 수 있는지에 따라 바뀐다.
  - Note: 일축 인장시 %EL 그리고 %RA는 재료에 따라 다르다.

# Fundamentals of Fracture

- Ductile fracture: 상당히 높은 에너지를 흡수한 뒤에야 파괴
- Brittle fracture: 소성변형이 일어나지 않거나, 혹은 매우 제한적인 양으로.

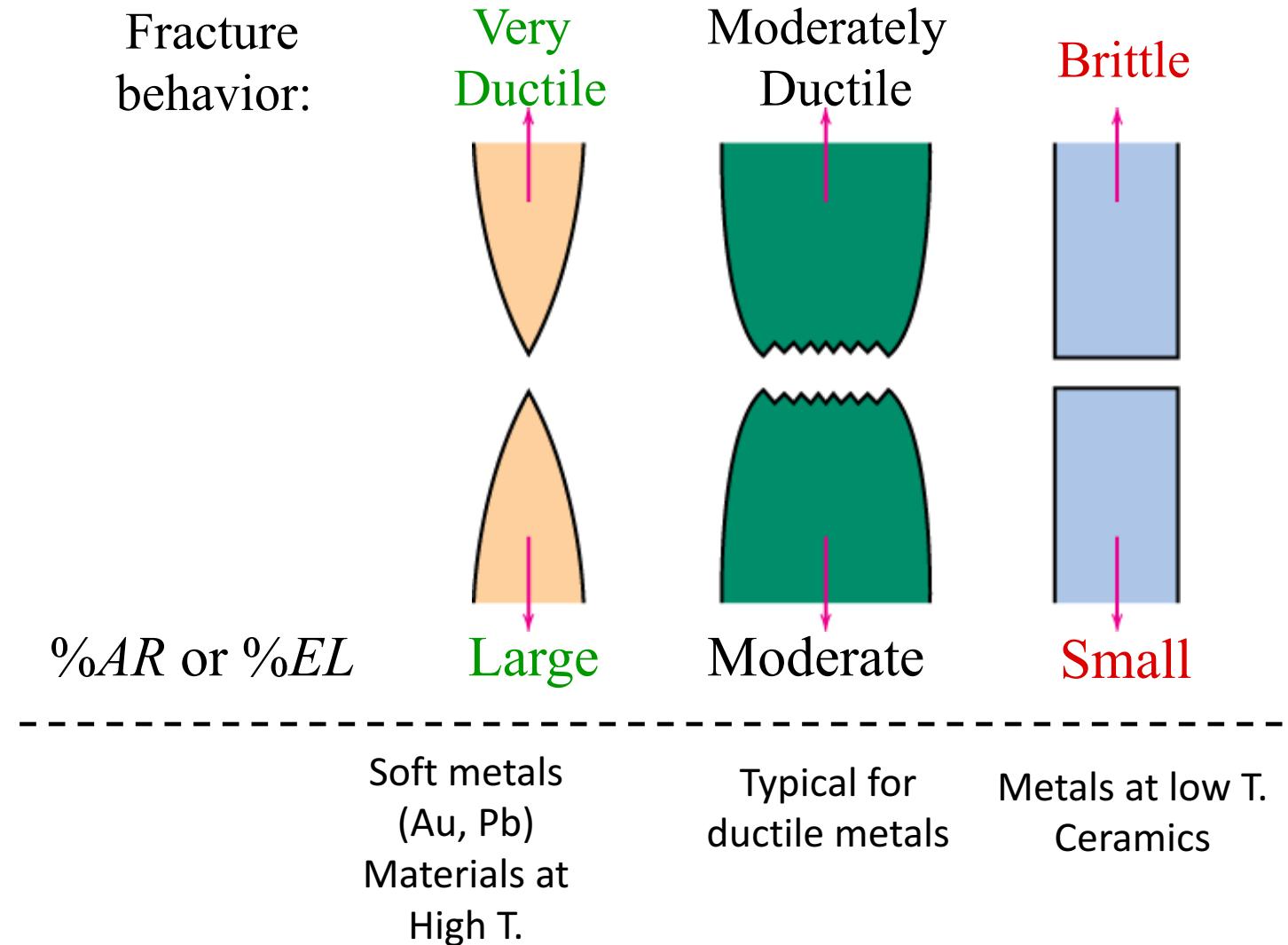


# Crack formation and propagation

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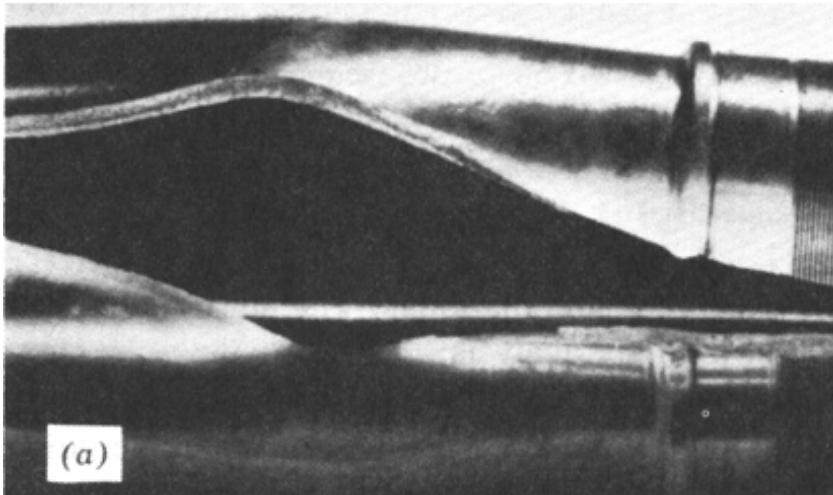
- 미시적으로 살펴보면 파괴는 두 단계로 이루어진다.
  - 1. 균열 (crack) 생성
  - 2. 균열의 전파 (propagation)
- The mode of fracture (파괴형태)는 균열의 전파 방식에 의해 결정
  - 균열이 천천히 진전; Stable; 이 경우 파괴 발생까지 상당한 소성변형량이 필요; No stress No propagation
  - 균열이 빠르게 진전; Unstable; Little plastic deformation; 작용 응력이 증가하지 않아도 진전 가능
- Q) Which type of fracture is preferred?
  - A) Ductile fracture; Because it ‘warns’ you.

# Ductile vs Brittle fracture

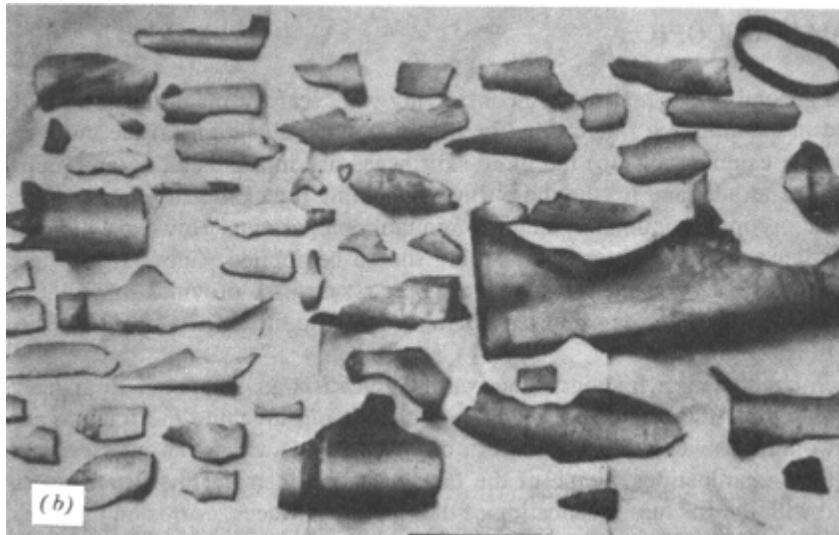


# Examples: pipe failures

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



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

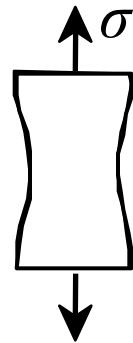


Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

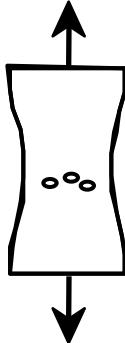
# Ductile fracture characteristics

- Failure Stages:

necking



void nucleation



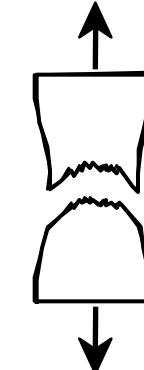
void growth and coalescence



shearing at surface



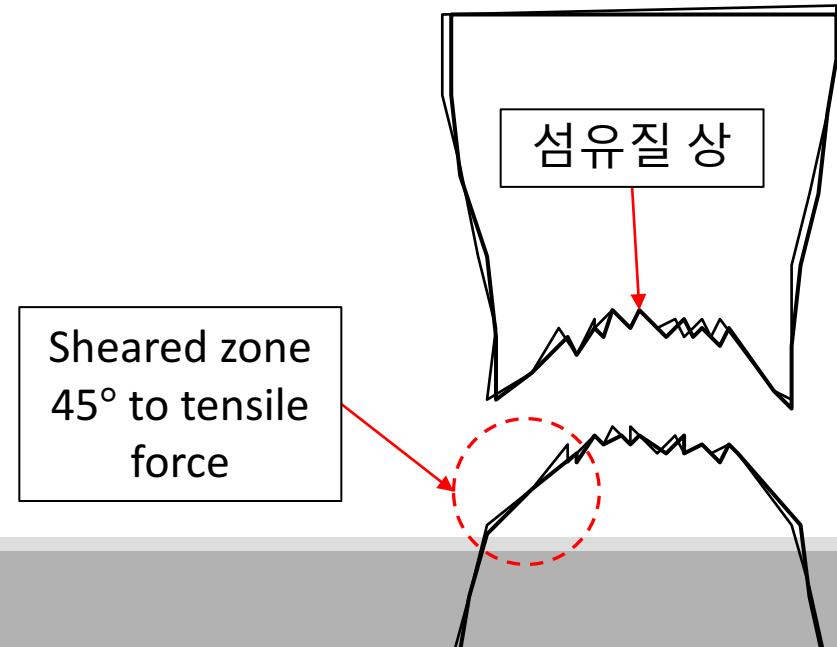
fracture



Cup and Cone  
(컵-원뿔 파괴)

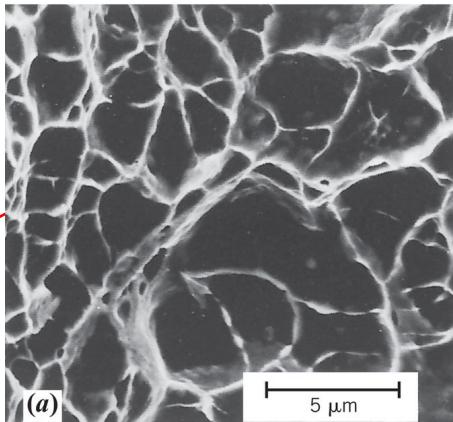
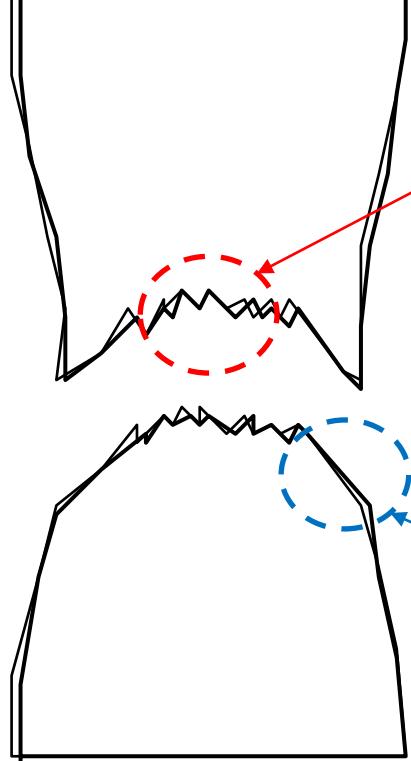


Sheared zone  
45° to tensile force

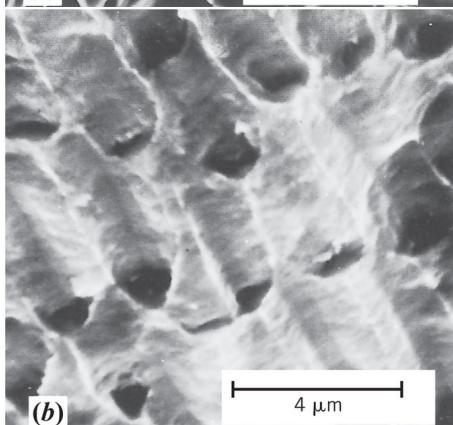


# Fractography (ductile fracture)

- Fractography (fracture+graph ; 파괴면 연구; 파괴사진학학)
  - 파괴의 단면으로, 파괴 형태, 응력 상태, 균열의 시작 위치 등 파악 가능
- SEM (scanning electron microscope)
  - 앞서 말한 ‘섬유질상’을 고배율로 살펴볼 수 있다.



Ductile fracture under  
'uniaxial tension'

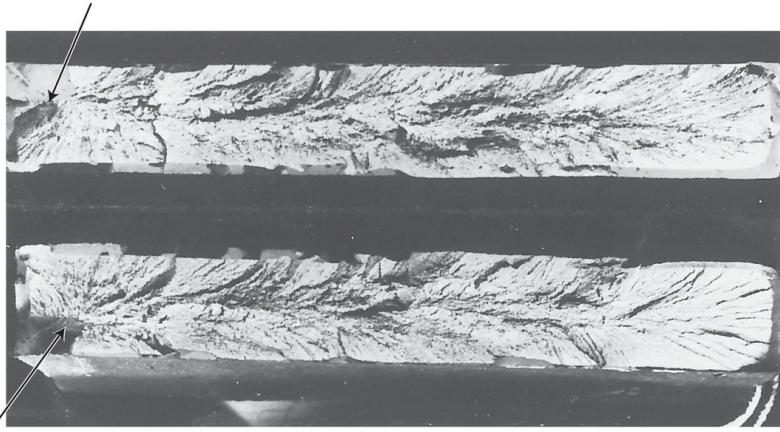


Ductile fracture under  
'shear'

한쪽으로  
늘어난 모양

# Fractography (brittle fracture)

Failure origin

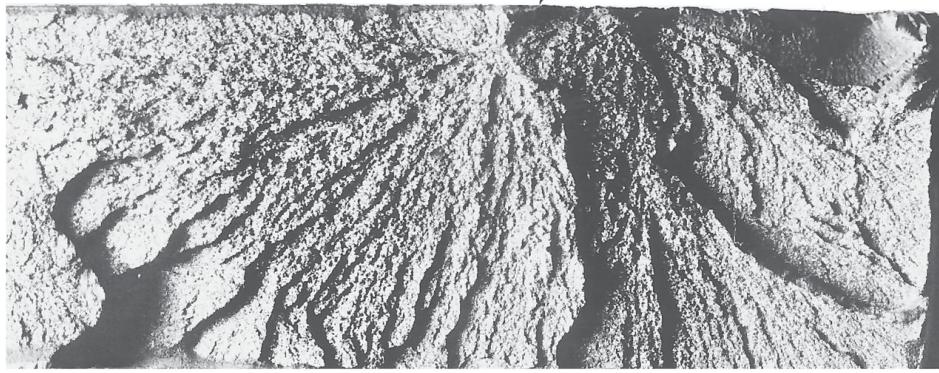


Failure origin

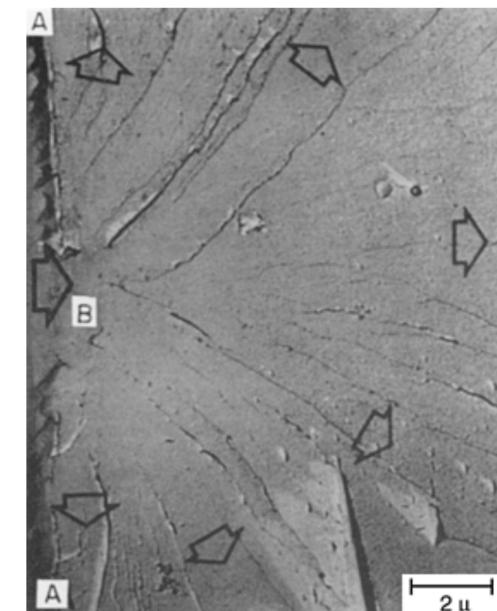
Failure origin

Chevron Marking: 쉐브론 표시  
(chevron: 갈매기 표기; 상사 계급표?)

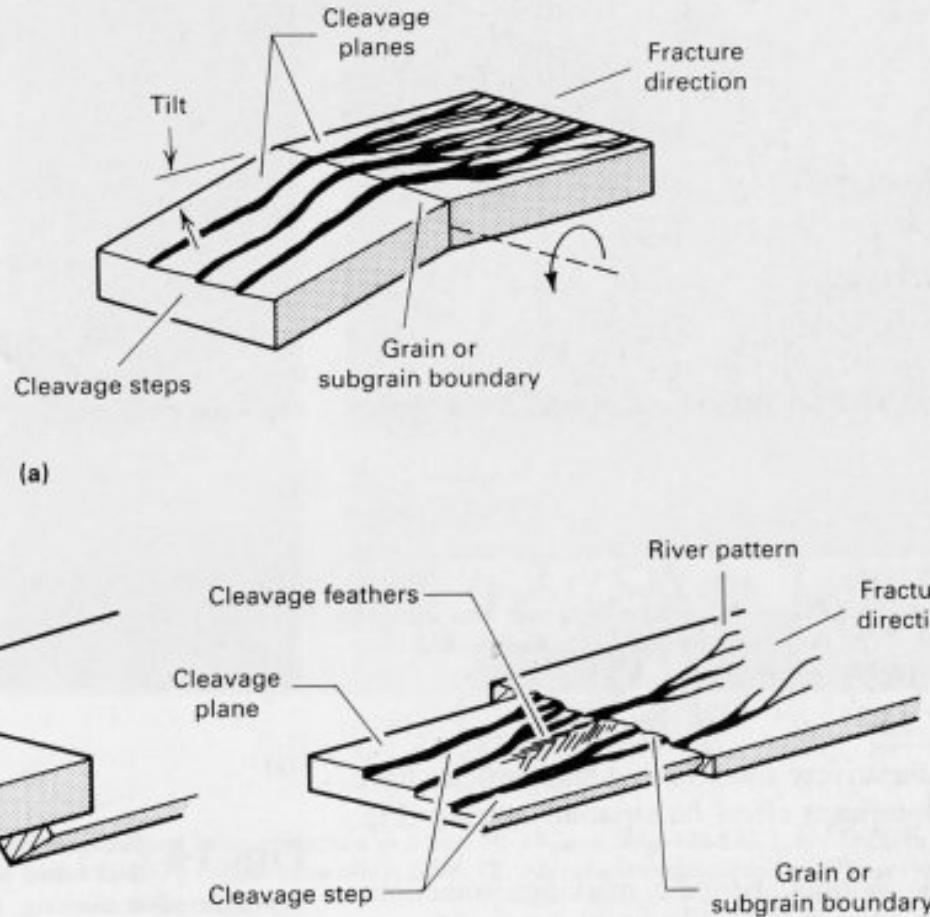
방사형, 부채꼴 형 (fan) 전파



(a) 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. (b) From D. J. Wulpi, Understanding How Components Fail, 1985. Reproduced by permission of ASM International, Materials Park, OH.

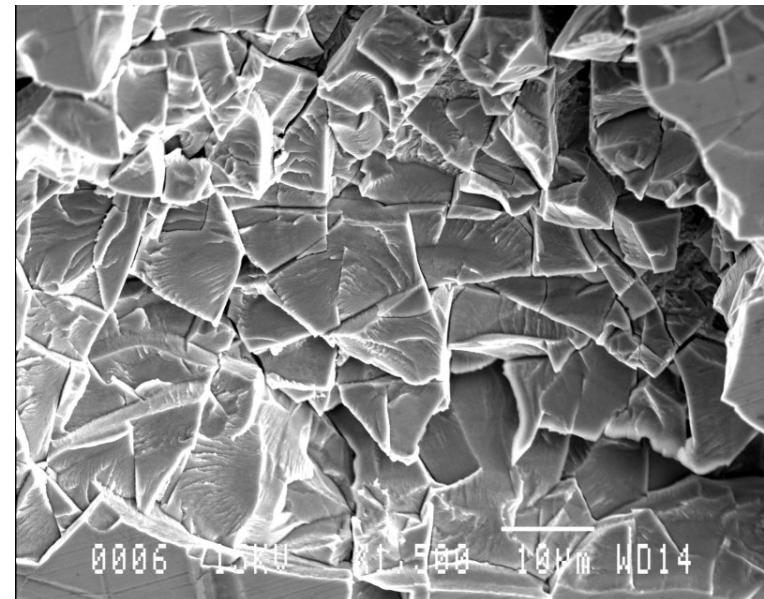


# Brittle fracture



# Brittle fracture

- 취성 파괴는 소성변형의 흔적이 거의 없다.
- Cleavage 파손 (fast fracture에서 보이는 특징; cleavage: sharp division)
  - 취성 결정 재료의 균열 전파는 특정 결정면 (crystal plane)을 따라 발생.
  - 따라서 grain을 가로질러 균열이 전파 따라서 transgranular 즉, 결정립 내부를 ‘관통’
  - Grainy (알갱이가 보이는 형상), 혹은 faceted texture; (facet: 깎은 면)



Cleavage on intersecting {100} planes in bcc Cr.

# Transgranular and Intergranular

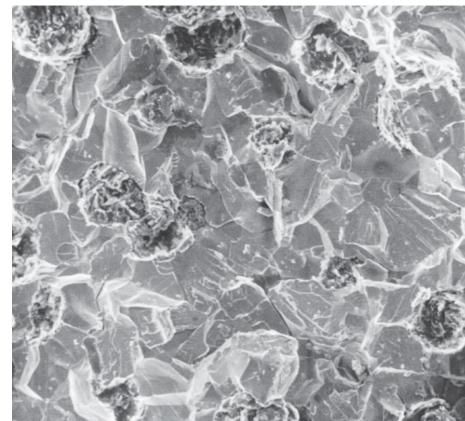
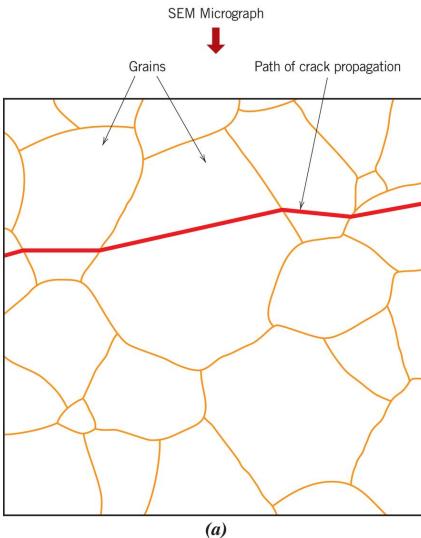
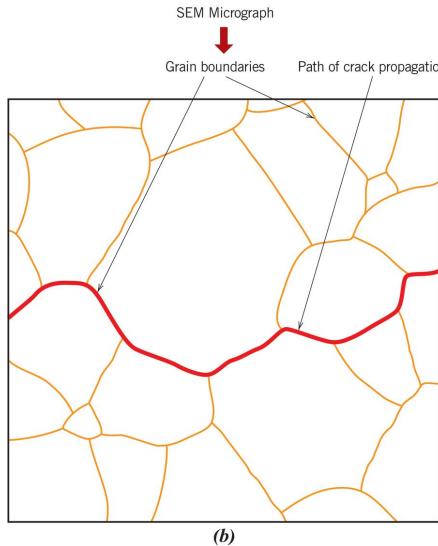


Figure (b) from V. J. Colangelo and F. A. Heiser, Analysis of Metallurgical Failures, 2nd edition. Copyright © 1987 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

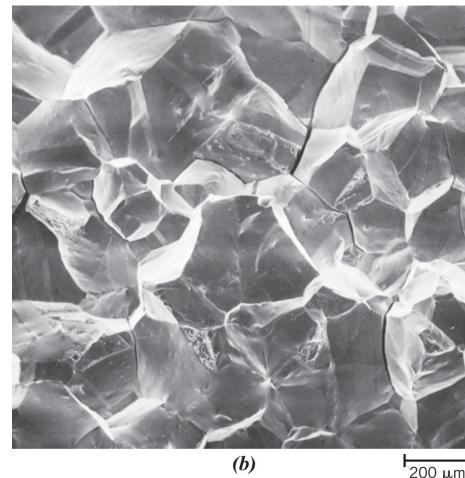


Figure (b) reproduced with permission from ASM Handbook, Vol. 12, Fractography, ASM International, Materials Park, OH, 1987.

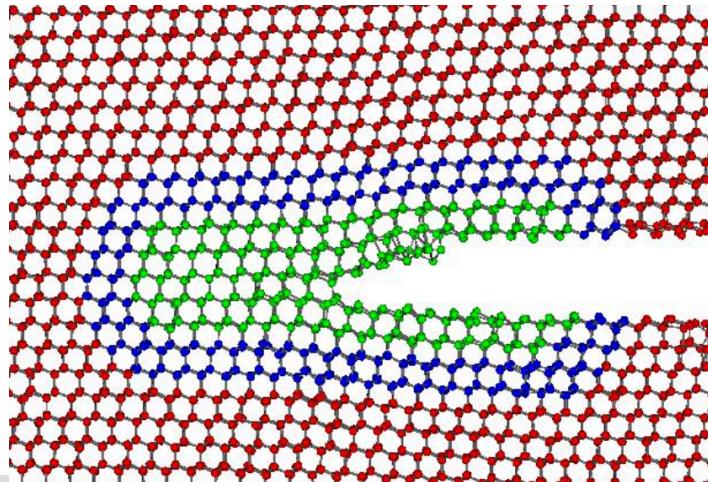
# Principles of Fracture Mechanics

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- Fracture Mechanics; 재료 파괴 역학;
- 재료에 결함(flaw)이 존재함을 가정. 재료 성질, 가해진 응력의 크기, 균열을 초래할 수 있는 결함의 존재 및 균열 전파 기구 사이의 관계를 '정량화' 하는 학문
- 설계 엔지니어는 구조물이 파괴에 대해 얼마나 정량적인 저항력이 있는지 알아야 한다.
- 학부생으로써, 이미 정립이 되어있는 관계식들을 살펴보고, 이를 활용하는 법을 살피는데 주력하자.

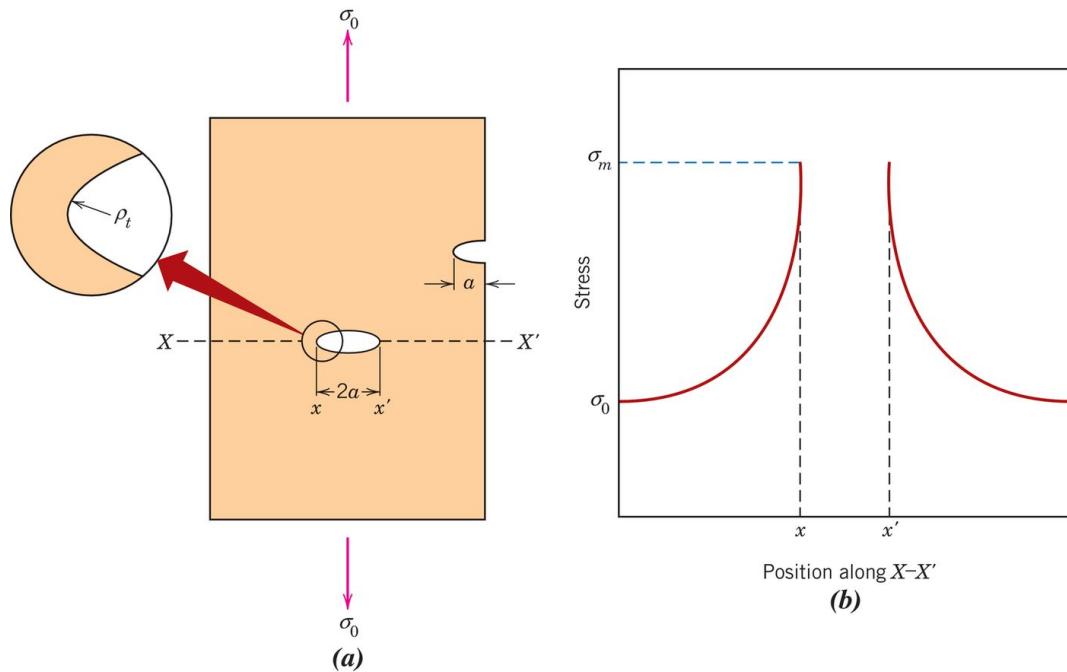
# Stress raiser 응력집중(인)자

- Fracture strength(파괴 강도; 즉 파괴가 일어나기 위해 필요한 응력)는 원자들간의 응집력과 관계 있다.
  - 이론적 추정치:  $\sim 0.1 \text{ E}$
  - 실험치:  $0.01 \text{ E} \sim 0.0001 \text{ E}$
- 위와 같이 원자 응집력(혹은 원자 결합 에너지)을 바탕으로 예상한 fracture strength는 실험치와 큰 차이가 있다 – 이는 이론적 추정치에는 물질 내외부의 flaw를 고려하지 않았기 때문이다.
- 실제로 이러한 microscopic flaw들의 주위에는 응력이 증폭 (amplified) 된다. 이러한 응력 증폭을 일으키는 voids, notches, surface scratches 등을 통틀어 stress-raiser 라고 부른다.



# Stress concentration (응력집중)

전술한바와 같이 응력은 void등의 defect 주위에서 '증폭' 된다. 이를 '응력집중' 이라 하는데, 그 정량적 크기는 defect의 기하학적 특성(ex. Void의 방위, 크기, 모양)에 영향을 받는다.



For a long crack oriented perpendicular to the applied stress, the maximum stress near the crack tip:

$$\sigma_m = 2\sigma_0 \left(\frac{a}{\rho_t}\right)^{0.5} \quad \text{where } \sigma_0: \text{(engineering) applied stress}$$

$a$ : 표면 균열 길이; half-length of crack (길수록  $\sigma_m$  상승)

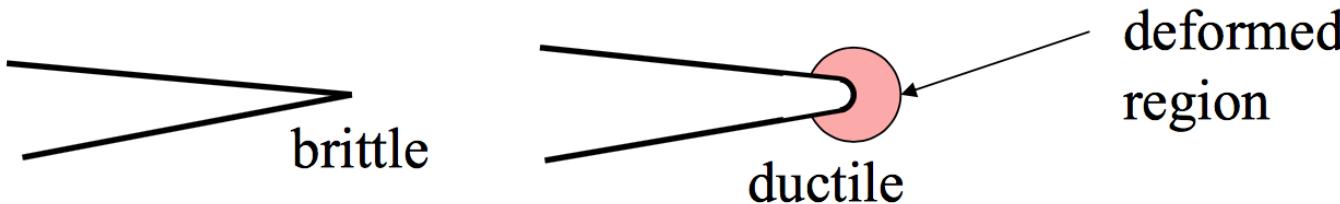
$\rho_t$ : 균열 첨단부(tip)의 곡률반경(radius of curvature)

(곡률이 완만할 수록, 곡률 반경이 클수록  $\sigma_m$  감소)

# Stress concentration factor

- 응력집중의 결과:  $\sigma_m > \sigma_0$  thus  $\frac{\sigma_m}{\sigma_0} \gg 1$
- 응력집중도(균열에 의해 외부의 응력이 집중되는 정도)를 응력 집중 계수(stress concentration factor  $K_t$ )로 표현하기도.
- $K_t = \frac{\sigma_m}{\sigma_0}$  앞서 소개된 Eq. 10.1을 통해  $K_t = 2 \left( \frac{a}{\rho_t} \right)^2$

In ductile materials, plastic deformation at a crack tip  
“blunts” the crack.



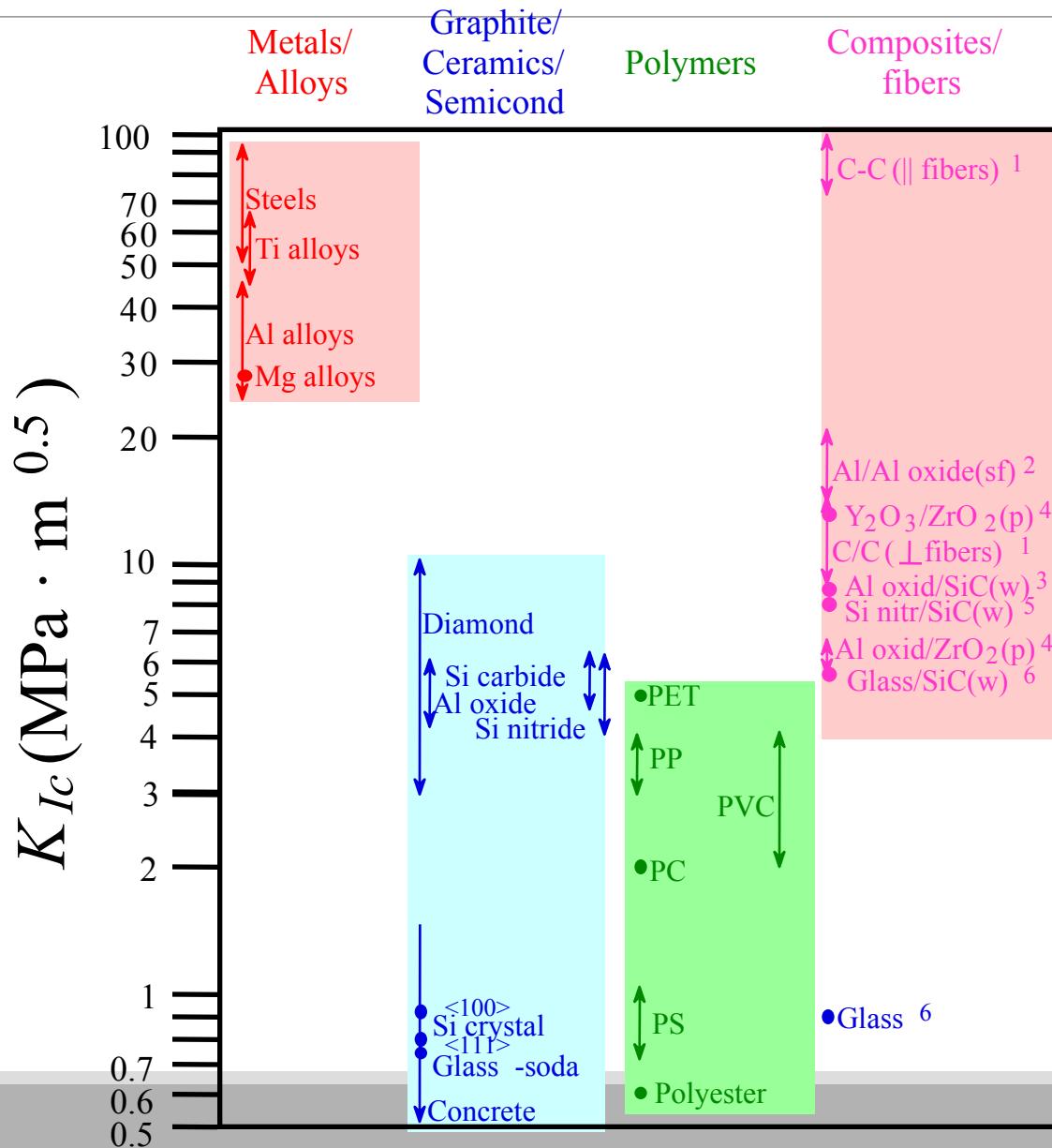
일반적으로 취성 재료가 응력상승에 더욱 취약하다. 연성 재료의 경우,  $\sigma_m$  가 증가하다 소성변형이 발생 (즉 crack tip 부근의 변형으로 인해 sharpness가 무뎌진다)

# Crack propagation

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- Elastic strain energy:
  - Energy stored in material as it is elastically deformed.
  - This energy is released (thus reduced) when the crack propagates (yes, the natural way)
  - When crack propagates, the number of atoms not fully connected with their neighbors increases. That means, the new 'surface' is created. Creation of incompletely connected atoms (surface) requires energy.
- Critical stress for crack propagation
$$\sigma_c = \left( \frac{2E\gamma_s}{\pi a} \right)^{0.5}$$
 (Griffith's criterion; applicable for elastic materials)  
where  $E$ : elastic modulus;  $\gamma_s$ : specific surface energy
- For ductile materials  $\gamma_s$  in the above is replaced by  $\gamma_s + \gamma_p$  ( $\gamma_p$ : plastic deformation energy)
- Apply the above eq. to Example 10.1

# Fracture Toughness Ranges



Based on data in Table B.5,  
*Callister & Rethwisch 9e*.

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.

# Crack growth condition

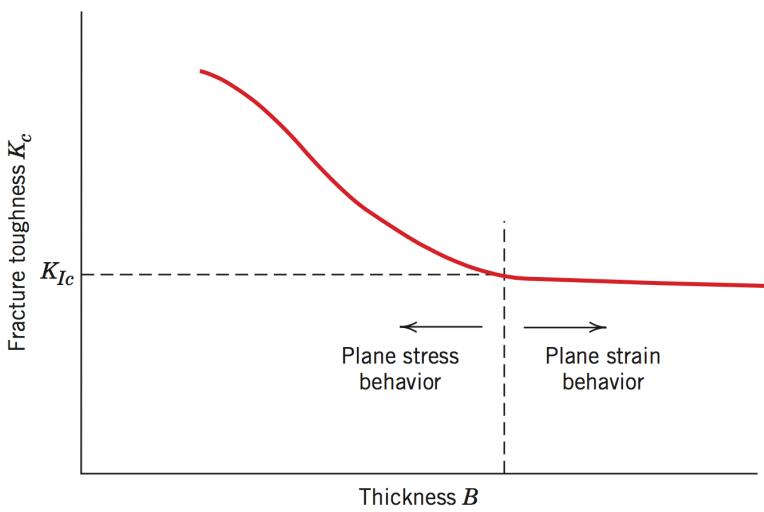
- 균열 전파에 대한 임계應력( $\sigma_c$ )과 균열 길이의 관계가 'Stress Intensity Factor'로 설명된다.

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

Where  $K_c$ : 파괴 인성 (fracture toughness); 균열 존재시 취성 파괴에 대한 재료의 저항정도

$Y$ : 균열 크기, 시편의 크기, 기하학적 형상, 하중 적용 방식 등에 의존하는 parameter

- For plates, or thin specimens,  $K_c$  depends on the thickness.

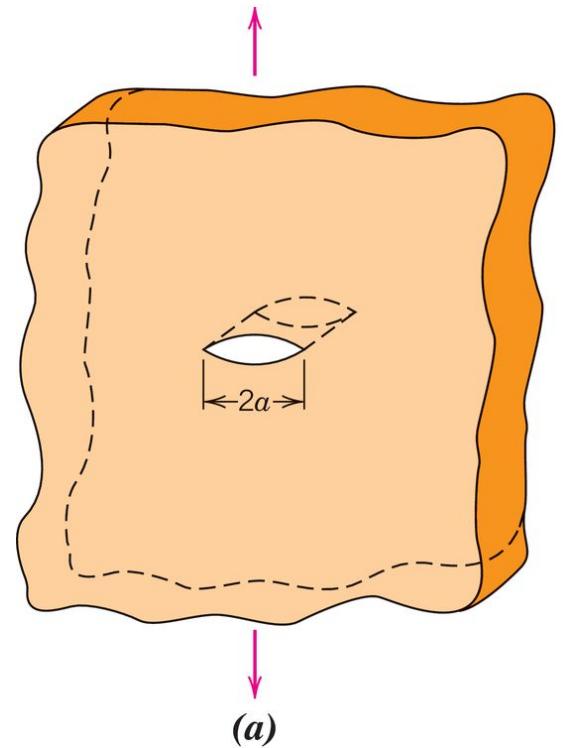


시편의 두께가 시편 전체 형상에 비해 충분히 두꺼울 때, 평면 변형률 조건(plane-strain condition)을 이룬다. 이 때의  $K_c$  값을 특별히  $K_{Ic}$ (평면 변형률 파괴 인성)라 한다.

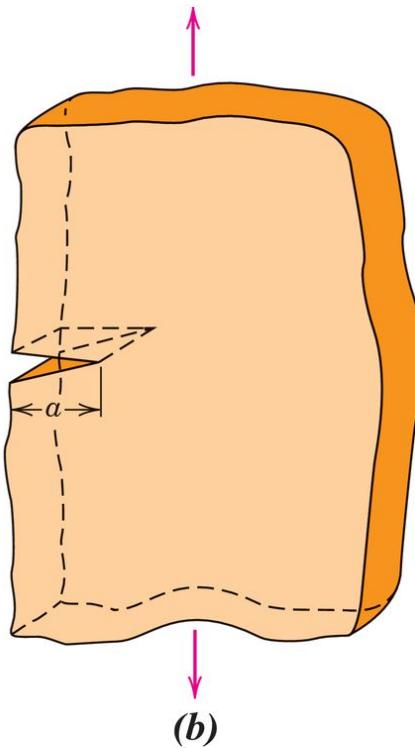
Subscript 'I'는 실제로 관련된 균열면 변위 형태를 이룬다(그림 10.10 참고)

$$K_{Ic} = Y \sigma_c \sqrt{\pi a}$$

# Plane-strain condition

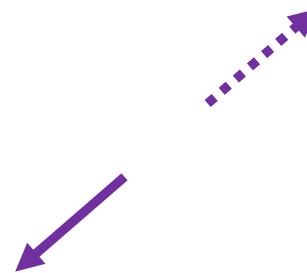


An interior crack in a plate of infinite width



Edge crack in a plate of semi-infinite width

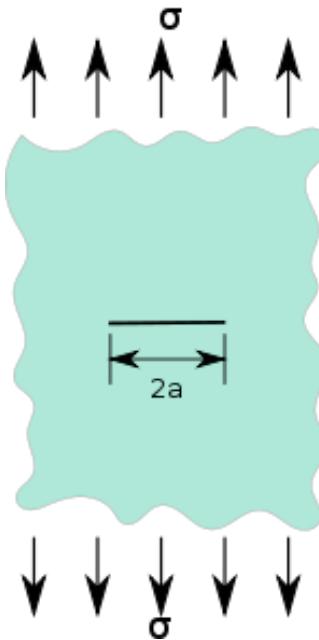
원편의 시편과 같이 충분히 두꺼운 재료에 in-plane uniaxial tension 상태를 가하면 두께방향으로 거의 strain이 없는 상태.



이를 plane-strain condition이라 한다.

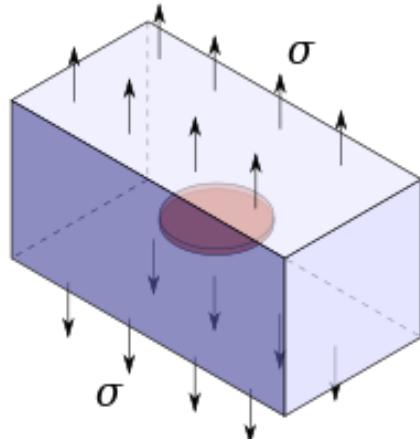
**Y**값은 균열 크기, 시편의 크기 및 기하학적 형상과 하중 적용 방식에 따라 달라진다.  
(a)  $Y=1$  (b)  $Y \approx 1.1$

# Y values under various conditions

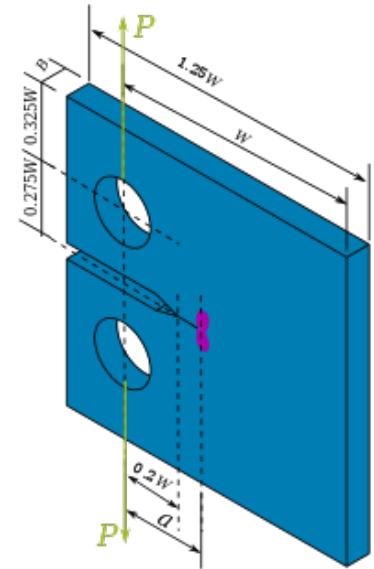


$$K_I = \sigma \sqrt{\pi a}$$

$$K_I = 2\sigma \sqrt{a/\pi} = \left(\frac{2}{\pi}\right) \sigma \sqrt{\pi a}$$

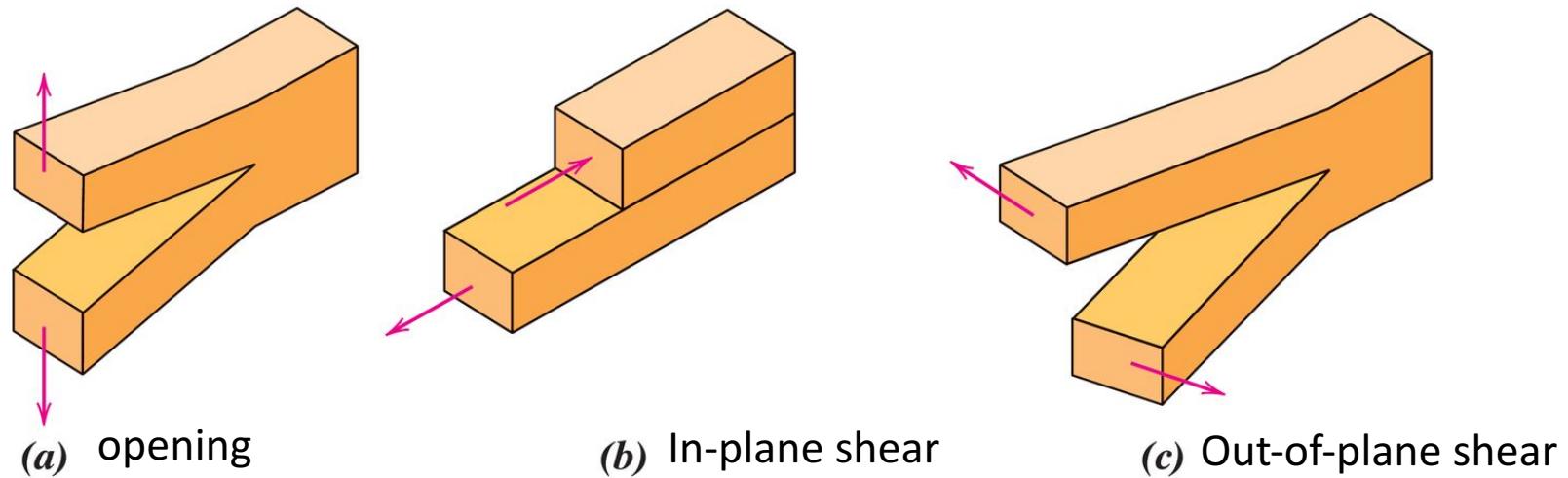


Complex example



$$\begin{aligned} K_I &= \frac{P}{B} \sqrt{\frac{\pi}{W}} \left[ 16.7 \left( \frac{a}{W} \right)^{\frac{1}{2}} - 104.7 \left( \frac{a}{W} \right)^{\frac{3}{2}} \right. \\ &\quad \left. + 369.9 \left( \frac{a}{W} \right)^{\frac{5}{2}} \dots \right] \end{aligned}$$

# Crack surface displacement modes



The three modes of crack surface (균열 표면) displacement (변위).

# 파괴 역학을 이용한 설계

- 구조물의 파괴 가능성을 진단/검사하기 위해서는 앞서 살펴본 파괴 인성 파라미터를 이용할 수 있다.
  - $K_{Ic} = Y\sigma\sqrt{\pi a}$  (평면 변형률 조건에서의 파괴 인성)
- 주어진 구조물과 기대되는 응력상태로 인해  $\gamma$  값이 알려져 있다면 파괴 인성( $K_{Ic}$ )은 구조물에 가해진 응력( $\sigma$ ), 균열 길이( $a$ )와 관련있다. 이 세 파라미터들 중, 실제 적용에 제약을 받는지, 혹은 설계 통제를 받을지를 결정할 수 있어야 한다. 세 파라미터들 중 두 개가 정해지면 나머지는 위의 공식을 통해 구할 수 있다.
- 예를 들어 만들고자 하는 구조물의 파괴는 구조물에 기대되는 응력과 구조물의 재료내의 균열 길이를 통해 예상할 수 있다.

# Design Against Crack Growth

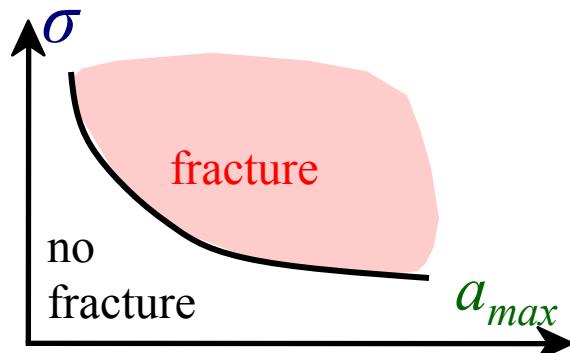
- Crack growth condition:

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

- Largest, most highly stressed cracks grow first!

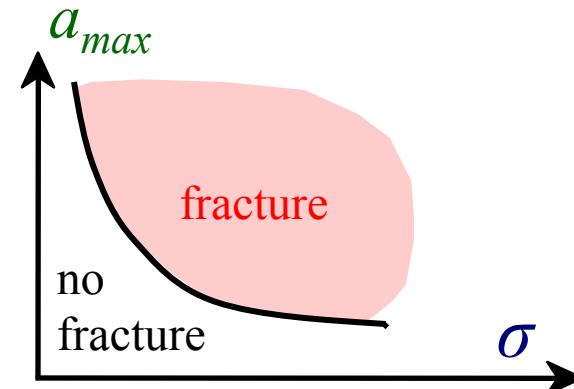
- 결함의 크기와 파괴 인성을 알 때, 허용되는 design stress의 범위를 아래와 같이 표현

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

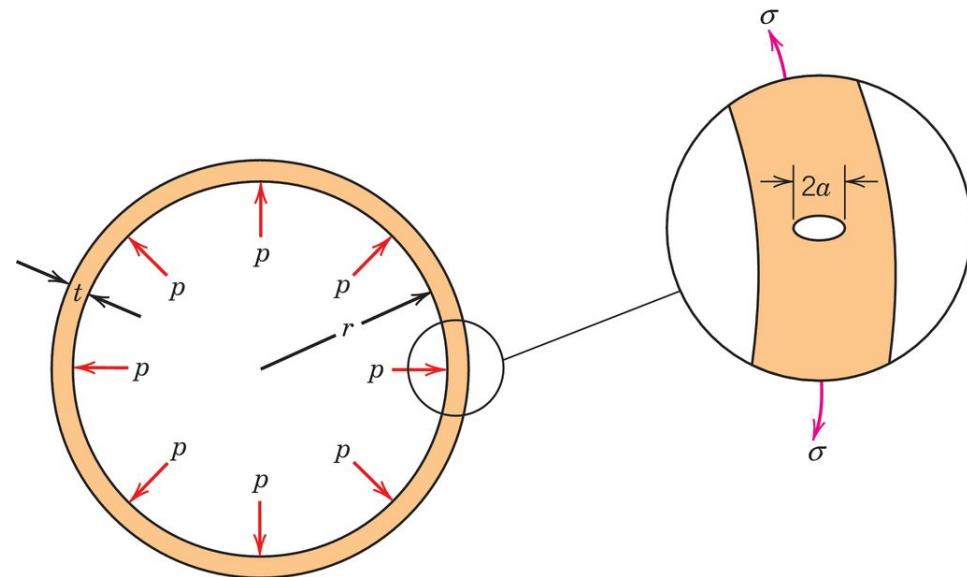


- 구조물의 허용되는(예상되는) design stress와 파괴 인성을 알 때, 허용되는 결함의 크기를 표현 아래와 같이 표현 가능.

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



# Example 10.1(a)



벽의 두께가  $t$ , 반지름이  $r$ 인 구형 (sphere)의 내부에  $p$  압력이 존재. 이로 인해, 파이프의 원주방향으로  $\sigma$  만큼의 인장력이 가해지고 있다.

해당 조건에서 plane-strain condition을 가정 – Eq. 10.5 혹은 Eq. 10.6 Eq. 10.7

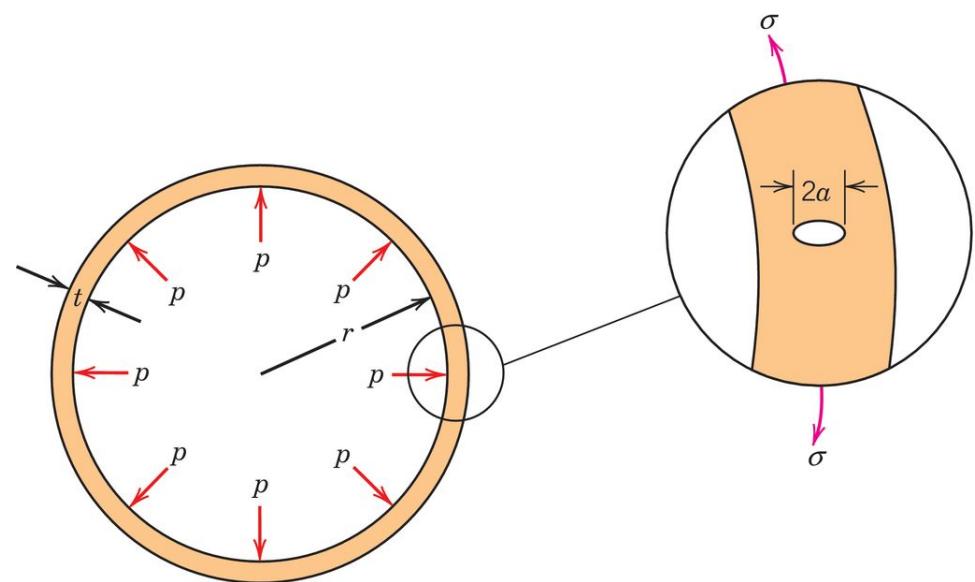
설계조건 1: 해당 탱크의 균열이 생성되어 **파손이 빠르게 진전되기 전에 항복이 일어나도록 설계한다.** 항복이 발생하면 급격한 파손이 일어나기 전에 소성 변형이 일어나 탱크 내부의 압력을 어느정도 나춰주는 효과 (소성변형으로 탱크모양 변화->탱크내부 부피 증가). 주어진 조건에서 제시하는 설계조건을 따라 항복을 발생을 유발하려면 어떤 재료를 사용해야 할까?

결과적으로 파괴가 발생할때의 균열크기 ( $a_c$ )가 커야된다 – Eq. 10.7사용;  $\gamma$ 는 고정

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

따라서 해당 설계법에 따르면  $\frac{K_{Ic}}{\sigma}$  값이 작은 재료가 선호된다.

# Example 10.1(b)



설계조건 2: 우리가 살펴볼 또 다른 설계 조건은, 파단전 누설 (leak-before-break) 원리를 따른다. 파이프의 전체 구조물이 break가 될 만큼의 빠른 균열 성장이 일어나기 전에 용기 벽 두께를 조절하여 균열 성장에 대한 여유를 준다. 균열이 매우 작으면 안정. 역설적이게도 하나의 균열이 벽의 두께와 동일한 길이를 가진다면 해당 부위에 균열 전파로 인해 탱크에 '구멍' -> 탱크 전체가 파손이 되지 않고 leak -> 내부 압력 감소 효과 및 catastrophic failure 방지; 이를 통해 최대로 허용되는 탱크내의 압력값(p)을 구해보자.

결과적으로 균열크기의 크기가  $t$ 와 같을 때 해당 조건을 만족한다. 이를 Eq. 10.5 대입하면

$$K_{Ic} = Y\sigma\sqrt{\pi t} \quad \text{Eq. (a)}$$

해당 구형 압력 탱크의 작용 응력( $\sigma$ )은 탱크내의 압력 ( $p$ ), 반지름( $r$ ), 두께( $t$ )와 연관되어 있다.

$$\sigma = \frac{pr}{2t} \quad \text{Eq. (b)}$$

그리고 해당 설계조건상에서 탱크는 항복이 일어나지 않아야 하므로, 응력을 항복 강도로 치환하여  $\sigma_Y = \frac{pr}{2t}$ ,

$$\text{즉 } t = \frac{pr}{2\sigma_Y}$$

해당 식을 Eq. (a)에 대입하여 정리하면

$$K_{Ic} = Y\sigma_Y \sqrt{\frac{\pi pr}{2\sigma_Y}} = Y \sqrt{\frac{\pi pr\sigma_Y}{2}} \rightarrow \left(\frac{K_{Ic}}{Y}\right)^2 = \frac{\pi pr\sigma_Y}{2}$$

이를 압력에 대해 정리하면

$$p = 2 \left(\frac{K_{Ic}}{Y}\right)^2 / (\pi r \sigma_Y)$$

다시 정리하자면

$$p = \left(\frac{K_{Ic}^2}{\sigma_Y}\right) \frac{2}{\pi r Y}$$

$r, Y$  등은 변수가 아니므로,  $\frac{K_{Ic}^2}{\sigma_Y}$  값이 높을 수록 견딜 수 있는 압력이 커진다.

# 예제: Aircraft Wing

- Material has  $K_{Ic} = 26 \text{ [MPa} \cdot \text{m}^{1/2}\text{]}$
- Two designs to consider...

Design A

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

- Use...

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

Design B

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

- Key point: *Y and  $K_{Ic}$  are the same for both designs (same material, same geometry, same type of stress).*

--Result:

$$\frac{K_{Ic}}{Y\sqrt{\pi}} = \sigma\sqrt{a} = \text{constant}$$

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

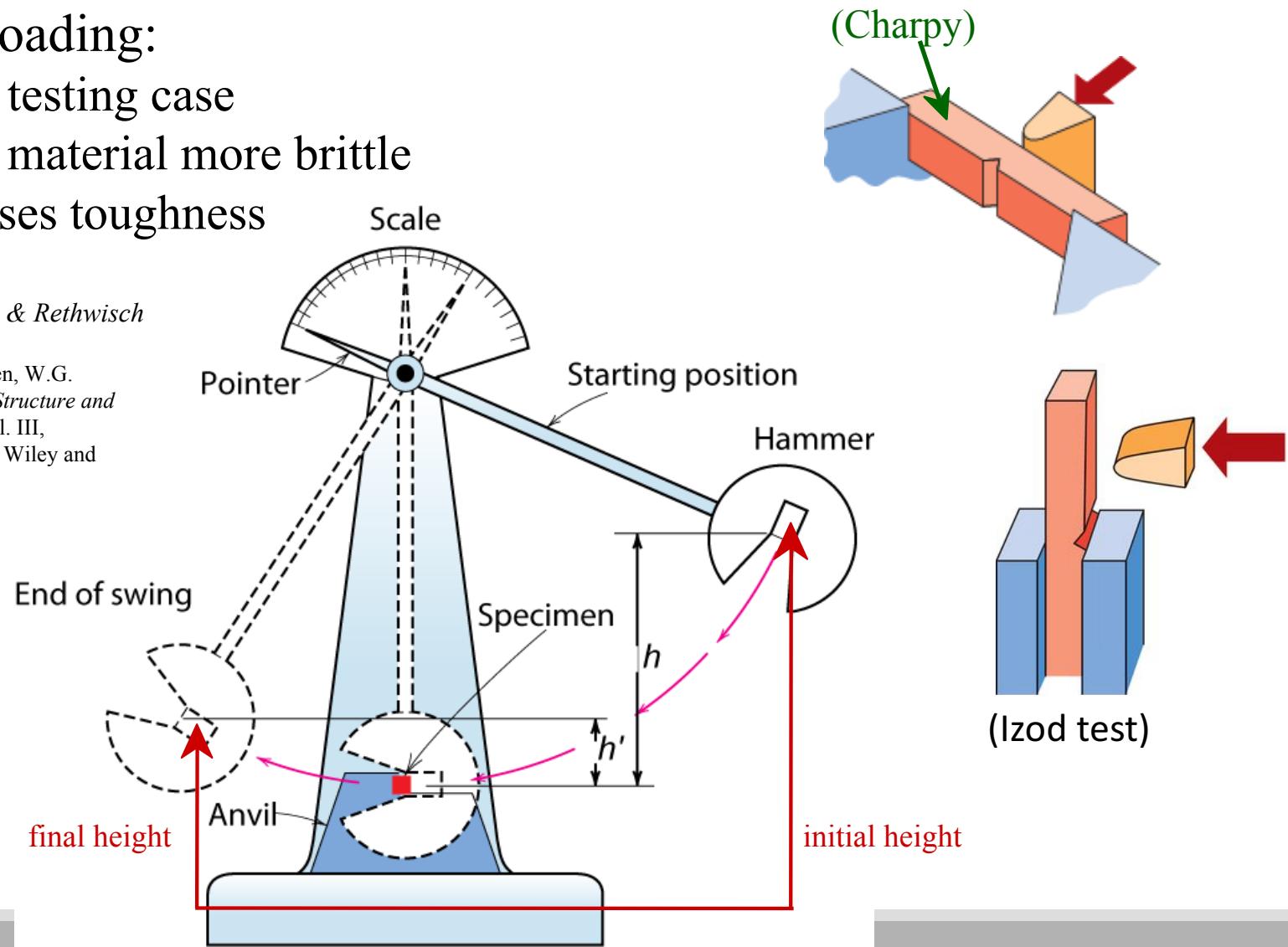
Answer:  $(\sigma_c)_B = 168 \text{ MPa}$

# Impact Testing: $K_{Ic}$ 의 정성적(qualitative) 측정

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

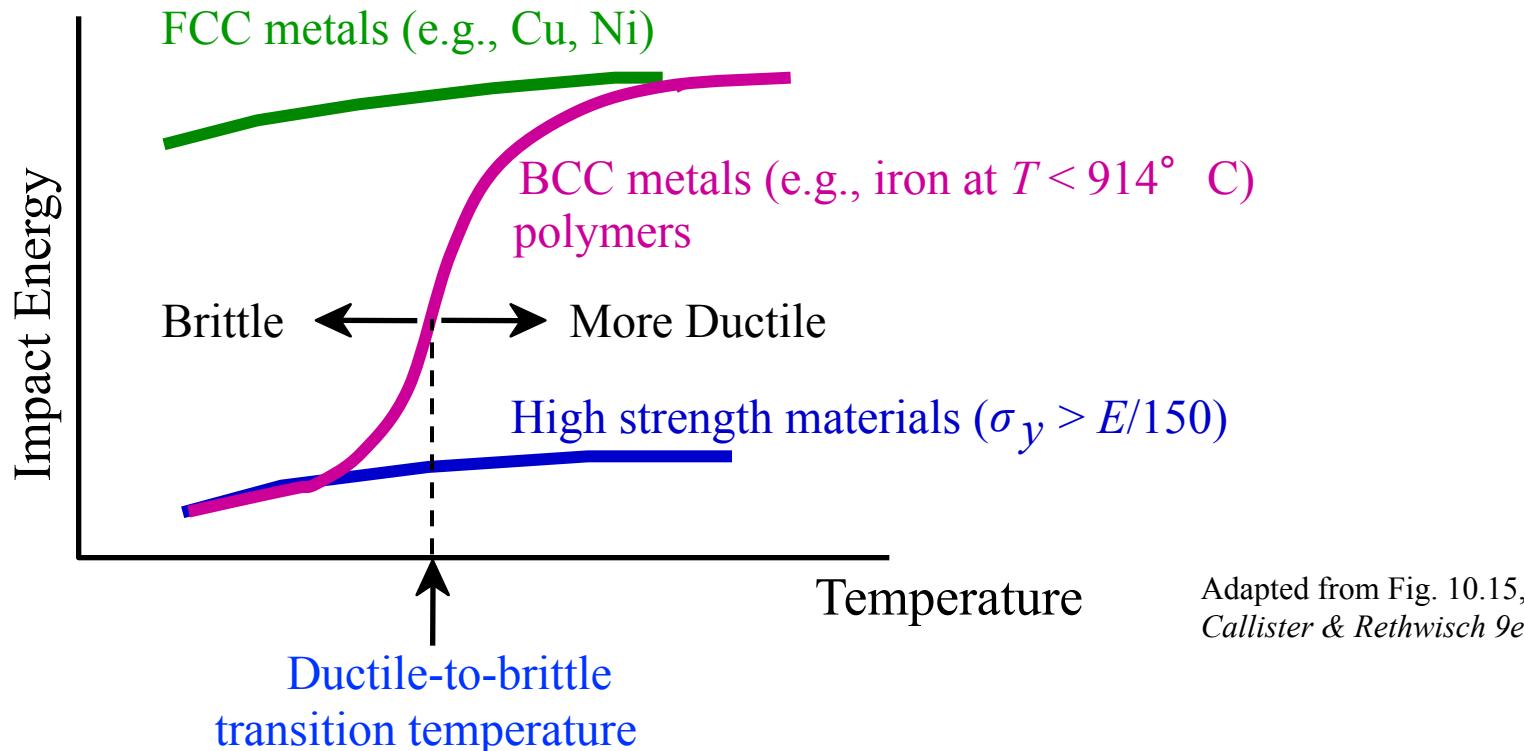
Fig. 10.12(b), Callister & Rethwisch  
9e.

(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.)



# Influence of Temperature on Impact Energy

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



Main application of Charpy/Izod tests: to see if DBT happens.

You can tell at which temp the brittle fracture would occur.

# CVN and DBTT

- CVN: Charpy + V-Notch – 즉 V 모양의 notch가 있는 시편 대상의 Charpy 실험

-59

-12

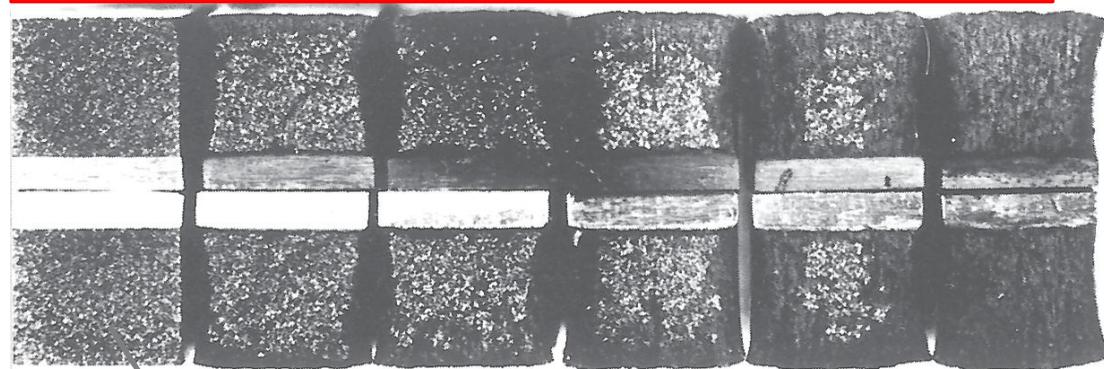
4

16

24

79

→ 실험 온도

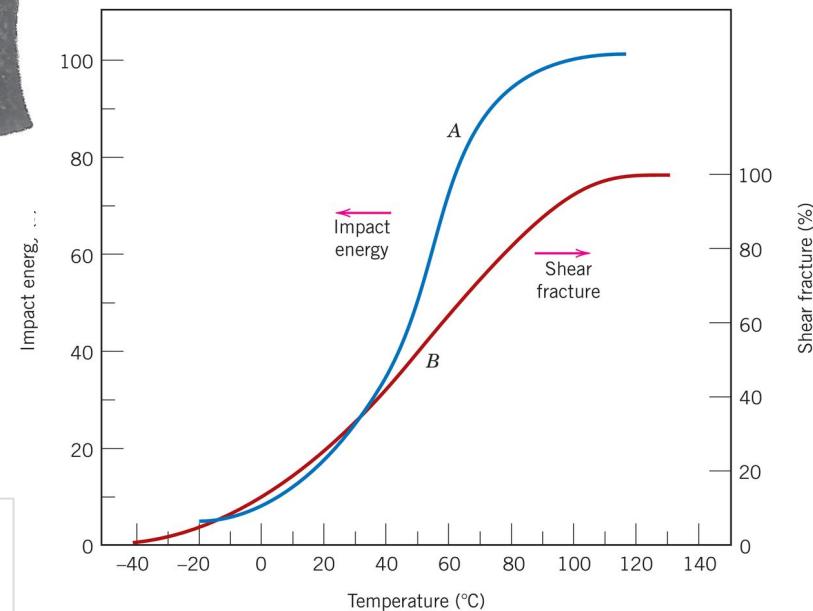


From R. W. Hertzberg, Deformation and Fracture Mechanics of Engineering Materials, 3rd edition, Fig. 9.6, p. 329. Copyright © 1989 by John Wiley & Sons, Inc., New York.  
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온도에 따른 파단면의 변화

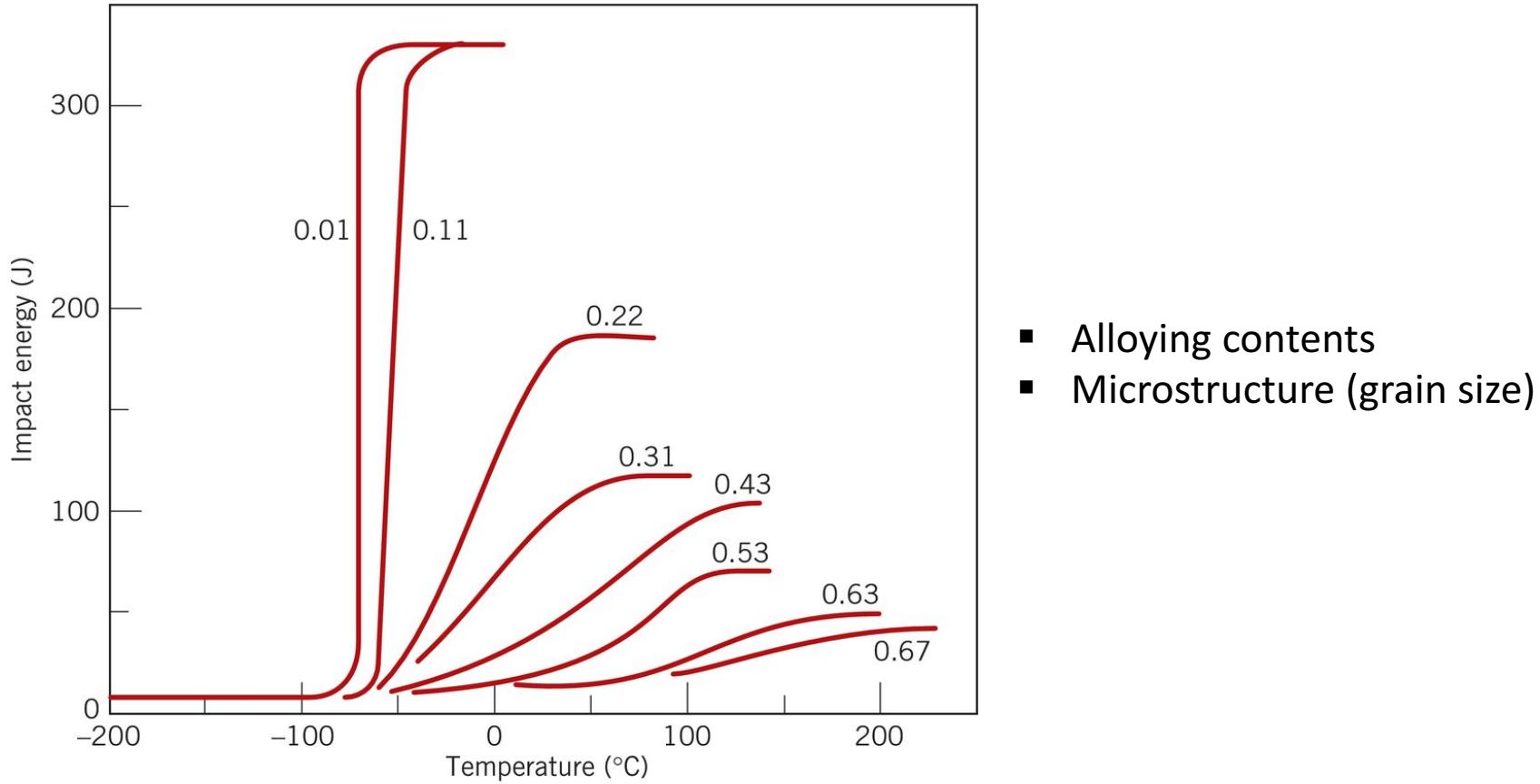
Grainy; faceted texture  
(Brittle fracture의 특징)

섬유질 모양, 어두운 색;  
이 두 가지 성질은 모두  
ductile fracture의 특성



Reprinted from Welding Journal. Used by permission of the American Welding Society.

# Factors affecting DBTT



Reprinted with permission from ASM International, Materials Park, OH  
44073-9989, USA; J. A. Reinbolt and W. J. Harris, Jr., "Effect of Alloying  
Elements on Notch Toughness of Pearlitic Steels," Transactions of ASM,  
Vol. 43, 1951.

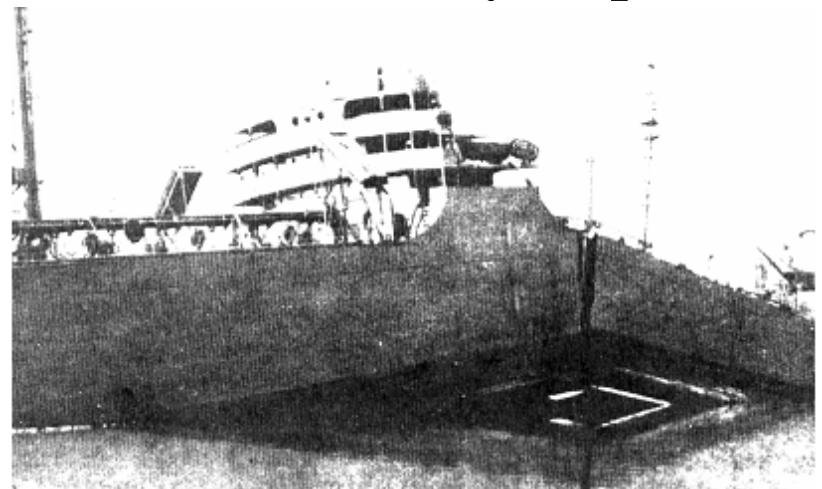
# Design Strategy: Stay Above The DBTT!

- 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 (in BCC) were used having DBTT's just below room temperature.

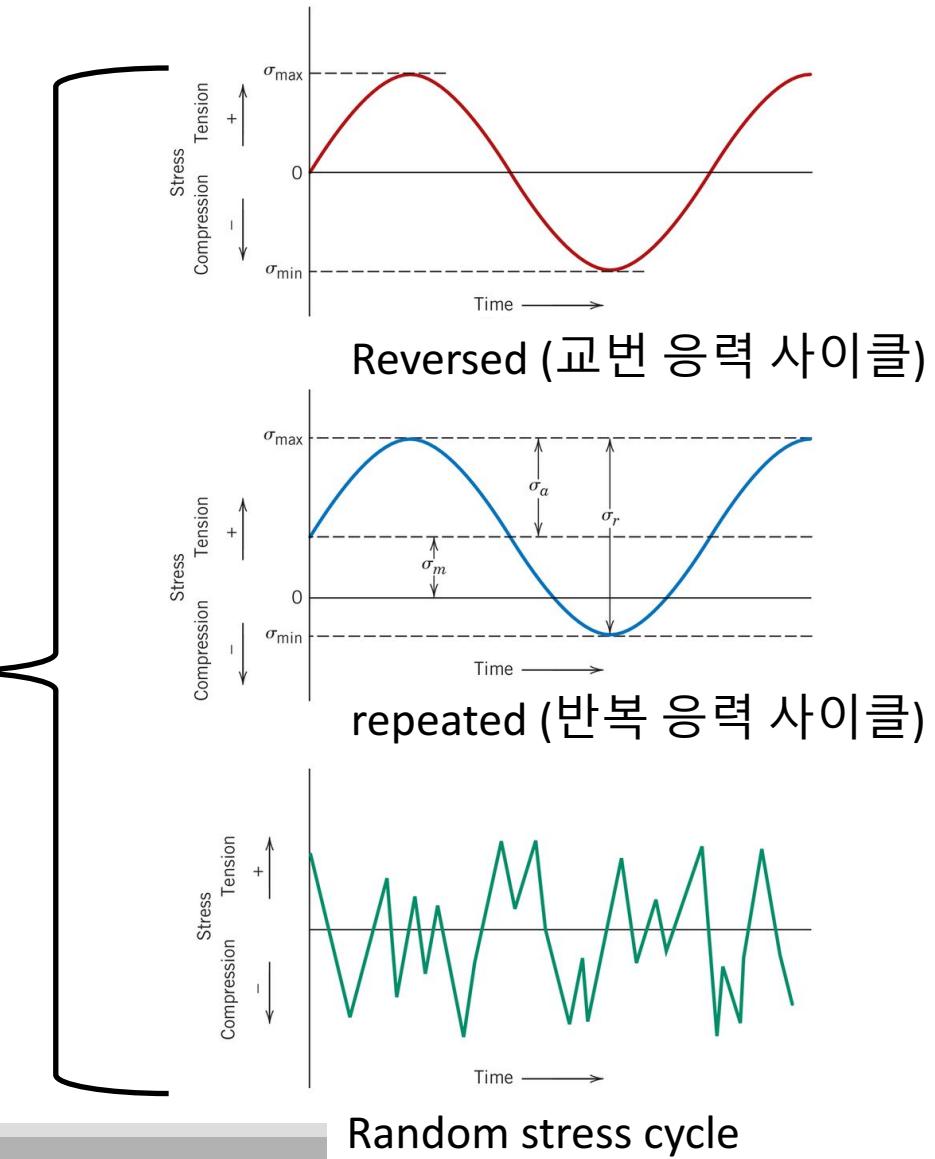
# Fatigue (피로)

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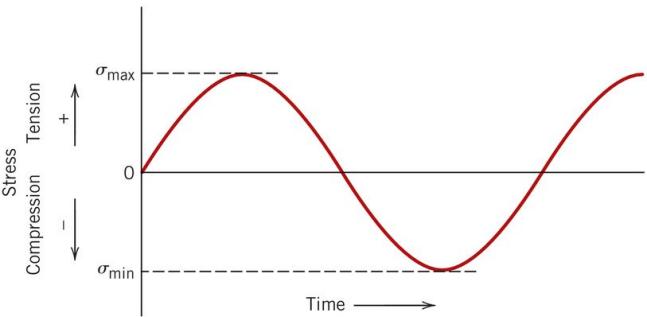
- 항복 강도나 인장강도보다 ‘매우’ 낮은 응력상태에 발생하는 파손. 일반적으로 ‘반복’되는 응력(혹은 변형률) 사이클에 의해 발생하는 파괴.
- 예: 교량 (bridge) – 자동차의 무게가 교량 구조물의 항복 강도나 인장강도에 비해 매우 낮으나, 반복적으로 되풀이 되어 파괴까지 이를 수 있다.
- 높은 응력상태가 아니므로, 소성변형이 거의 발생하지 않고, 그 특징도 전술한 brittle fracture와 유사.
- 주로 두 단계로 진행되어 최종 파손까지
  - 균열의 생성 (crack initiation)
  - 균열의 전파 (crack propagation)
  - 최종 파손 (final failure)

# Fatigue and stress cycle

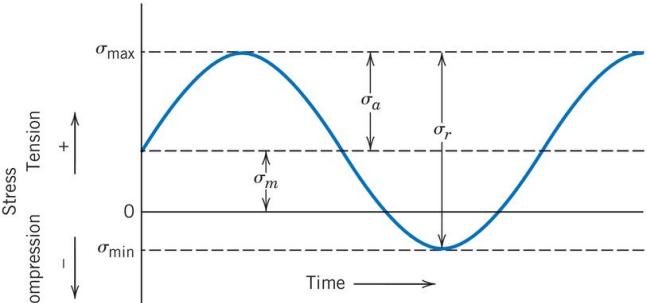
- Fatigue = failure under applied cyclic stress.
- The types of cyclic stress expected for Fatigue:
  - tension-compression
  - bending – unbending
  - twisting – untwisting
- Types of stress-time modes



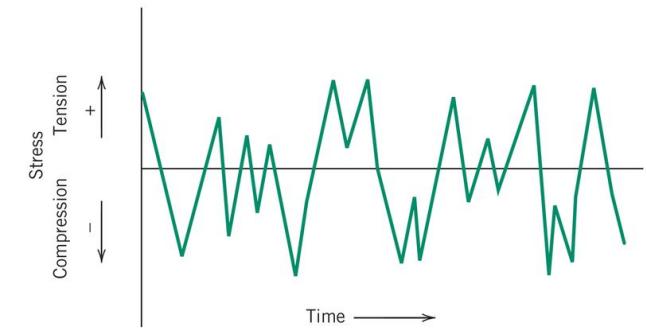
# Parameterization of stress cycles



Reversed (교번 응력 사이클)



repeated (반복 응력 사이클)

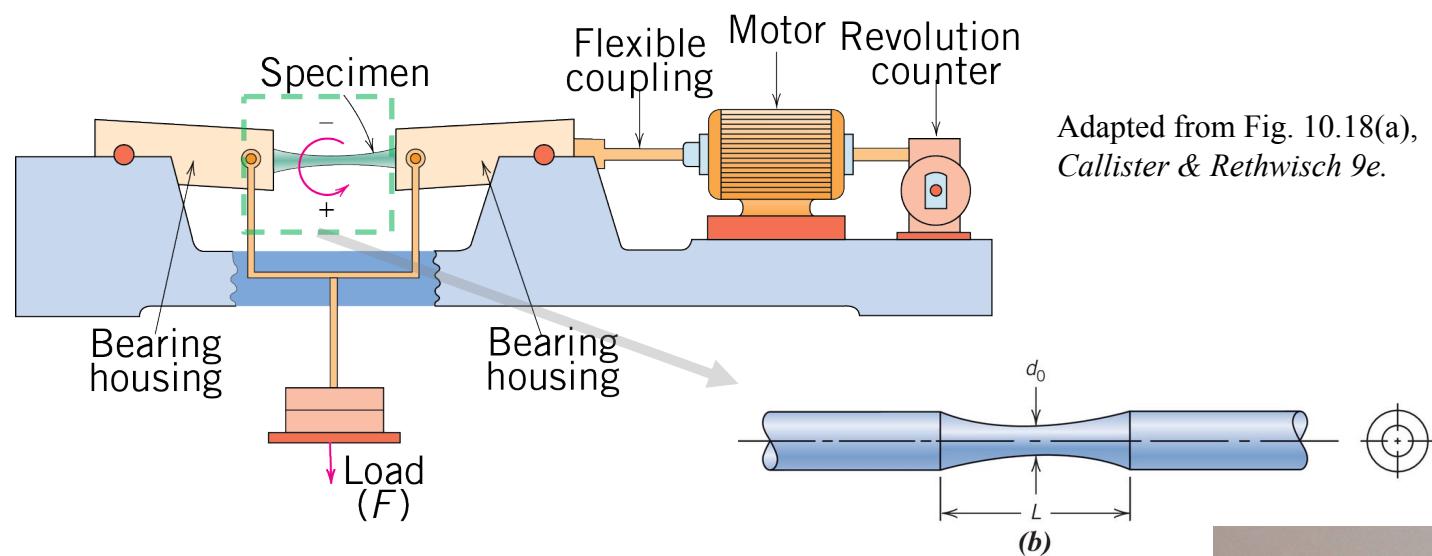


Random stress cycle

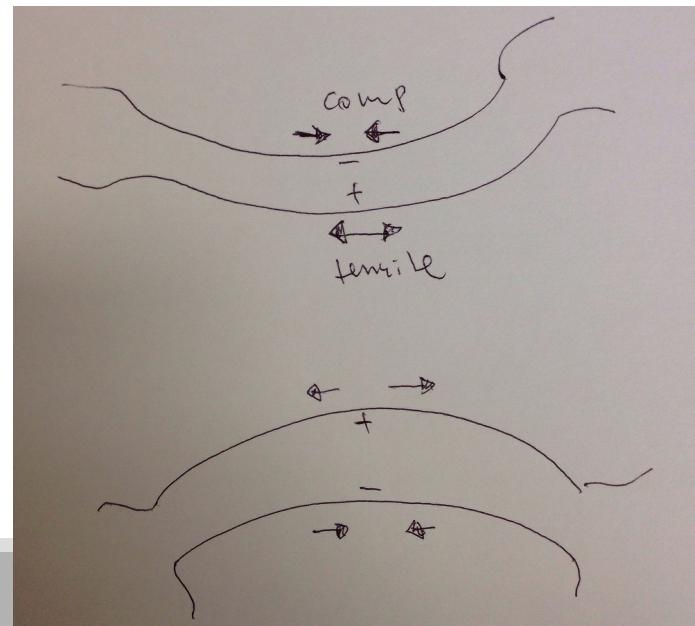
■ 응력 사이클을 매개변수화 – 즉 적은 개수/종류의 간단한 parameter를 통해서 표현해내는 방식으로 응력 사이클을 나타내기도 한다.

- $\sigma_{\text{mean}} = \frac{\sigma_{\max} + \sigma_{\min}}{2}$
- $\sigma_{\text{range}} = \sigma_{\max} - \sigma_{\min}$
- $\sigma_{\text{amplitude}} = \frac{\sigma_{\text{range}}}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2}$
- Stress ratio (R) =  $\frac{\sigma_{\min}}{\sigma_{\max}}$

# A typical fatigue test

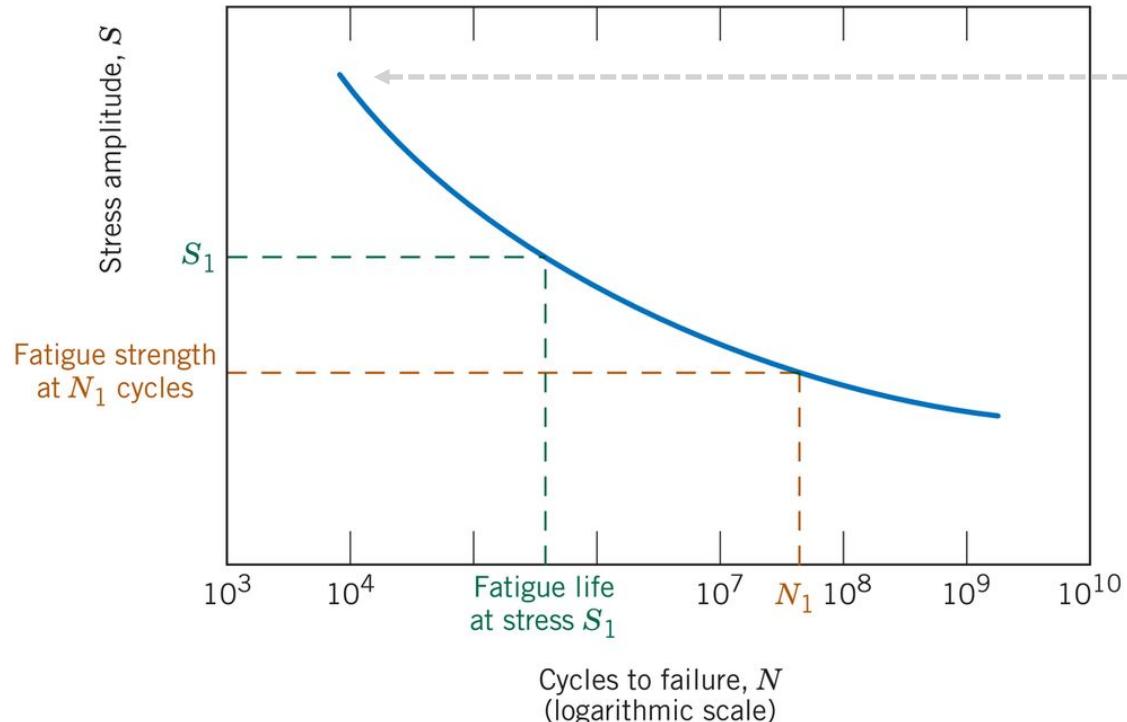


An example where the stress cycle is realized in combination of '**rotation**' and '**bending**'.



# S-N curve 측정

- 응력 진폭과 파손이 될 때 까지의 cycle 수를 각각 y축 x축으로 나타낸다.
- 응력 진폭을 바꾸면서 실험을 반복.
- Cycle 수는 주로 log scale로 표시한다.



대개 TS의 2/3을  $\sigma_{\text{amplitude}}$ 로 설정한 실험부터 시작

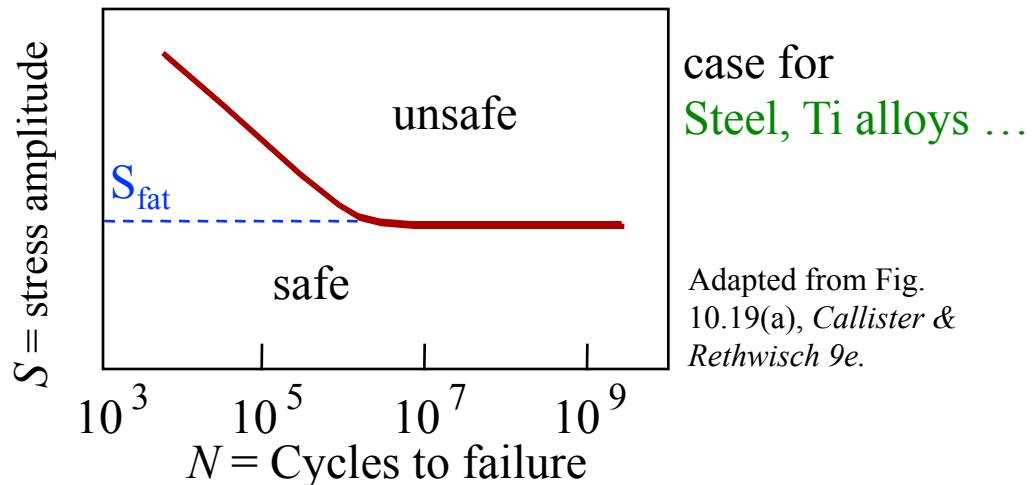
점점 낮은  $\sigma_{\text{amplitude}}$  값을 설정후 실험을 반복

Low-cycle  
fatigue

High-cycle fatigue

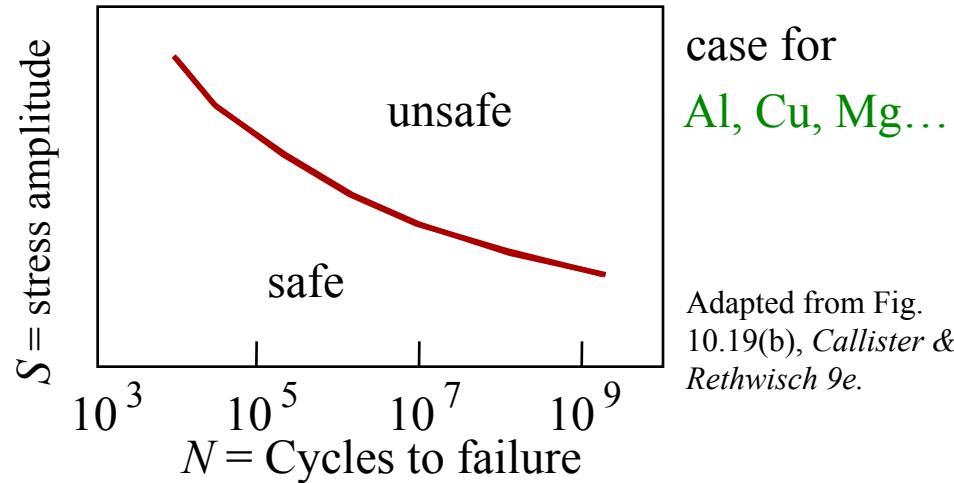
# Types of Fatigue Behavior

- Fatigue limit (endurance limit),  $S_{\text{fat}}$ :  
--no fatigue if  $S < S_{\text{fat}}$



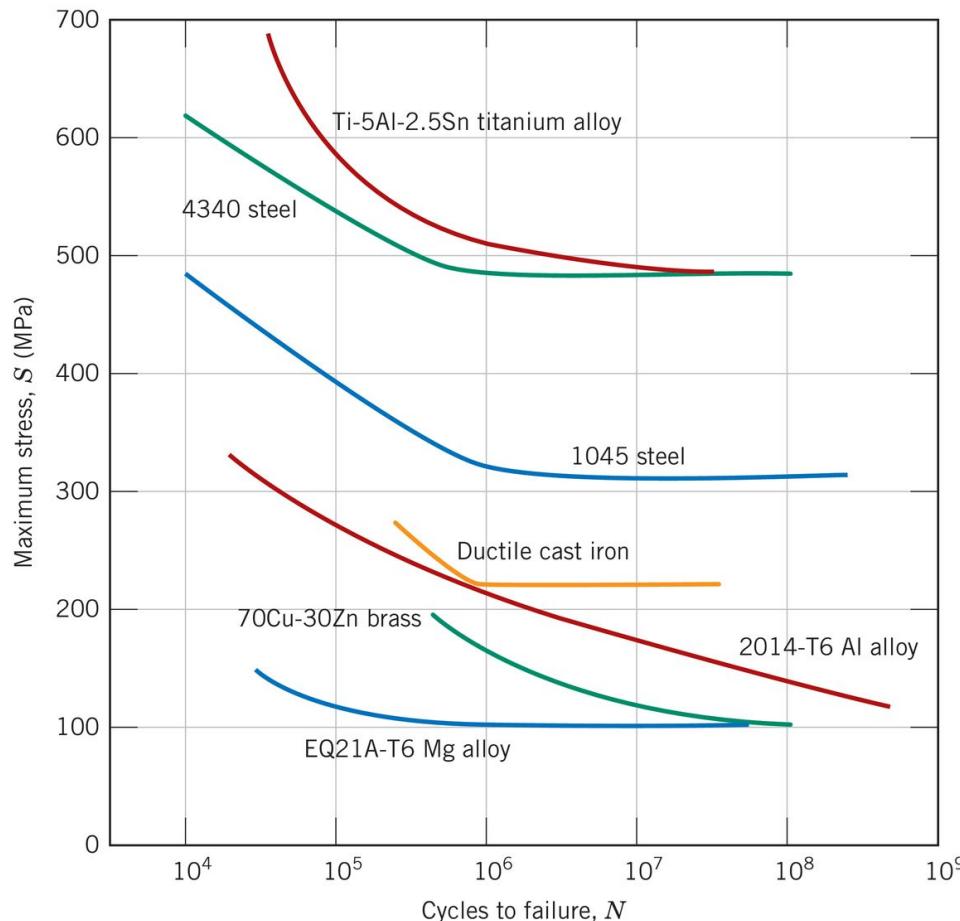
Adapted from Fig.  
10.19(a), Callister &  
Rethwisch 9e.

- For some materials, there is no fatigue limit!



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

# S-N curves for various materials

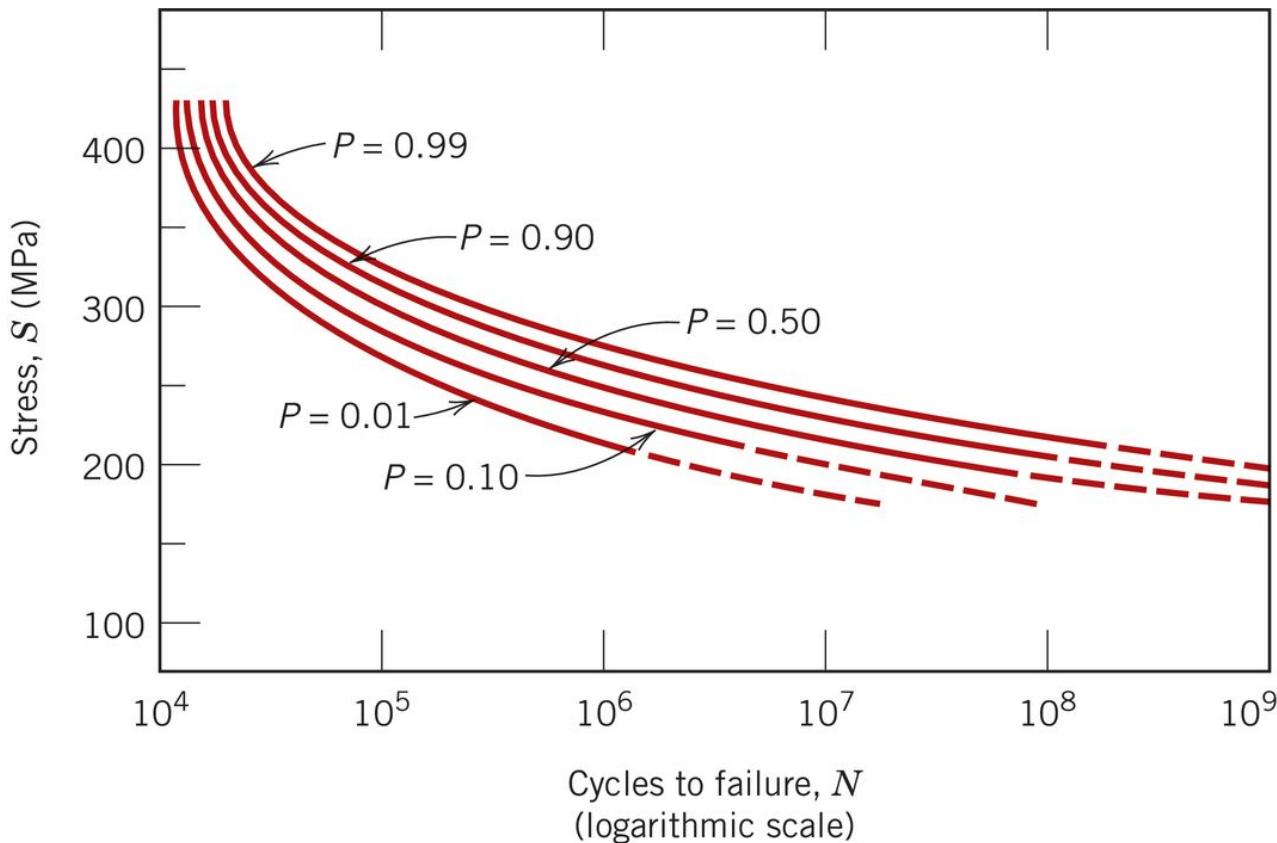


- 교번 응력 실험으로 얻어진 다양한 금속 재료의 S-N 곡선
- Fatigue limit을 보여주는 재료를 찾아보자.

예제 10.2 와 10.3

Data taken from the following sources and reproduced with permission of ASM International, Materials Park, OH, 44073: ASM Handbook, Vol. I, Properties and Selection: Irons, Steels, and High-Performance Alloys, 1990; ASM Handbook, Vol. 2, Properties and Selection; Nonferrous Alloys and Special-Purpose Materials, 1990; G. M. Sinclair and W. J. Craig, "Influence of Grain Size on Work Hardening and Fatigue Characteristics of Alpha Brass," Transactions of ASM, Vol. 44, 1952.

# Fatigue S-N probability



From G. M. Sinclair and T. J. Dolan, Trans. ASME, 75, 1953, p. 867. Reprinted with permission of the American Society of Mechanical Engineers.

# Fatigue failure: initiation and propagation

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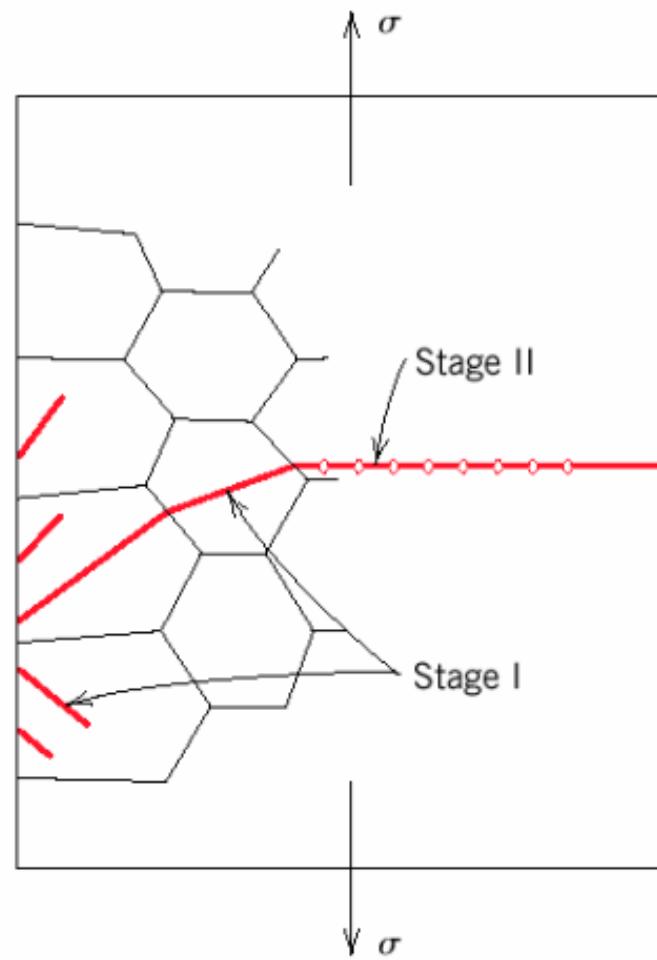
- 1) Crack initiation (균열 생성)
  - Small crack is created where the stress is ‘concentrated’.
- 2) Crack propagation (균열 전파)
  - Crack advances incrementally with each stress cycle
- 3) Final failure
  - When crack reaches the ‘critical’ size, failure rapidly occurs
- Cyclic loading can produce ‘steps’ caused by dislocation slip.
- $N_{\text{failure}} = N_{\text{crack initiation}} + N_{\text{crack propagation}}$
- For high cycle fatigue (load loads);  $N_{\text{crack initiation}}$  is high.
- With increasing loads,  $N_{\text{crack initiation}}$  decreases while  $N_{\text{crack propagation}}$  increases.

# Fatigue failure: initiation and propagation

- Crack initiation at the sites of stress concentration (microcracks, scratches, indents, dislocation slip steps and the like). Surface defect provides stress concentration thus surface quality is important.

## Crack propagation

- Stage I: initial slow propagation along crystal planes with high resolved shear stress.
- Stage II: Faster propagation perpendicular to the applied stress (i.e., typical feature observed for brittle fracture)



# Fractography of fatigue failure

- Two types of markings
  - Beachmarks (해변 무늬 – 혹은 clamshell markings) – 육안으로 판별 가능 Fig. 10.22
  - Striations (줄무늬) – 매우 작아 SEM, TEM 관찰찰 – Fig. 23
- 위의 마킹들은 특정 순간마다의 crack tip의 위치 – 나무의 나이테처럼 ; 비록 작은 외부의 응력이라도 stress concentration 으로 인해 crack tip은 소성변형 가능; 이런 marking들은 이런 소성 변형의 흔적.



Fig. 23

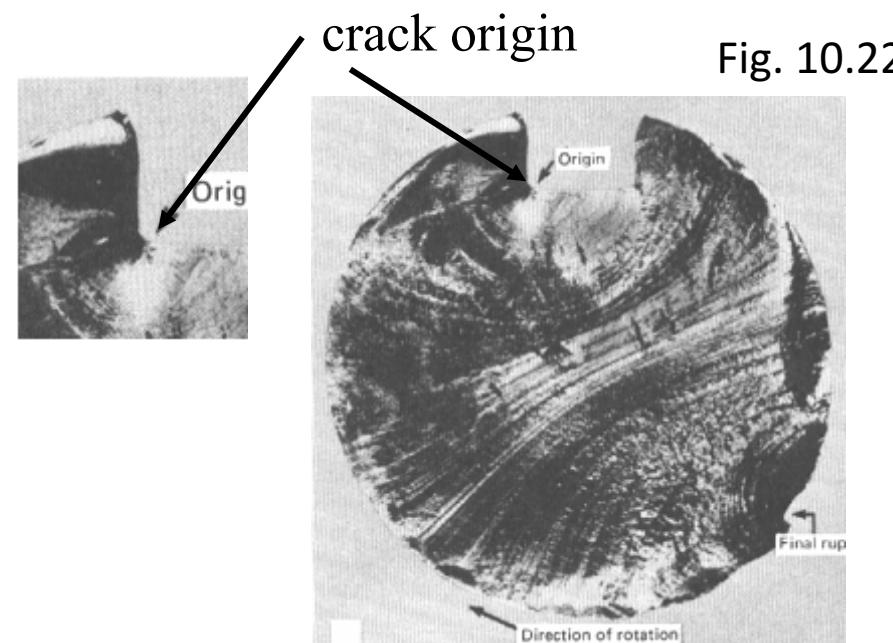


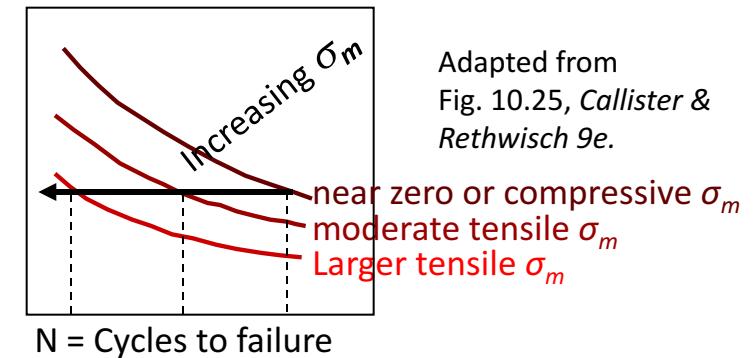
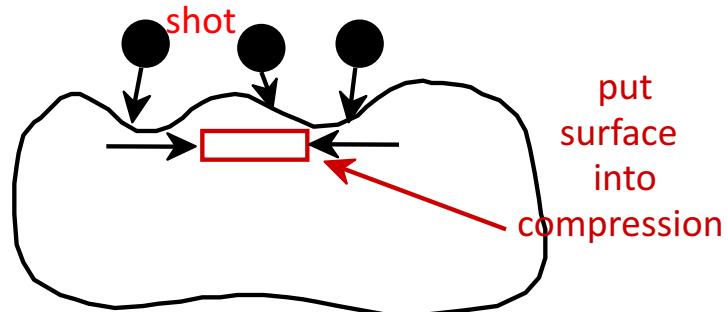
Fig. 10.22

From V. J. Colangelo and F. A. Heiser, Analysis of Metallurgical Failures, 2nd edition. Copyright © 1987 by John Wiley & Sons, New York.  
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# How to Improve Fatigue Life (Read Ch 10.10)

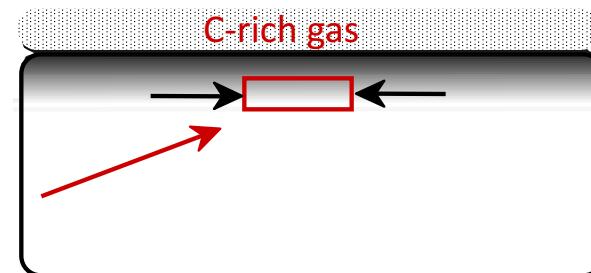
1. Impose compressive surface stresses (to suppress surface cracks from growing)

--Method 1: shot peening (Fig. 10.27)



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

--Method 2: carburizing (see Fig. 10.28)



2. Remove stress concentrators.

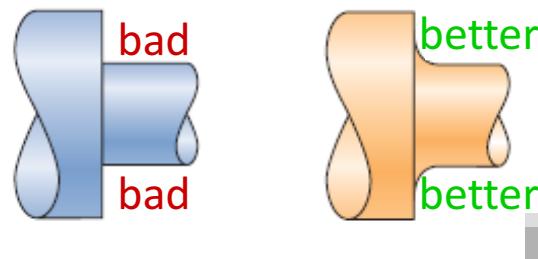
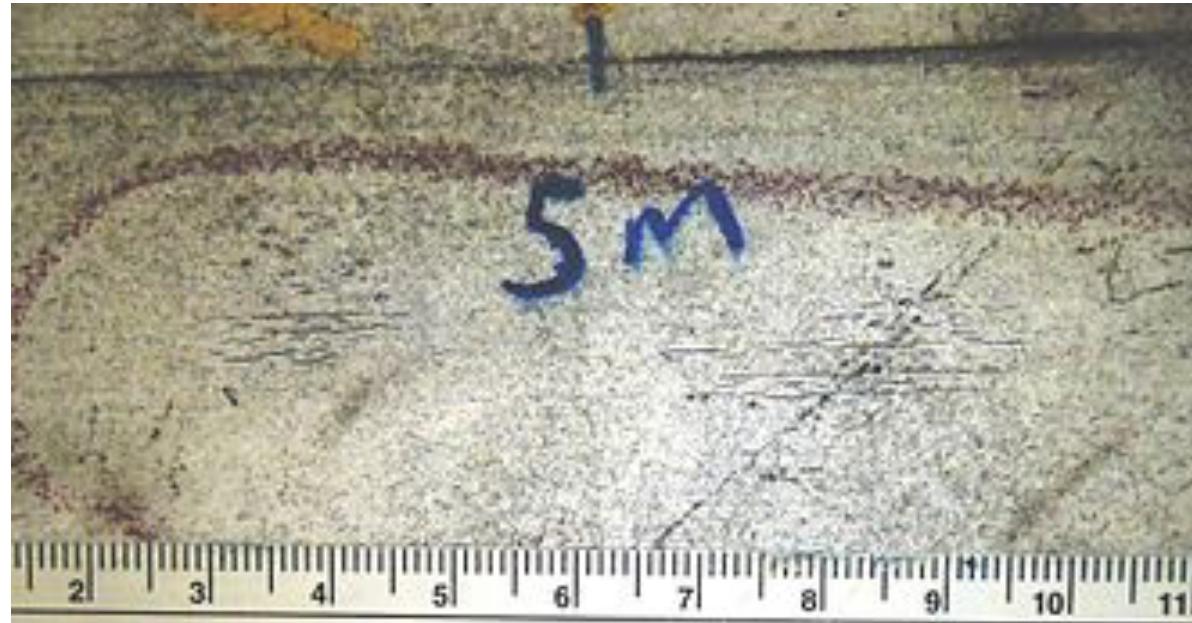


Fig. 10.26, Callister &  
Rethwisch 9e.

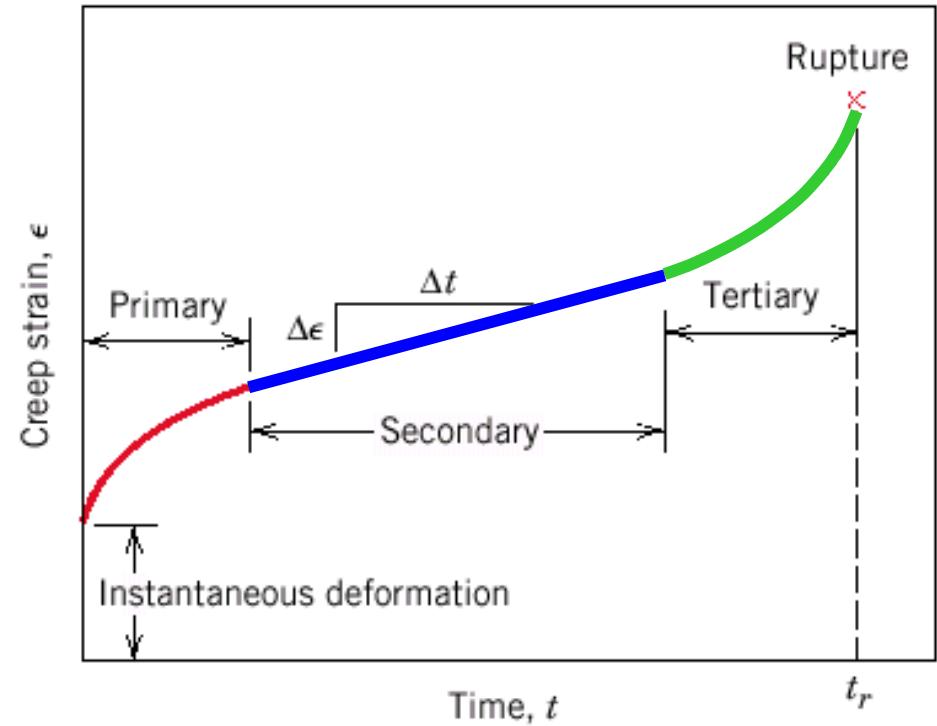
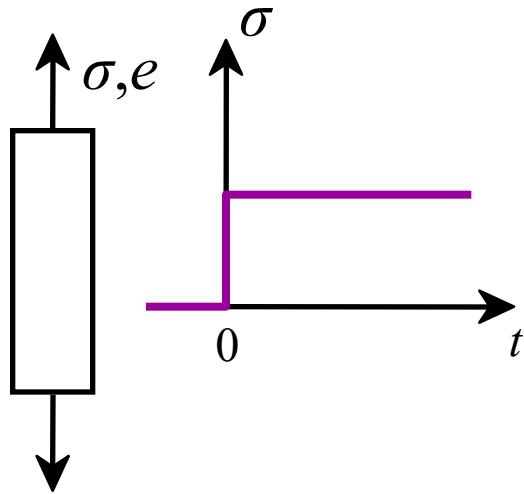
# Other factors

- Thermal (thermal cyclic fatigue) – 열피로
  - 기계적應력 없이, 고온에서의 온도 변화로 인한 피로.
  - 온도 변화는 ‘열팽창’ 및 ‘열수축’으로 이어진다. 이로인해 온도 변화에 따른應력 발생
- Corrosion fatigue;
  - Combination of stress and chemical attacks.
  - Stress Corrosion Cracking (SCC)



# Creep

Sample deformation at a constant stress ( $\sigma$ ) vs. time



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

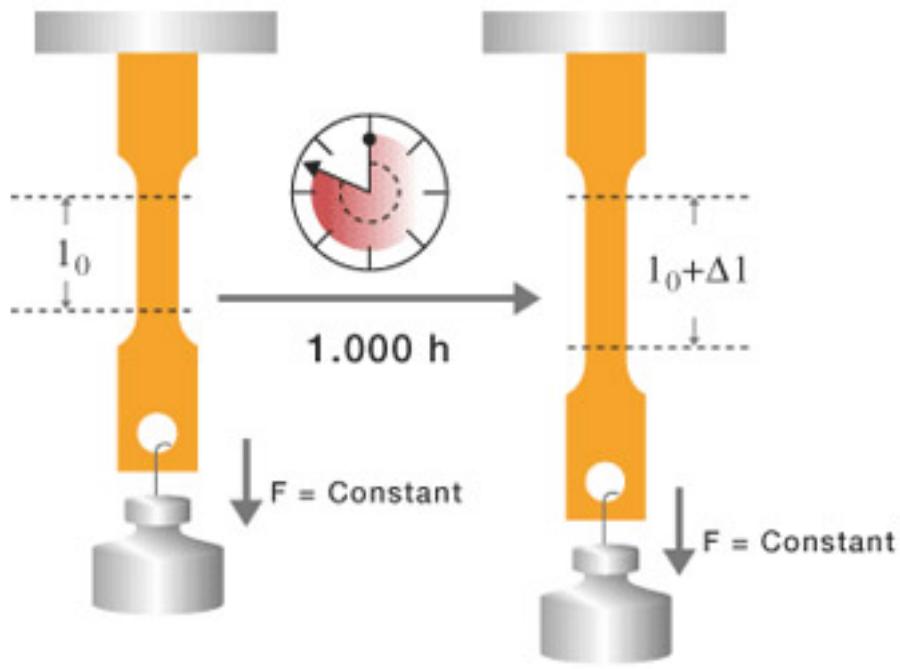
**Secondary Creep:** steady-state i.e., constant slope ( $\Delta\epsilon / \Delta t$ ).

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

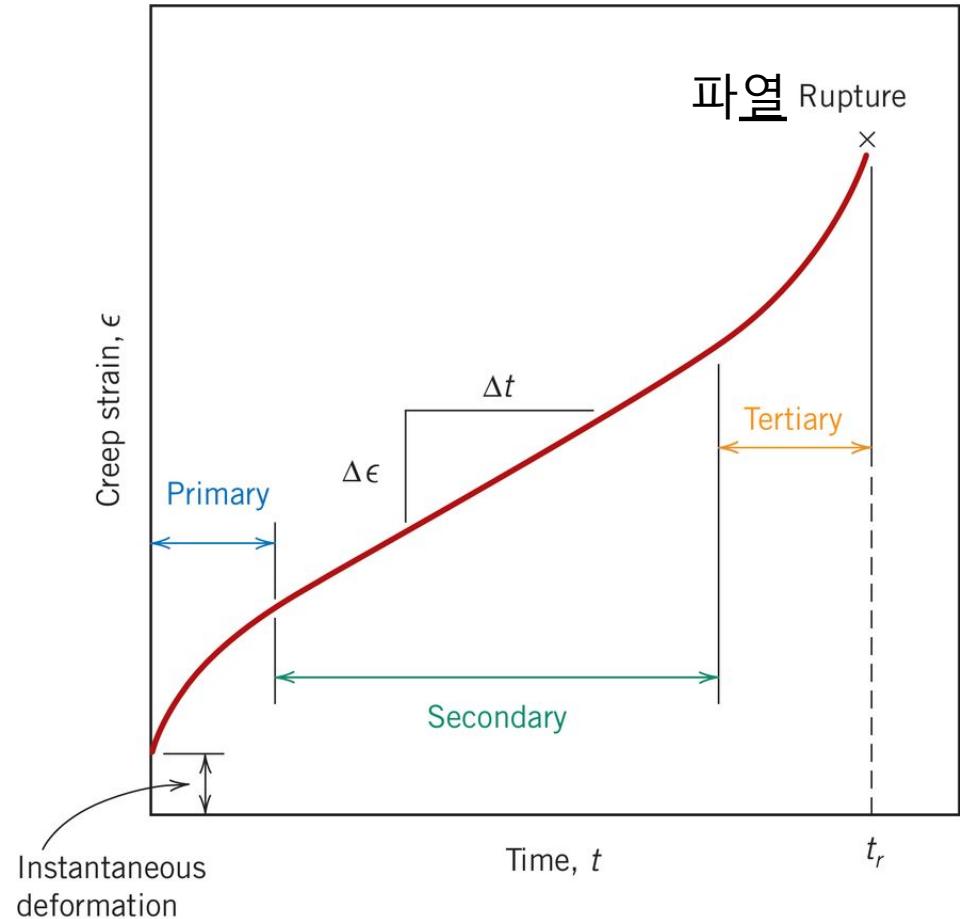
Adapted from  
Fig. 10.29, Callister & Rethwisch 9e.

# Creep

- 흐물흐물 변형
- Deformation under 'static' load / Stress changes under 'static' deformation – here by static means a 'fixed' constant load or deformation.
- **Time-dependent** and **permanent** deformation.
- Creep tests divided into two controls:
  - Static load control
  - Static deformation control
- For metal alloys for structures, creep usually occurs at high temperature ( $0.4 > T_m$ )

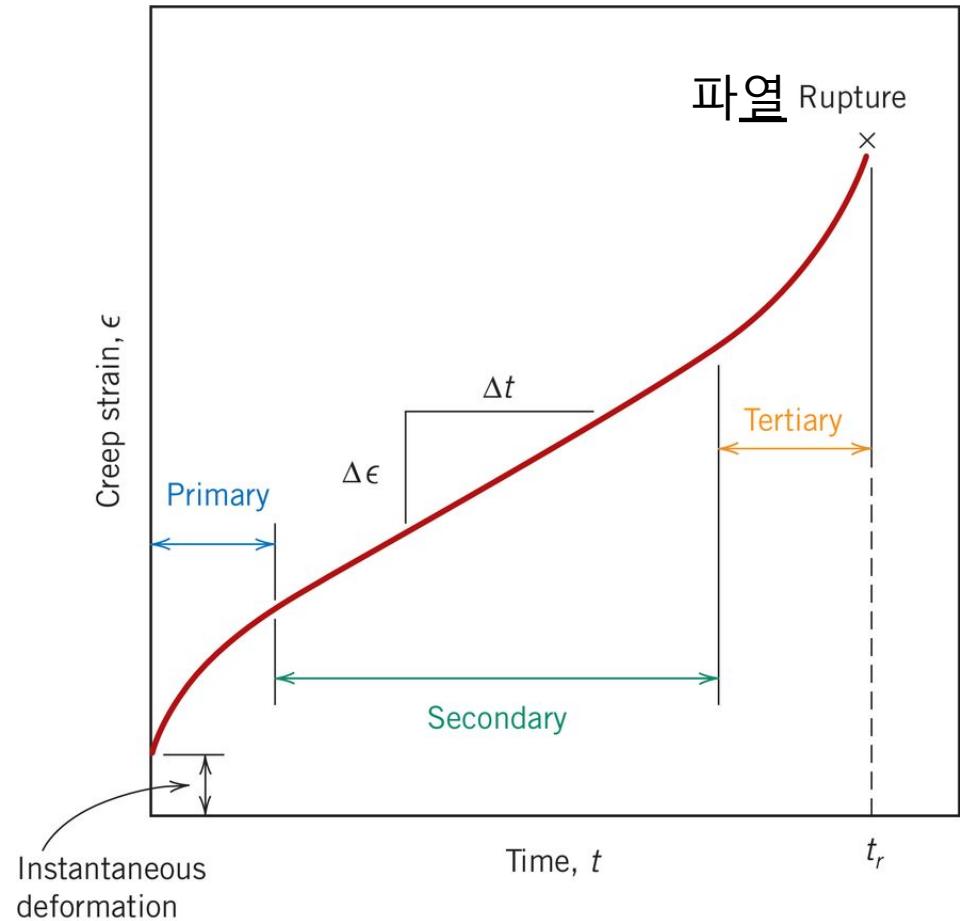


# Creep test under constant load



1. Instantaneous deformation: 하중이 가해지는 순간 즉시 발생; Elastic
2. Primary creep (1차 크리프) / transient creep (전이 크리프); strain hardening occurs thus creep strain rate decrease
3. Secondary creep (steady-state creep 정상 크리프); creep strain and recovery are in equilibrium
4. Tertiary (3차 크리프); creep strain rate increases; due to necking;
5. Rupture;

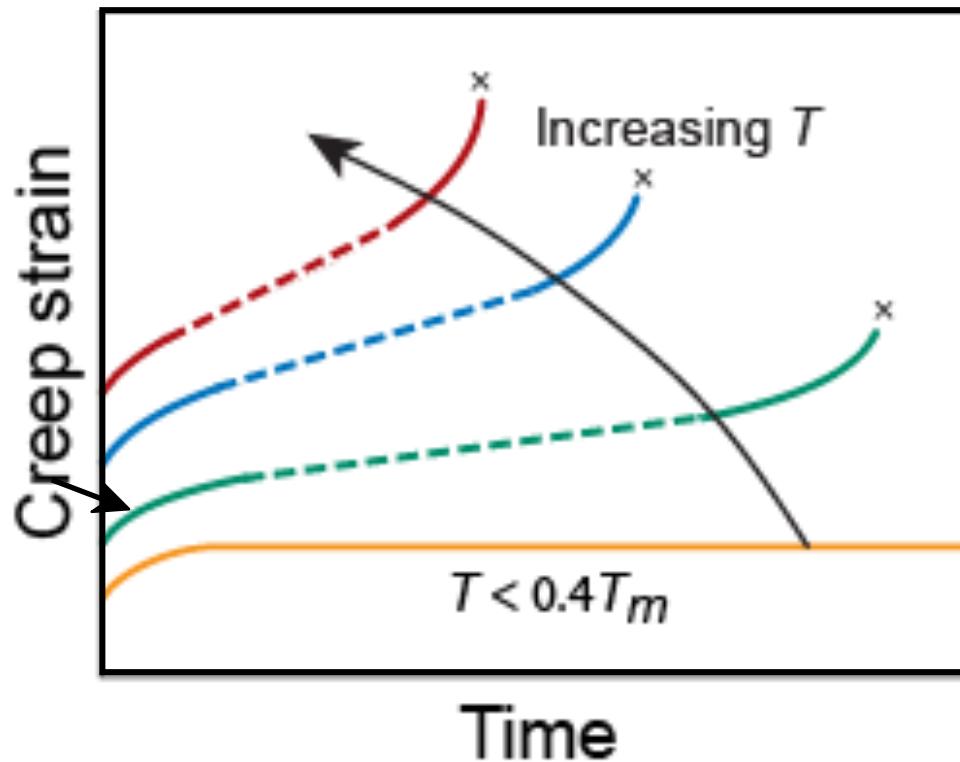
# Two parameters from creep test



- 정상 크리프 구간에서의  $\Delta\epsilon/\Delta t$  ( $\dot{\epsilon}_s$ ) 를 정상 크리프 속도 (steady-state creep rate). 원자로용 재료; creep resistant materials for long-term usage.
- 파열시간:  $t_r$ ; 예상수명이 짧은 경우, 예를 들어 군용기의 turbine blade, rocket motor nozzle.

Creep characteristics는 크게 작용 **응력**과 **온도**에 영향을 받는다.

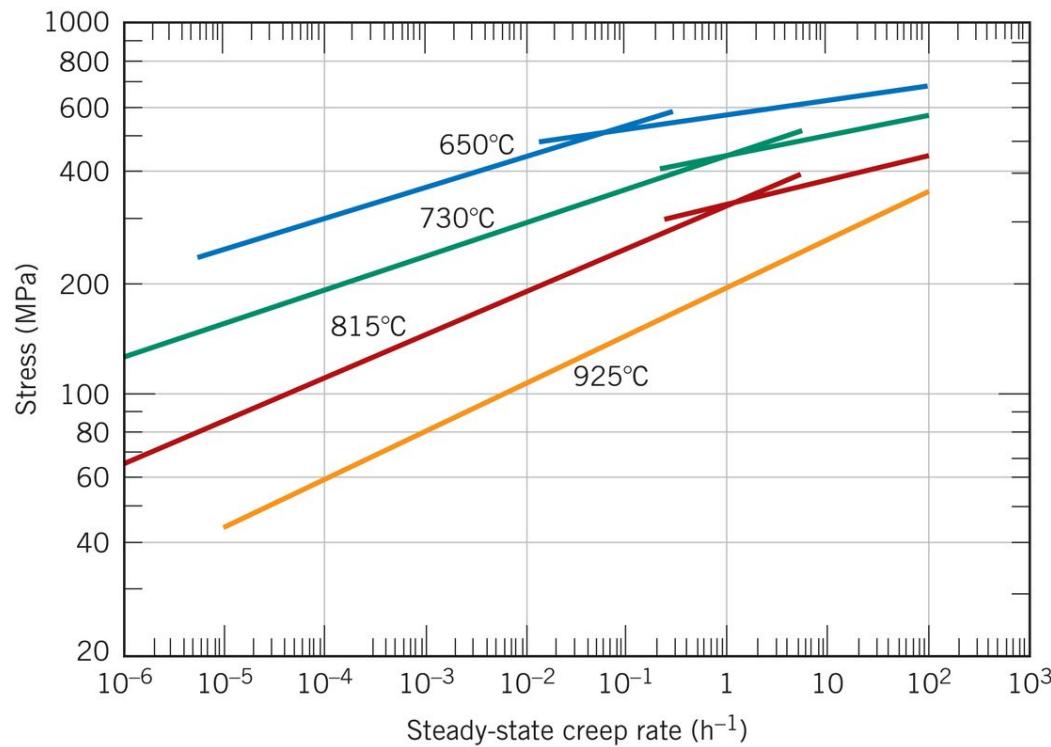
# Creep: Temperature Dependence



Figs. 10.30, Callister &  
Rethwisch 9e.

# Creep characteristic affected by stress

- $\dot{\epsilon}_s = K_1 \sigma^n$
- 정상 크리프 속도의應력 의존성을 power-law type 의 실험식으로 설명



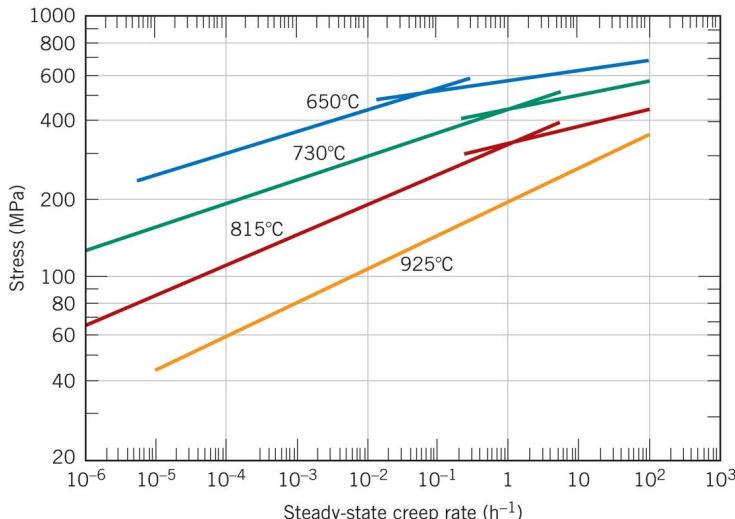
$$\ln \dot{\epsilon}_s = n \ln \sigma + \ln K_1$$

$$\ln \sigma = \frac{1}{n} \ln \dot{\epsilon}_s - \frac{1}{n} \ln K_1$$

$y=ax+b$  的 형태 (즉, 선형 관계)

# Creep characteristic affected by stress and temperature

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



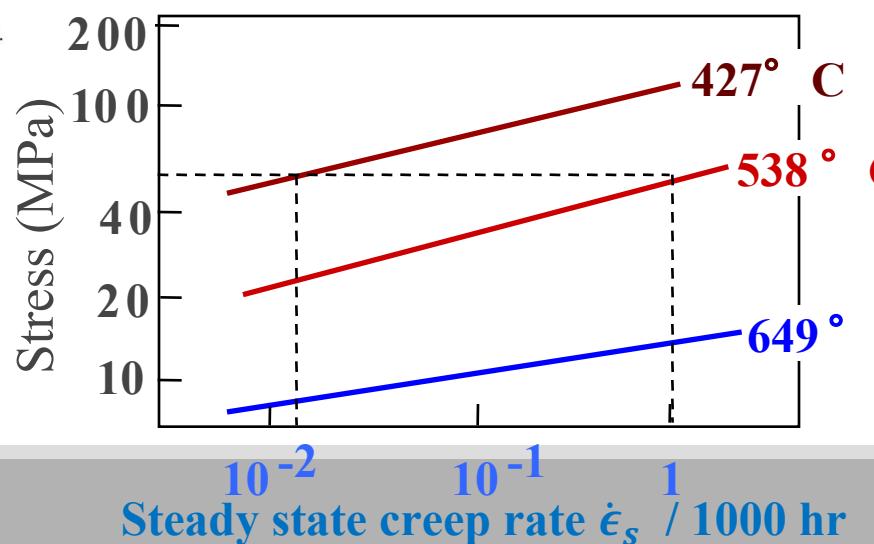
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온도 구간에 따라 다른 '기울기'. 이는 온도에 따라  $n, Q_c$  값이 달라지기 때문.

$n$  과  $Q_c$  값이 변하는 이유는 크리프를 발생시키는 mechanism이 달라지기 때문이다.

- 기공확산
- 입계확산
- 전위 이동 및 입계 슬립

- Creep Strain rate increases with increasing  $T, \sigma$

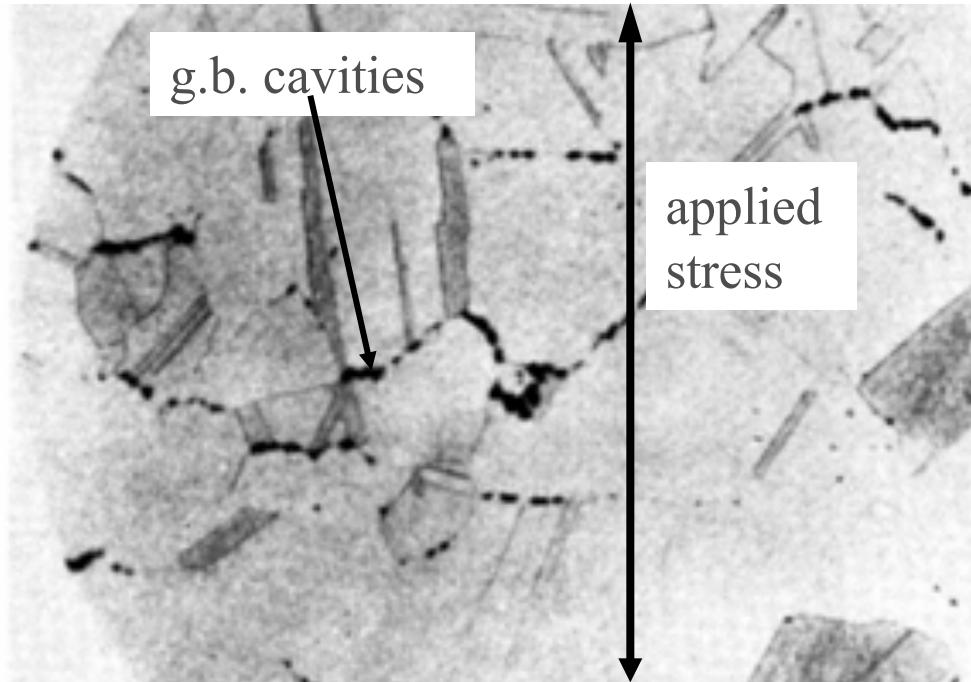


Adapted from  
Fig. 9.38, Callister &  
Rethwisch 4e.  
[Reprinted with permission from  
Metals Handbook: Properties  
and Selection: Stainless Steels,  
Tool Materials, and Special  
Purpose Metals, Vol. 3, 9th ed.,  
D. Benjamin (Senior Ed.), ASM  
International, 1980, p. 131.]

# Creep Failure

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- 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.)

# Data extrapolation methods

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- Need creep data for testing conditions that require impractically long time to collect the experimental data (years of testing time – material used for nuclear power plants)
- One way to obtain experimental data for prolonged tests is to impose an excessively harsh conditions (higher temperature than in-service condition) to shorten the time periods.
- You are ‘extrapolating’ the data since you ‘guess’ the behavior that you actually didn’t measure.
- A common extrapolation procedure employs Larson-Miller parameter ( $m$ ) defined as
$$m = T(C + \log t_r)$$
- We assume the above  $m$  remains constant;

# Example

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- You were conduct to rupture-test an alloy that obeys Larson-Miller parameter:
- $T(20 + \log t_r)$
- Your boss asked you to test the material at  $700K$  which is expected to complete in a year.
- If you want to finish the test in a month, what should you do?
  
- $T_1(20 + \log t_{r,(1)}) = T_2(20 + \log t_{r,(2)})$
- $700K \times [20 + \log(24h \times 365)] = T_2(20 + \log 24h \times 30)$
- Solve for  $T_2$

# 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 (crack .. ) produce large stress concentrations and premature failure.
- Failure type depends on  $T$  and  $\sigma$  :
  - For simple fracture (noncyclic  $\sigma$  and  $T < 0.4T_m$ ), failure stress decreases with:
    - increased maximum flaw size,
    - decreased  $T$ ,
    - increased rate of loading.
  - For fatigue (cyclic  $\sigma$ ):
    - cycles to fail decreases as  $\Delta\sigma$  increases.
  - For creep ( $T > 0.4T_m$ ):
    - time to rupture decreases as  $\sigma$  or  $T$  increases.

# References

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- <http://jpkc.fudan.edu.cn/picture/article/348/1b/ee/6dce0ae740cf8673b53e4e96abb8/6ad0c8ee-53c3-4790-a931-211df202df69.pdf>
- <http://people.virginia.edu/~lz2n/mse209/Chapter8.pdf>
- Fracture Mechanics – Fundamentals and Application by TL Anderson.