

Chapter4

Failure

강의명: 기계재료공학 (MFA9009)

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Recap

- 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

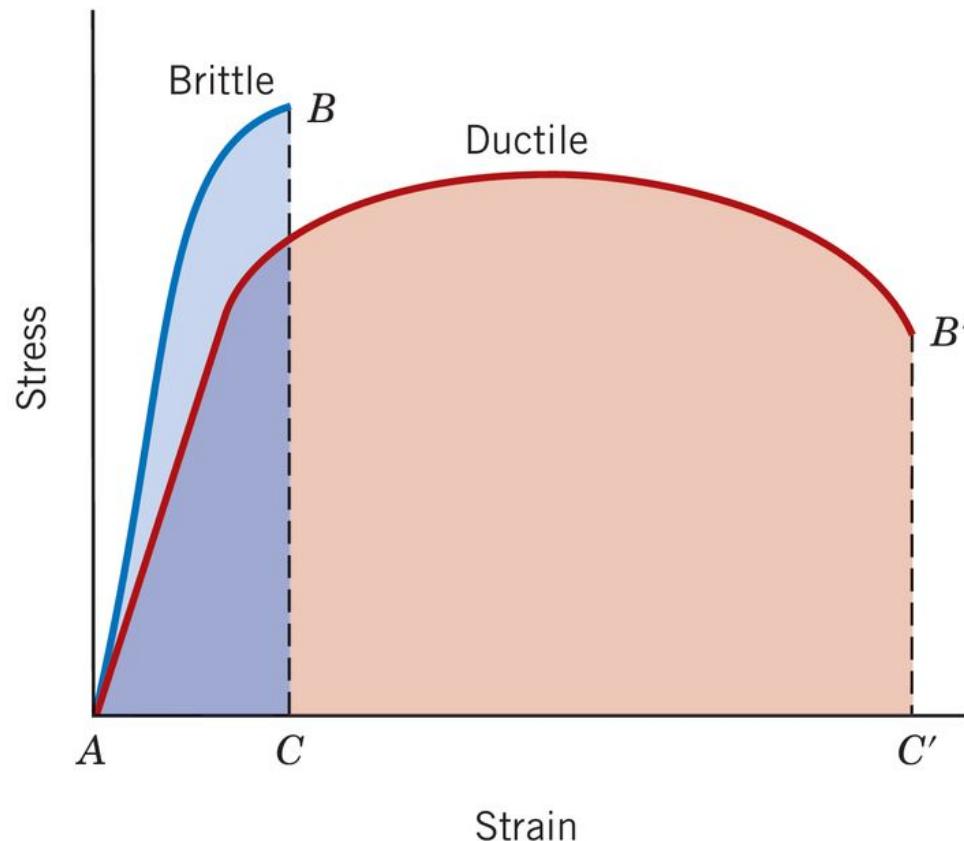
- Failure: occurs by three main mechanisms
 - Fracture
 - Fatigue
 - Creep
- Fractography
- Fracture (파고)
 - Brittle fracture
 - Ductile fracture
 - DBTT
 - Basic Fracture mechanics and application to design problems
- Fatigue (피로)
 - Failure under stress far below YS, TS; Cyclic loading
- Creep (크리프)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

Fundamentals of Fracture

- 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

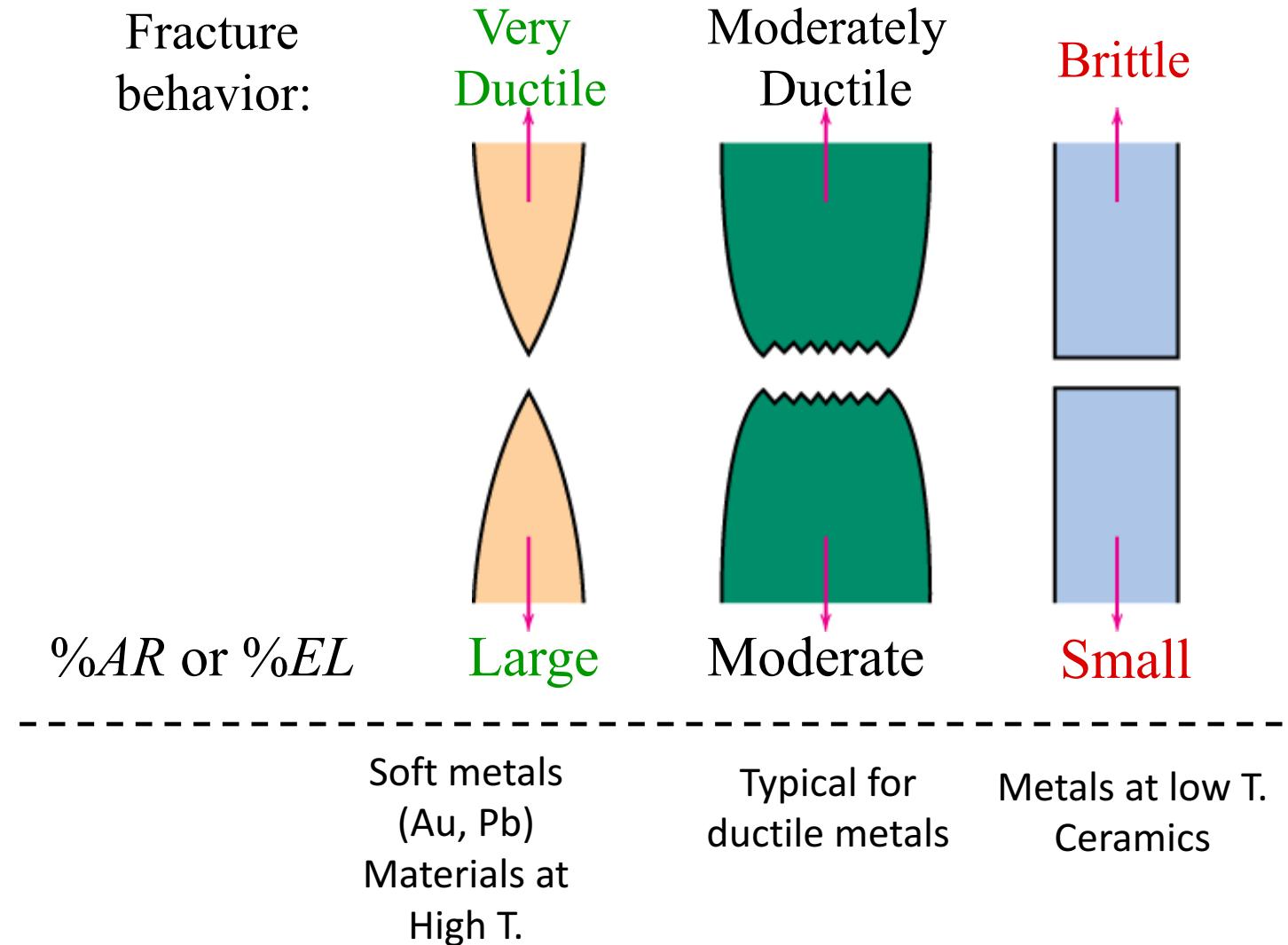
- Ductile fracture: 상당히 높은 에너지를 흡수한 뒤에야 파괴
- Brittle fracture: 소성변형이 일어나지 않거나, 혹은 매우 제한적인 양으로.



Crack formation and propagation

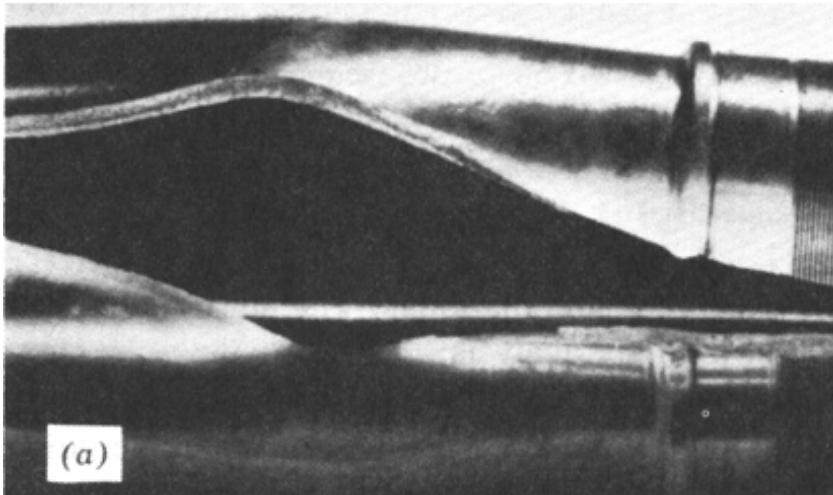
- 미시적으로 살펴보면 파괴는 두 단계로 이루어진다.
 - 1. 균열 (crack) 생성
 - 2. 균열의 전파 (propagation)
- The mode of fracture (파괴형태)는 균열의 전파 방식에 의해 결정
 - 균열이 천천히 진전; Stable; 이 경우 파괴 발생까지 상당한 소성변형량이 필요; No stress No propagation
 - 균열이 빠르게 진전; Unstable; Little plastic deformation; 작용 응력이 증가하지 않아도 진전 가능
- Q) Which type of fracture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

Ductile vs Brittle fracture

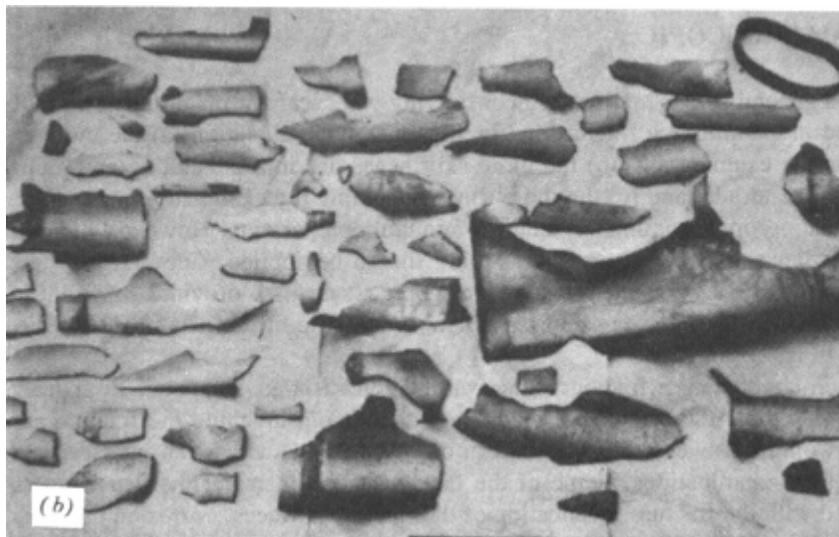


Examples: pipe failures

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



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

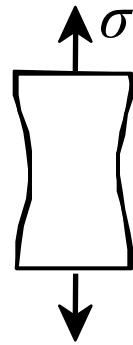


Figures from V.J. Colangelo and F.A. Heiser, *Analysis of Metallurgical Failures* (2nd ed.), Fig. 4.1(a) and (b), p. 66 John Wiley and Sons, Inc., 1987. Used with permission.

Ductile fracture characteristics

- Failure Stages:

necking



void nucleation



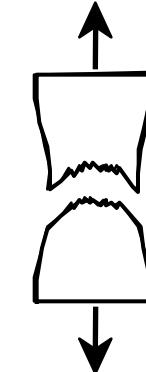
void growth and coalescence



shearing at surface



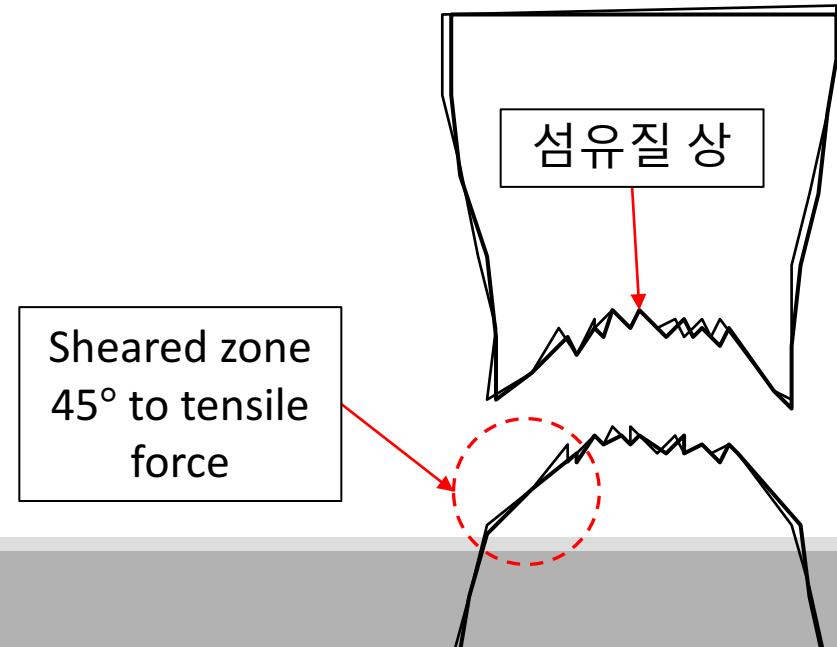
fracture



Cup and Cone
(컵-원뿔 파괴)

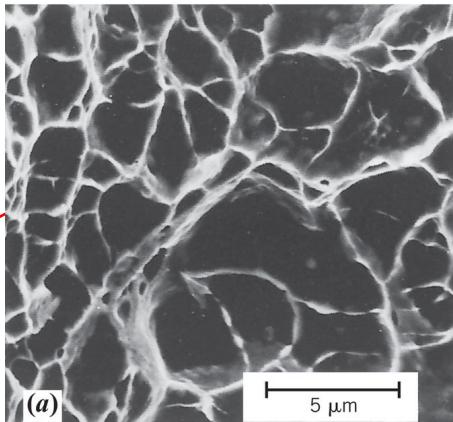
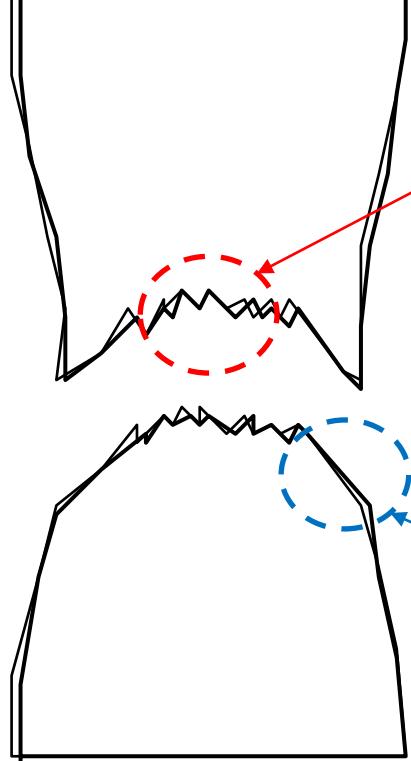


Sheared zone
45° to tensile force

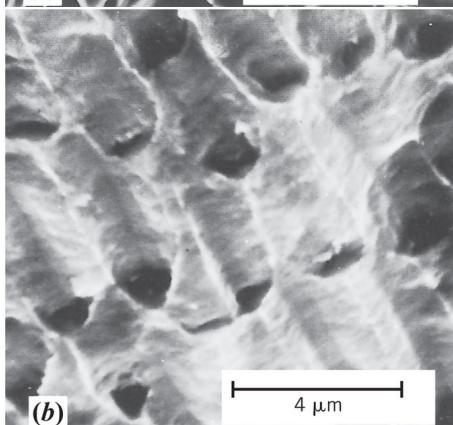


Fractography (ductile fracture)

- 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'

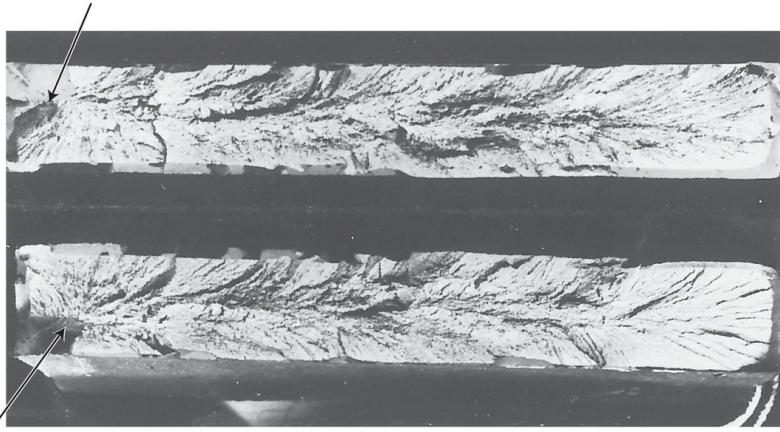


Ductile fracture under
'shear'

한쪽으로
늘어난 모양

Fractography (brittle fracture)

Failure origin

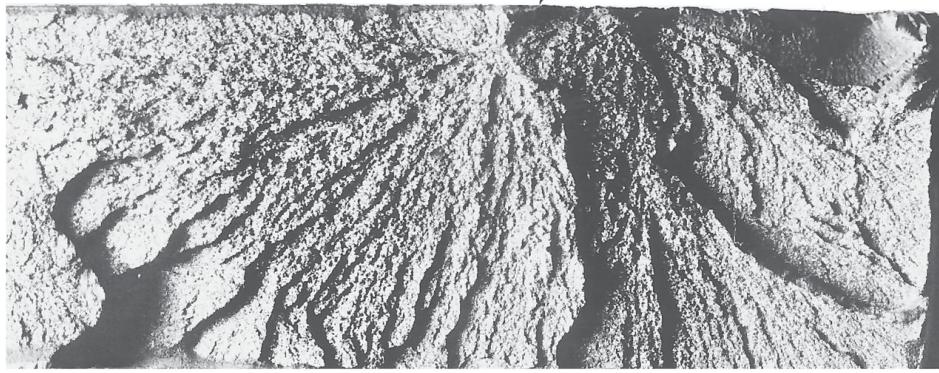


Failure origin

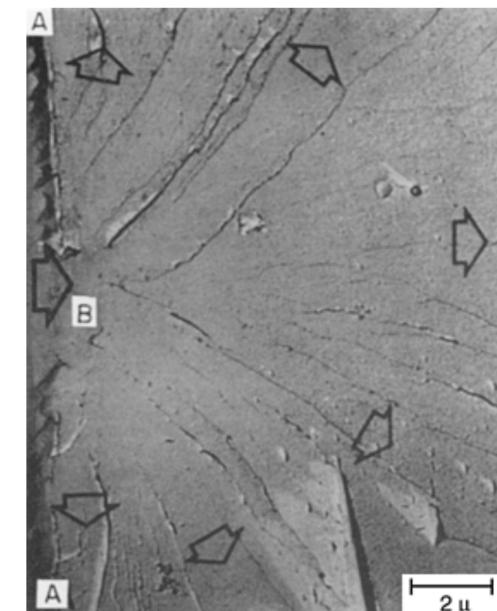
Failure origin

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

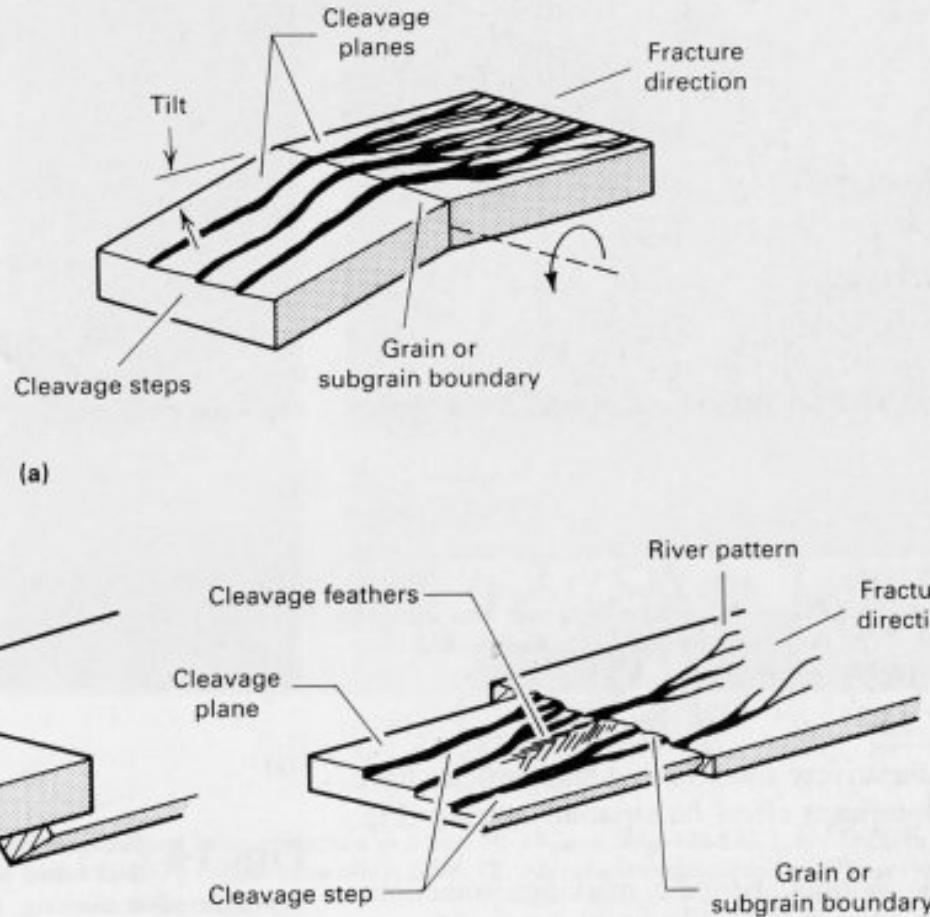
방사형, 부채꼴 형 (fan) 전파



(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.

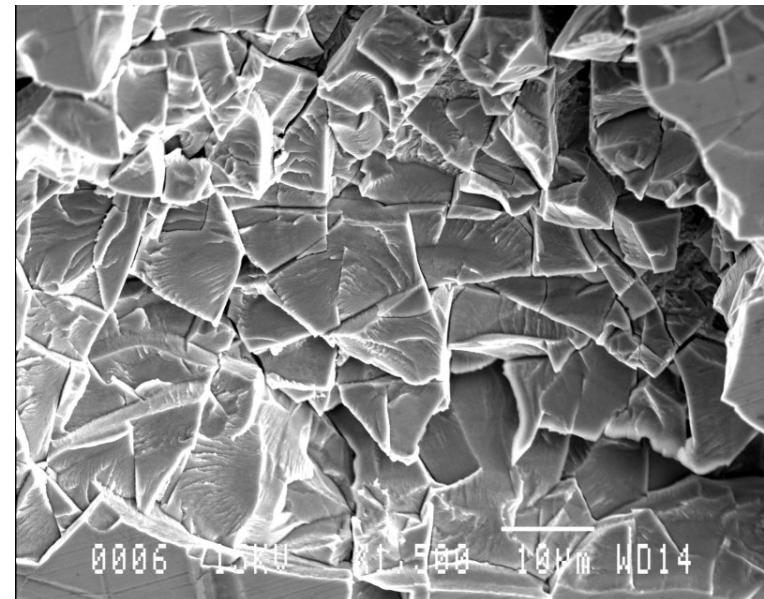


Brittle fracture



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

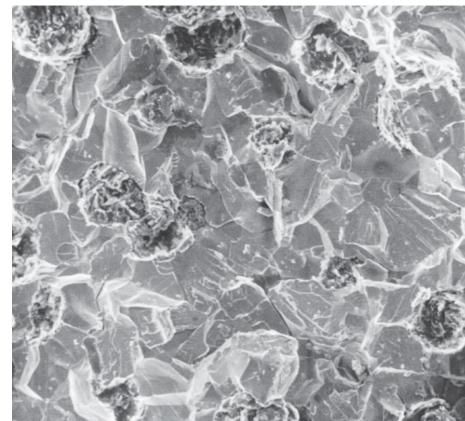
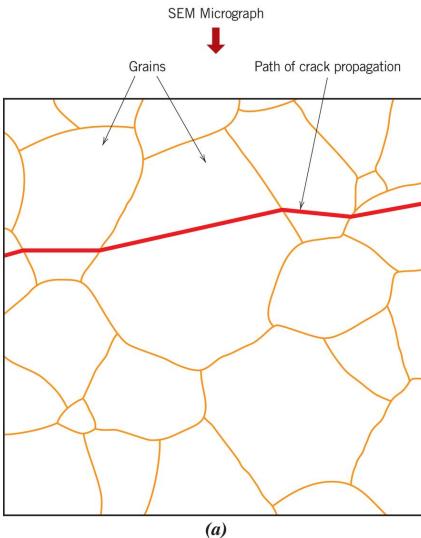
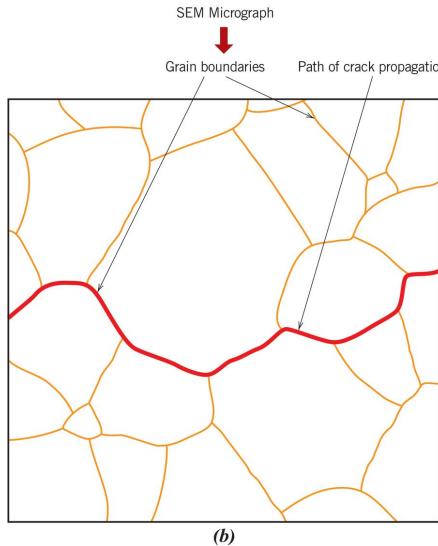


Figure (b) from V. J. Colangelo and F. A. Heiser, Analysis of Metallurgical Failures, 2nd edition. Copyright © 1987 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

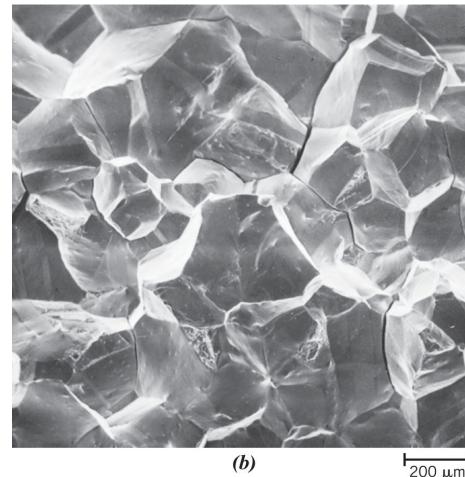


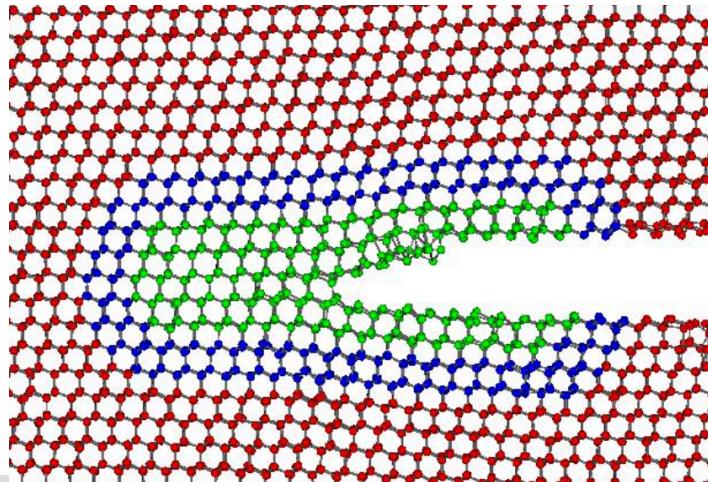
Figure (b) reproduced with permission from ASM Handbook, Vol. 12, Fractography, ASM International, Materials Park, OH, 1987.

Principles of Fracture Mechanics

- 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.

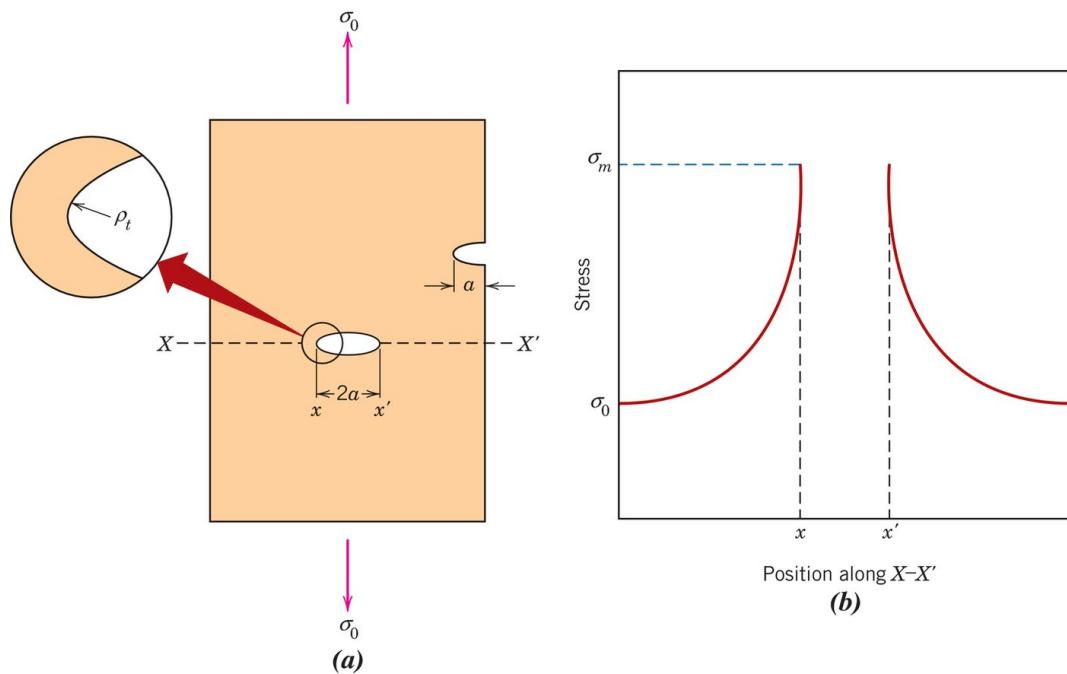
Stress raiser 응력집중(인)자

- 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 σ_m 상승)

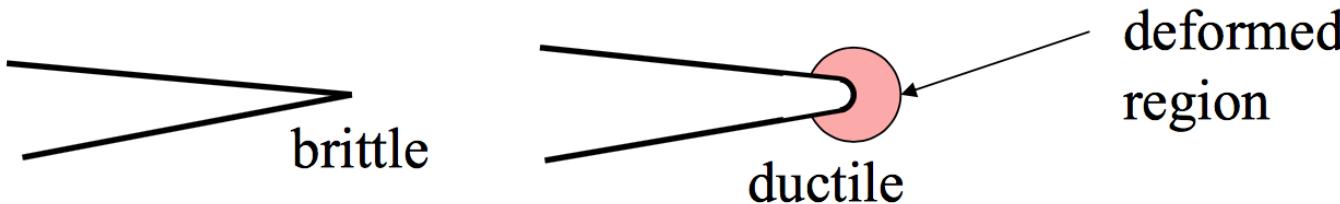
ρ : 균열 첨단부(tip)의 곡률반경(radius of curvature)

(곡률이 완만할 수록, 곡률 반경이 클수록 σ_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.



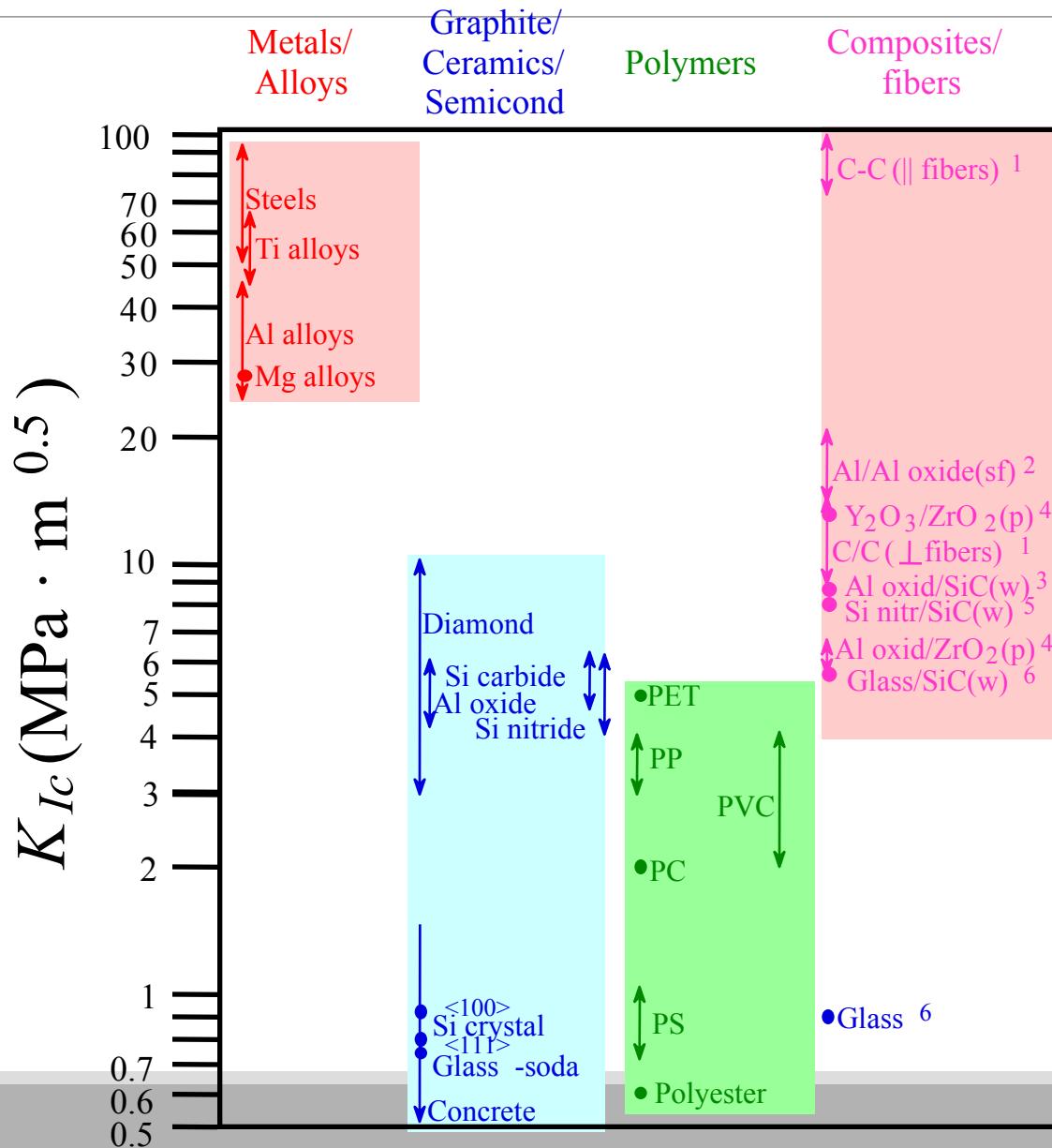
일반적으로 취성 재료가 응력상승에 더욱 취약하다. 연성 재료의 경우, σ_m 가 증가하다 소성변형이 발생 (즉 crack tip 부근의 변형으로 인해 sharpness가 무뎌진다)

Crack propagation

- 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; γ_s : specific surface energy
- For ductile materials γ_s in the above is replaced by $\gamma_s + \gamma_p$ (γ_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

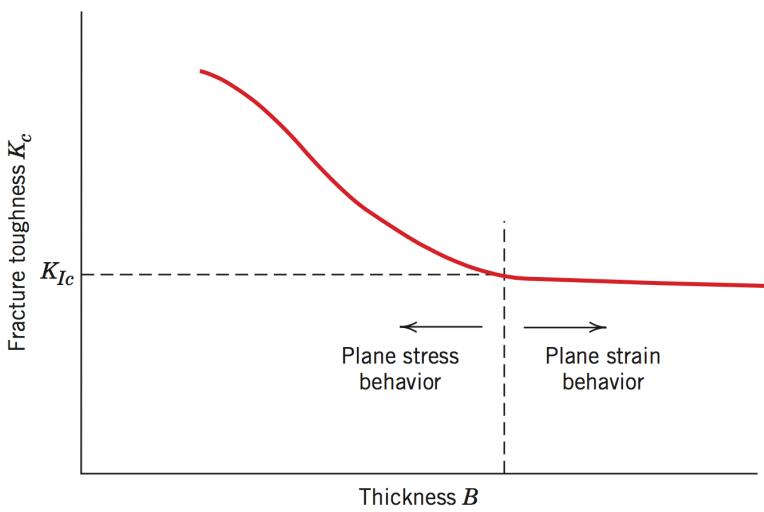
- 균열 전파에 대한 임계應력(σ_c)과 균열 길이의 관계가 'Stress Intensity Factor'로 설명된다.

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

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.

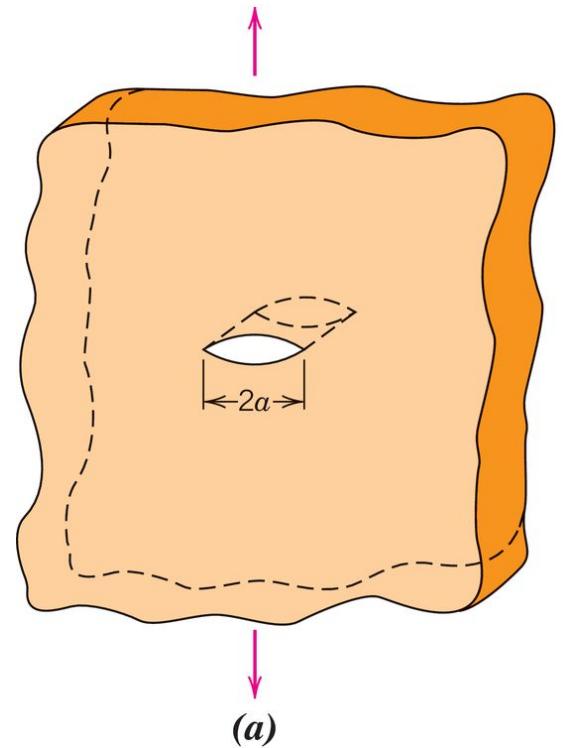


시편의 두께가 시편 전체 형상에 비해 충분히 두꺼울 때, 평면 변형률 조건(plane-strain condition)을 이룬다. 이 때의 K_c 값을 특별히 K_{Ic} (평면 변형률 파괴 인성)라 한다.

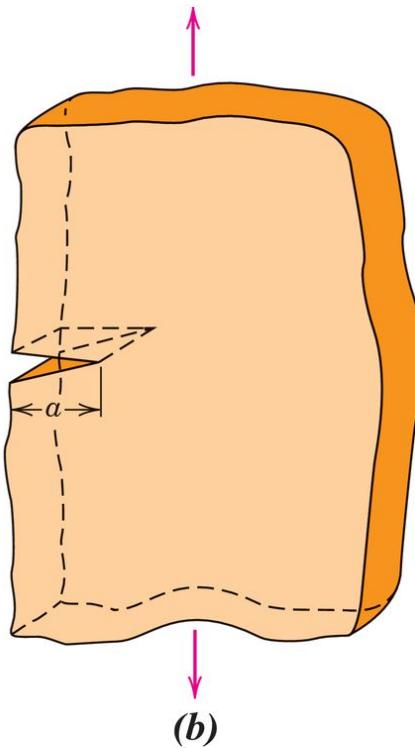
Subscript 'I'는 실제로 관련된 균열면 변위 형태를 이룬다(그림 10.10 참고)

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

Plane-strain condition

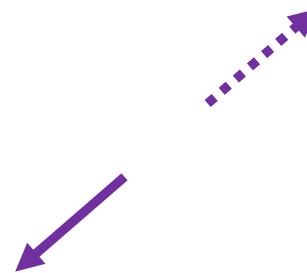


An interior crack in a plate of infinite width



Edge crack in a plate of semi-infinite width

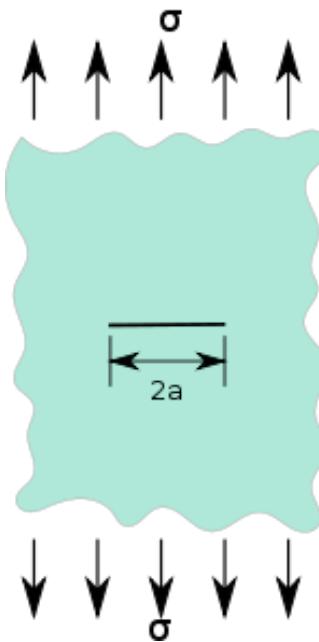
원편의 시편과 같이 충분히 두꺼운 재료에 in-plane uniaxial tension 상태를 가하면 두께방향으로 거의 strain이 없는 상태.



이를 plane-strain condition이라 한다.

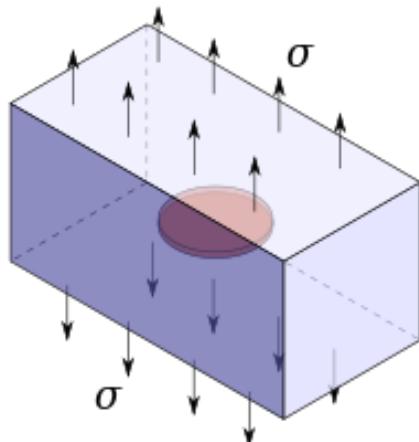
Y값은 균열 크기, 시편의 크기 및 기하학적 형상과 하중 적용 방식에 따라 달라진다.
(a) $Y=1$ (b) $Y \approx 1.1$

Y values under various conditions

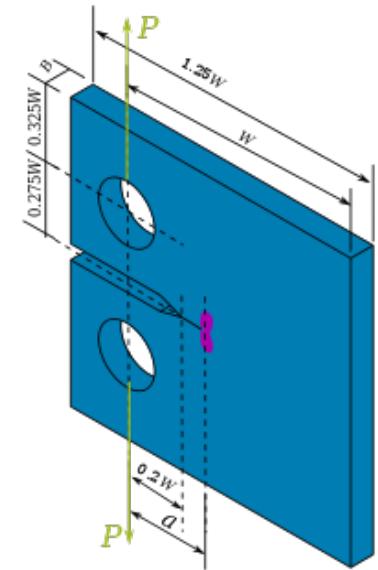


$$K_I = \sigma \sqrt{\pi a}$$

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

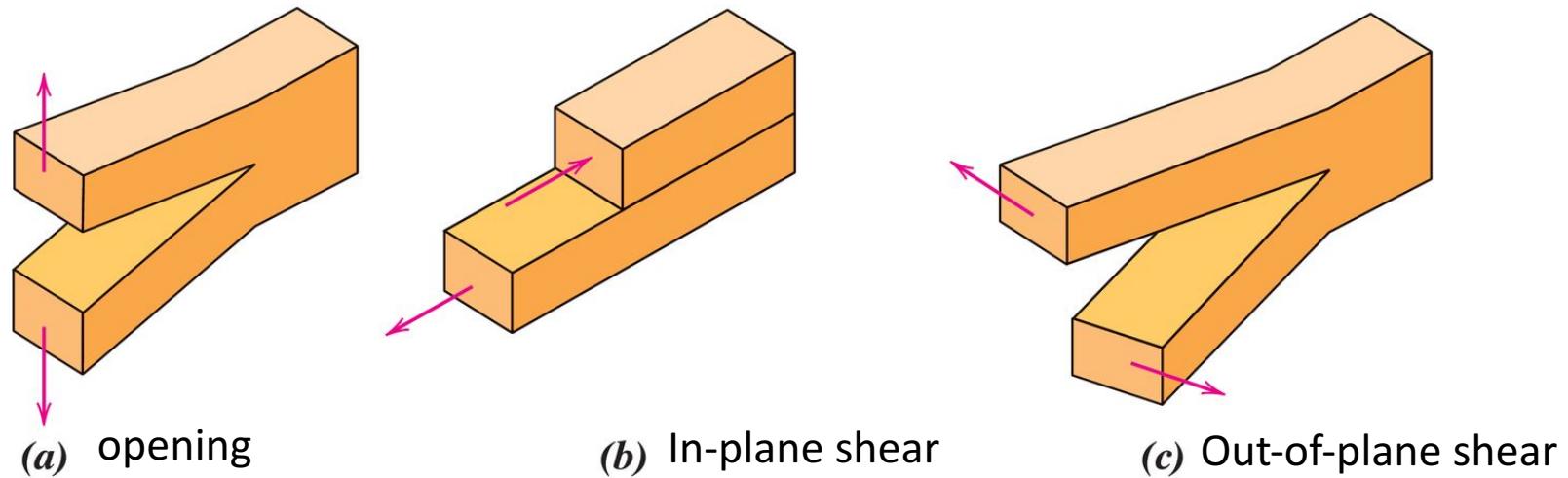


Complex example



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

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 γ 값이 알려져 있다면 파괴 인성(K_{Ic})은 구조물에 가해진 응력(σ), 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

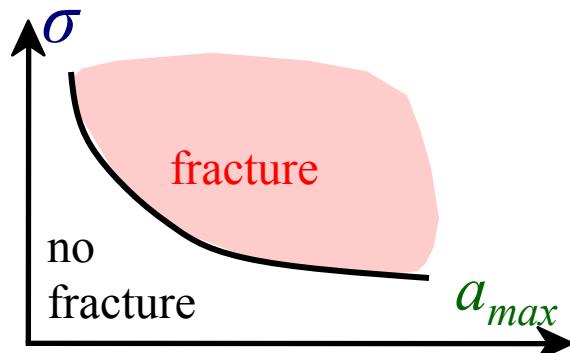
- Crack growth condition:

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

- Largest, most highly stressed cracks grow first!

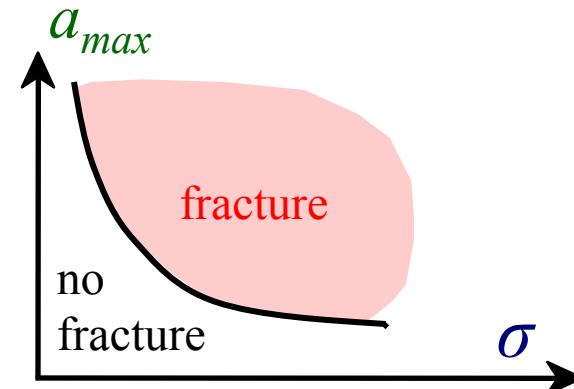
- 결함의 크기와 파괴 인성을 알 때, 허용되는 design stress의 범위를 아래와 같이 표현

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

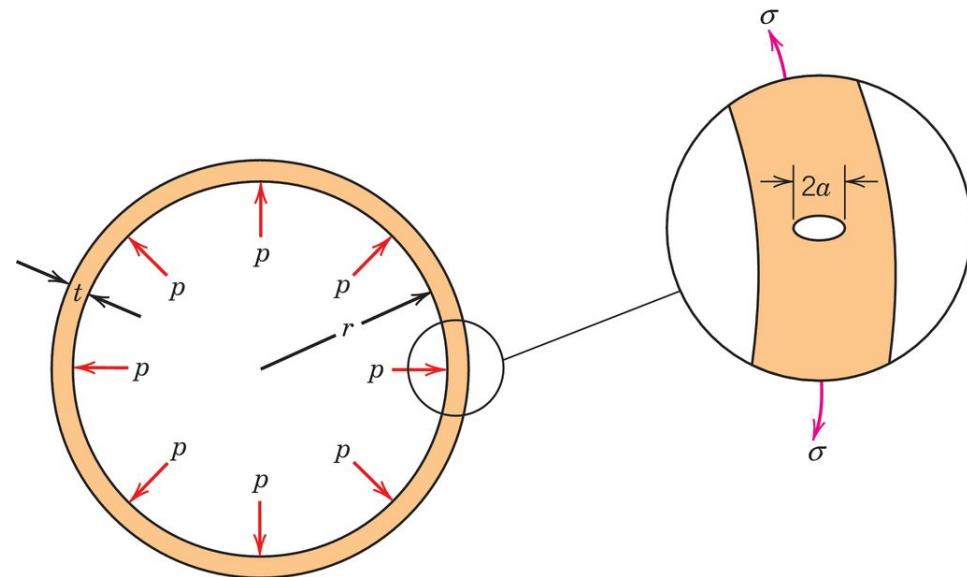


- 구조물의 허용되는(예상되는) design stress와 파괴 인성을 알 때, 허용되는 결함의 크기를 표현 아래와 같이 표현 가능.

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



Example 10.1(a)



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

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

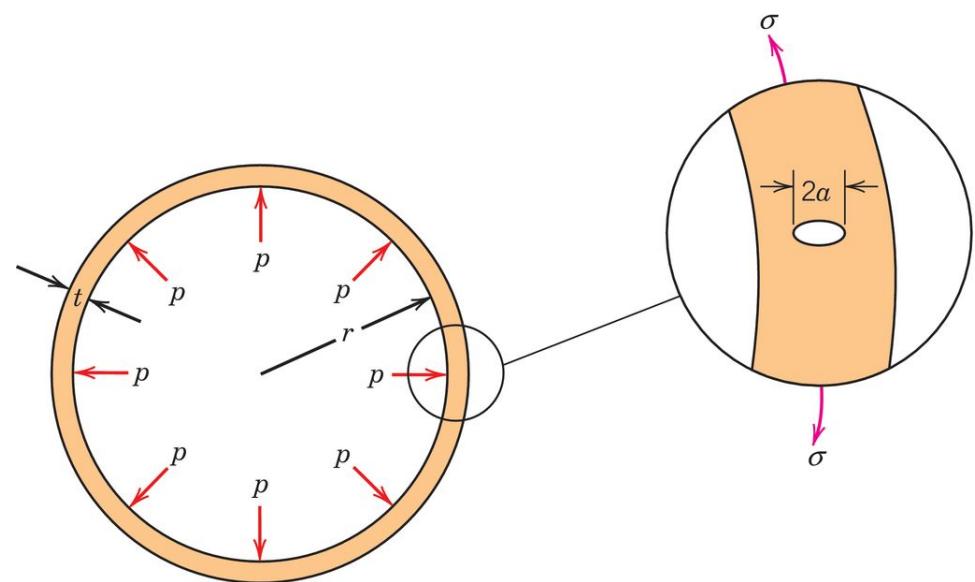
설계조건 1: 해당 탱크의 균열이 생성되어 **파손이 빠르게 진전되기 전에 항복이 일어나도록 설계한다.** 항복이 발생하면 급격한 파손이 일어나기 전에 소성 변형이 일어나 탱크 내부의 압력을 어느정도 나춰주는 효과 (소성변형으로 탱크모양 변화->탱크내부 부피 증가). 주어진 조건에서 제시하는 설계조건을 따라 항복을 발생을 유발하려면 어떤 재료를 사용해야 할까?

결과적으로 파괴가 발생할때의 균열크기 (a_c)가 커야된다 – Eq. 10.7사용; γ 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(σ)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:

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

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

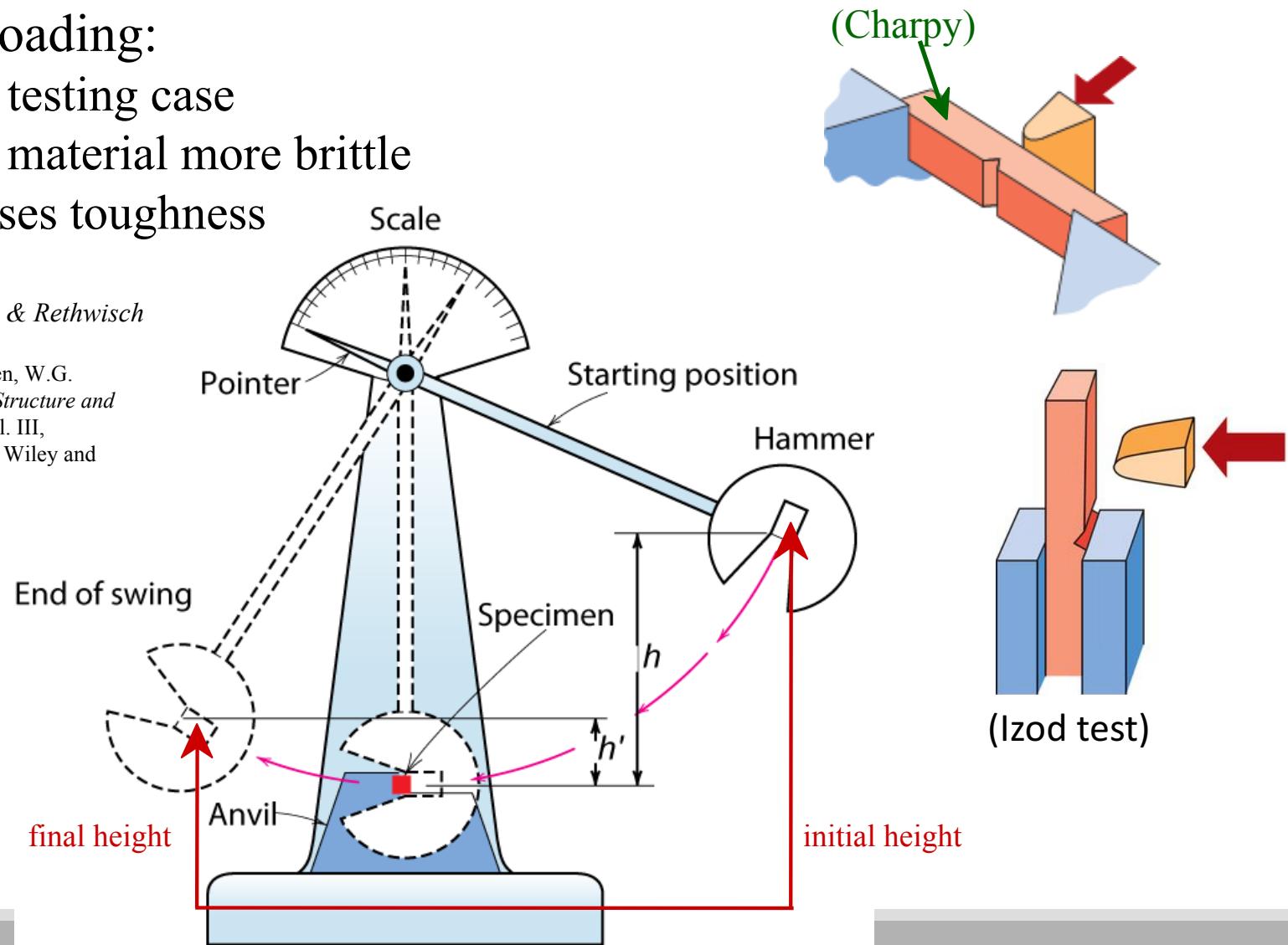
Answer: $(\sigma_c)_B = 168 \text{ MPa}$

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

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

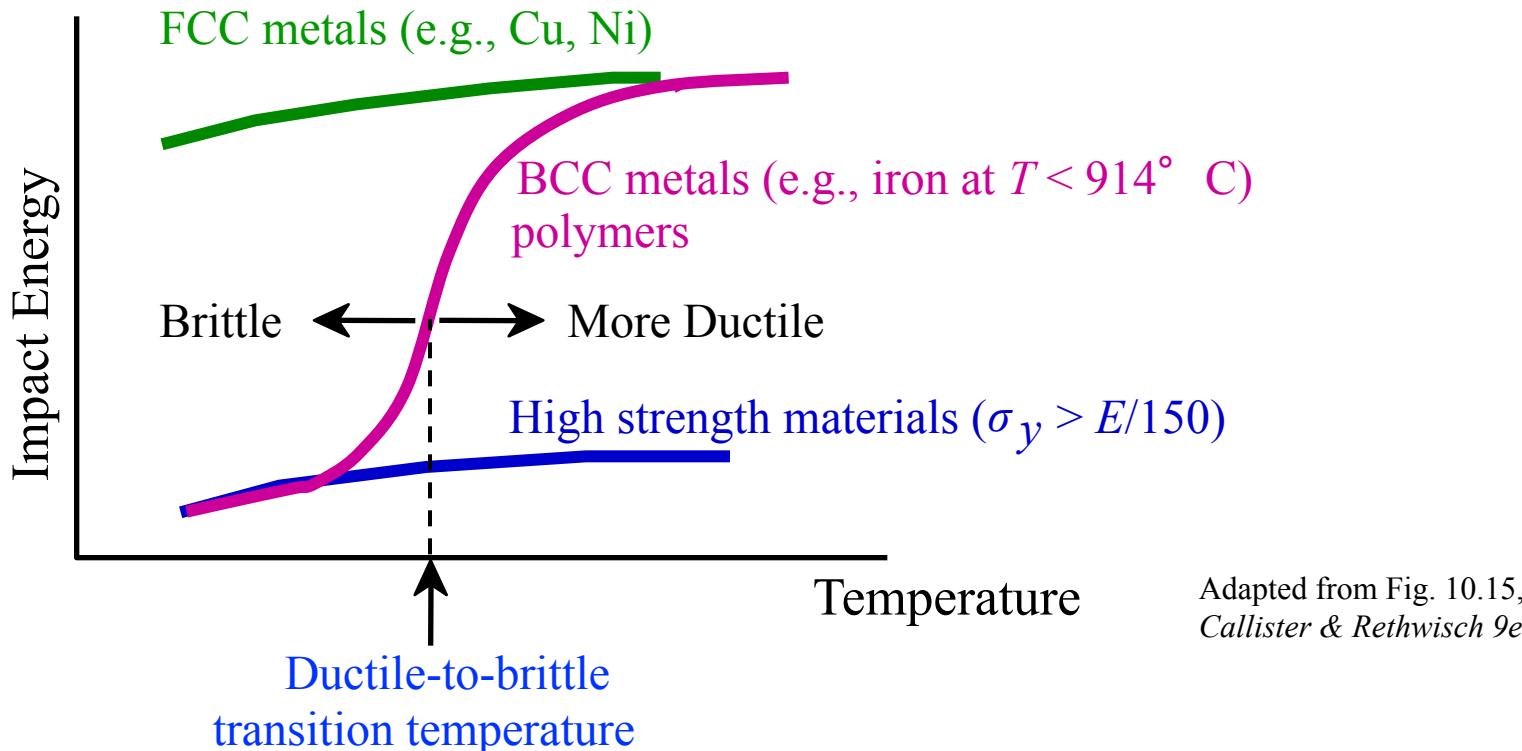
Fig. 10.12(b), Callister & Rethwisch
9e.

(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

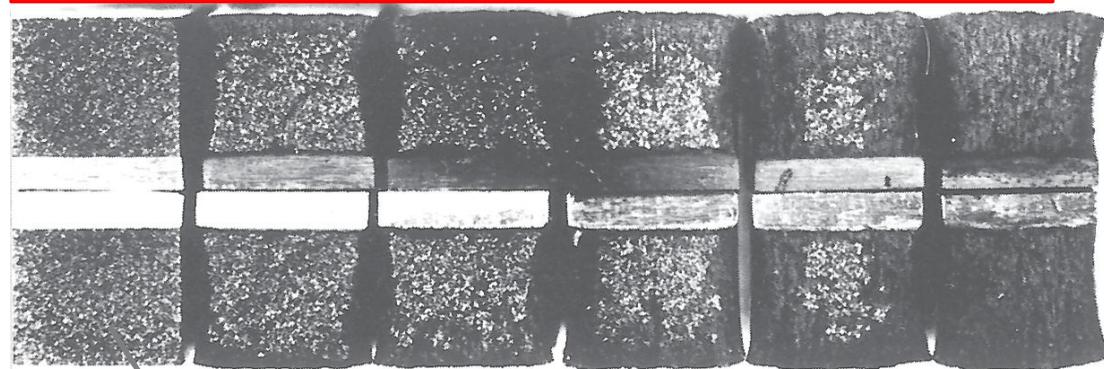
4

16

24

79

→ 실험 온도

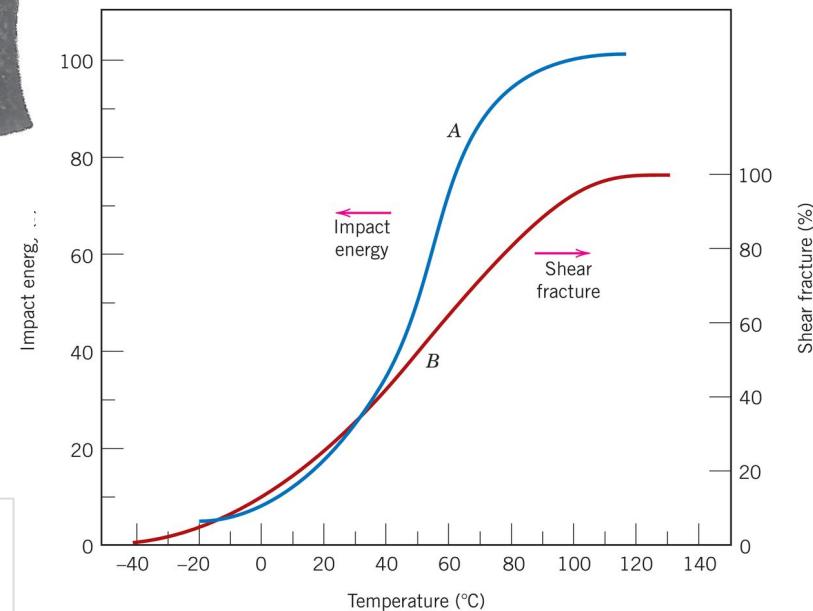


From R. W. Hertzberg, Deformation and Fracture Mechanics of Engineering Materials, 3rd edition, Fig. 9.6, p. 329. Copyright © 1989 by John Wiley & Sons, Inc., New York.
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온도에 따른 파단면의 변화

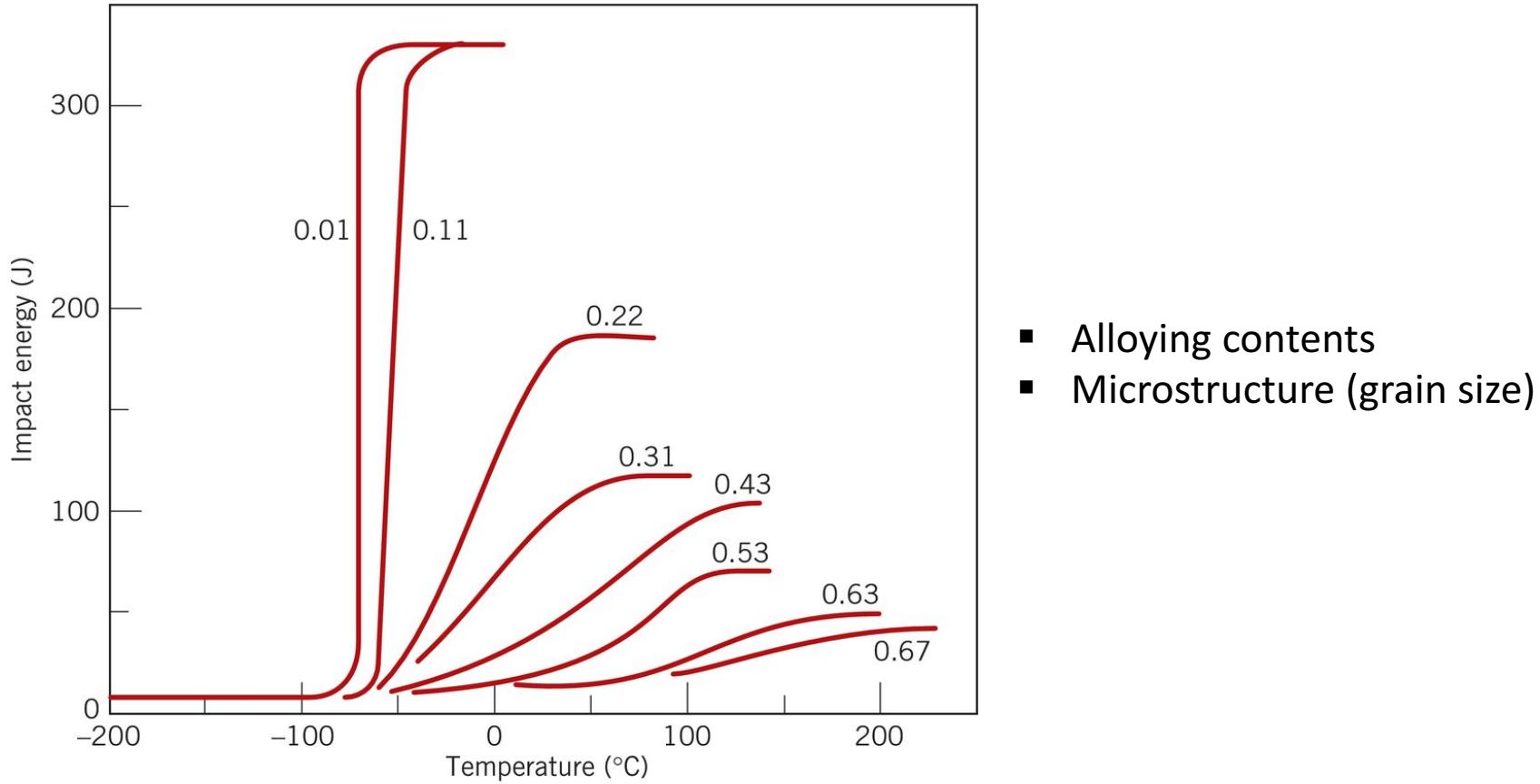
Grainy; faceted texture
(Brittle fracture의 특징)

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



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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.

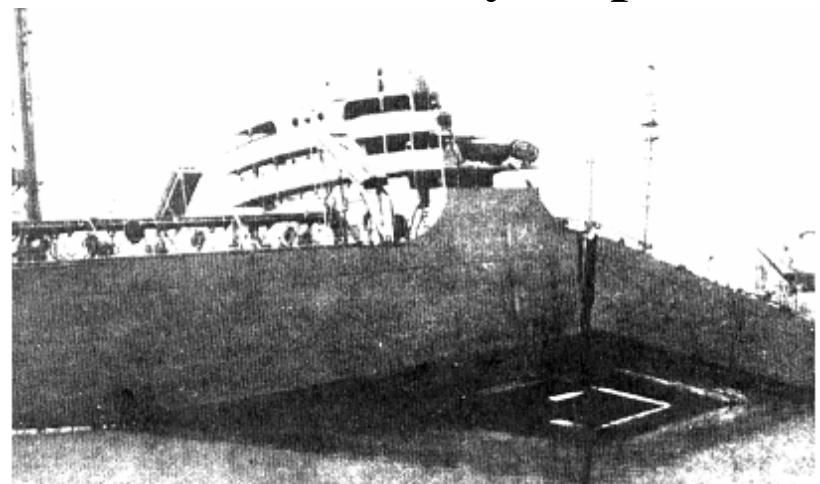
Design Strategy: Stay Above The DBTT!

- 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.)

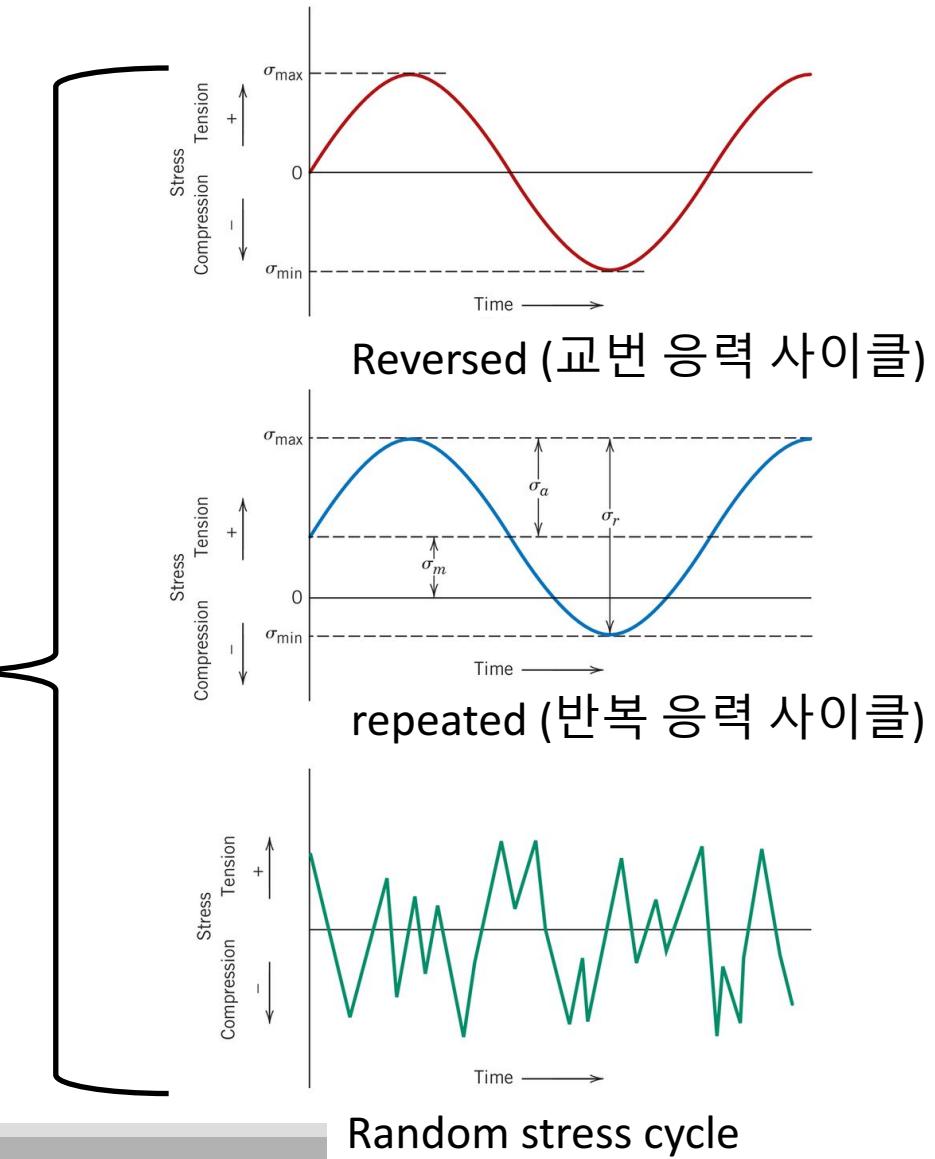
- Problem: Steels (in BCC) were used having DBTT's just below room temperature.

Fatigue (피로)

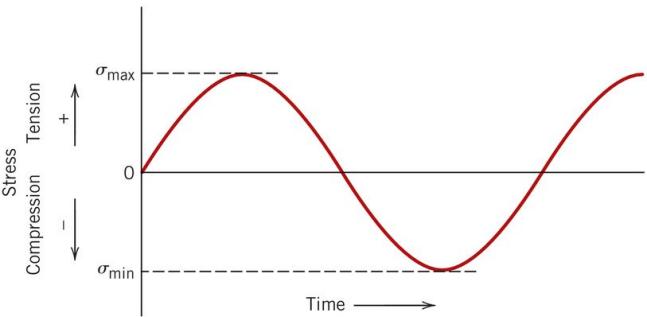
- 항복 강도나 인장강도보다 ‘매우’ 낮은 응력상태에 발생하는 파손. 일반적으로 ‘반복’되는 응력(혹은 변형률) 사이클에 의해 발생하는 파괴.
- 예: 교량 (bridge) – 자동차의 무게가 교량 구조물의 항복 강도나 인장강도에 비해 매우 낮으나, 반복적으로 되풀이 되어 파괴까지 이를 수 있다.
- 높은 응력상태가 아니므로, 소성변형이 거의 발생하지 않고, 그 특징도 전술한 brittle fracture와 유사.
- 주로 두 단계로 진행되어 최종 파손까지
 - 균열의 생성 (crack initiation)
 - 균열의 전파 (crack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

Fatigue and stress cycle

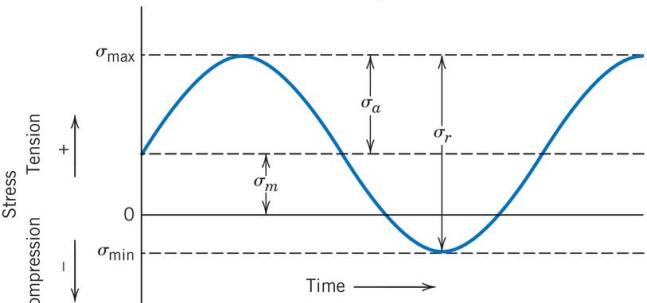
- Fatigue = failure under applied cyclic stress.
- The types of cyclic stress expected for Fatigue:
 - tension-compression
 - bending – unbending
 - twisting – untwisting
- Types of stress-time modes



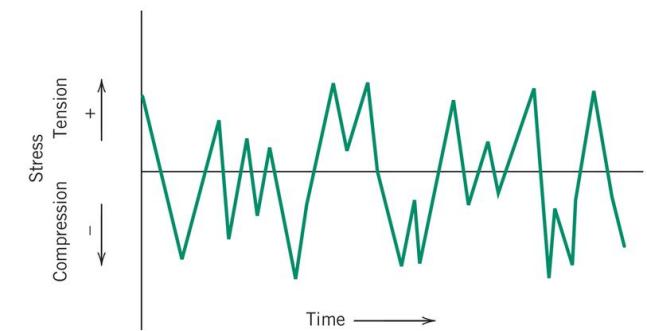
Parameterization of stress cycles



Reversed (교번 응력 사이클)



repeated (반복 응력 사이클)

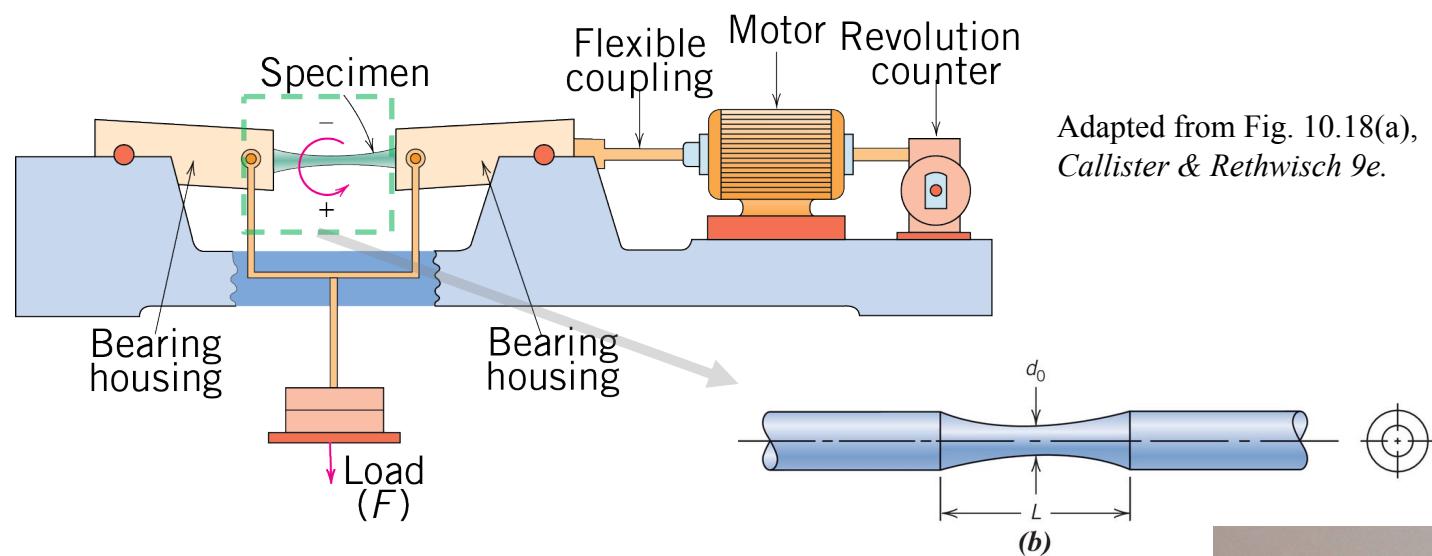


Random stress cycle

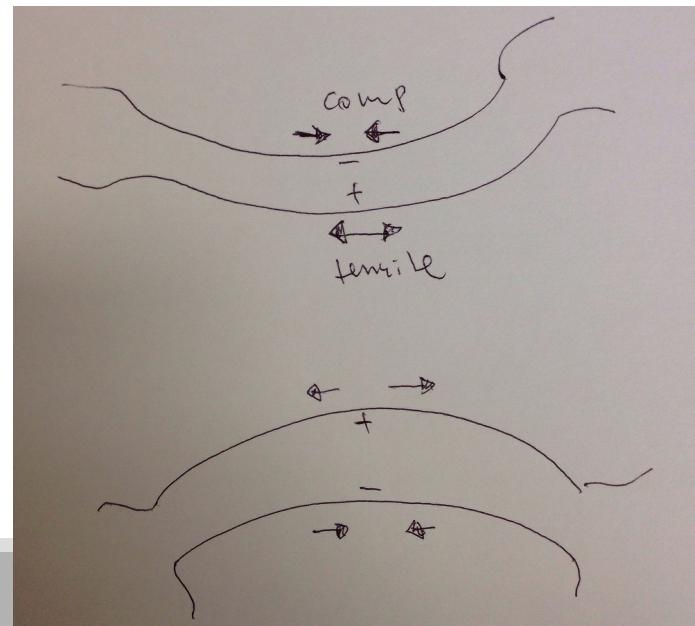
■ 응력 사이클을 매개변수화 – 즉 적은 개수/종류의 간단한 parameter를 통해서 표현해내는 방식으로 응력 사이클을 나타내기도 한다.

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

A typical fatigue test

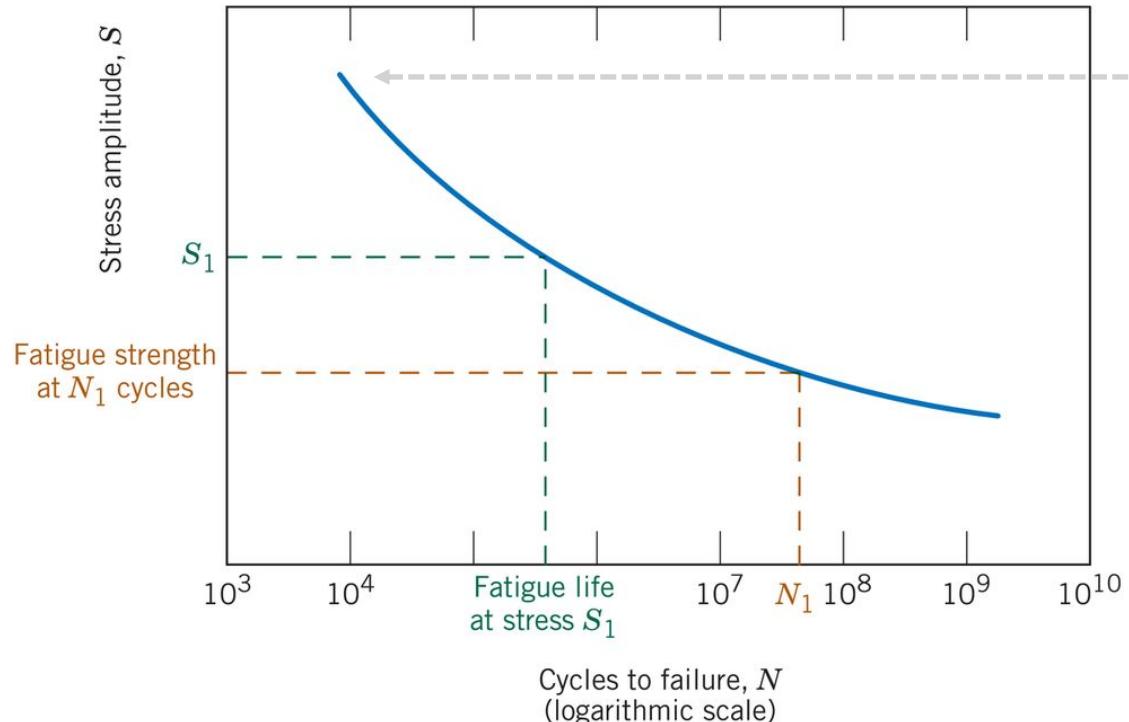


An example where the stress cycle is realized in combination of '**rotation**' and '**bending**'.



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

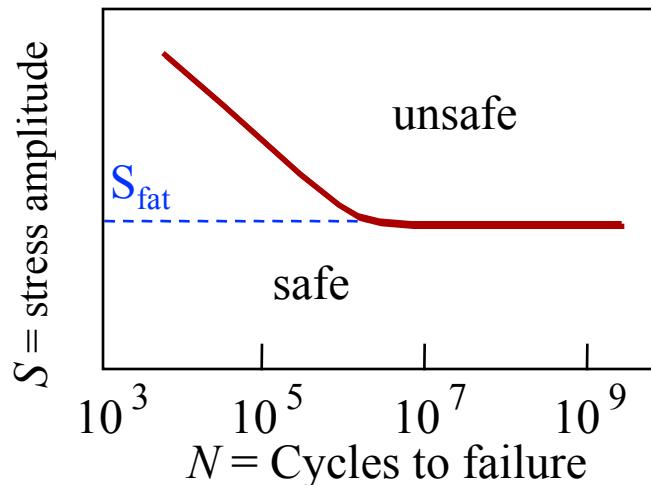
점점 낮은 $\sigma_{\text{amplitude}}$ 값을 설정후 실험을 반복

Low-cycle
fatigue

High-cycle fatigue

Types of Fatigue Behavior

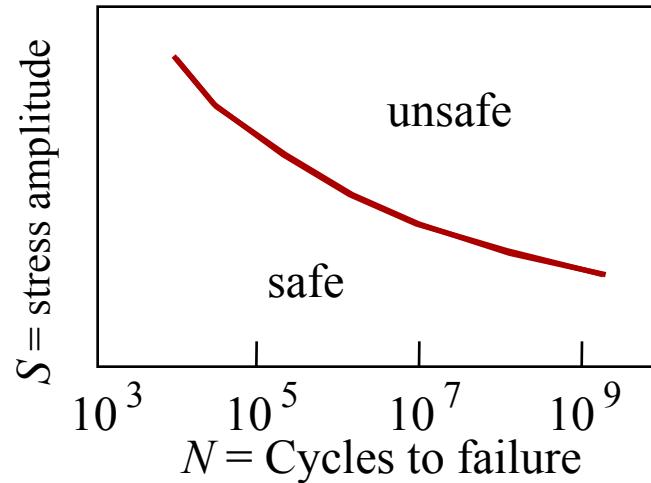
- Fatigue limit (endurance limit), S_{fat} :
--no fatigue if $S < S_{\text{fat}}$



case for
Steel, Ti alloys ...

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

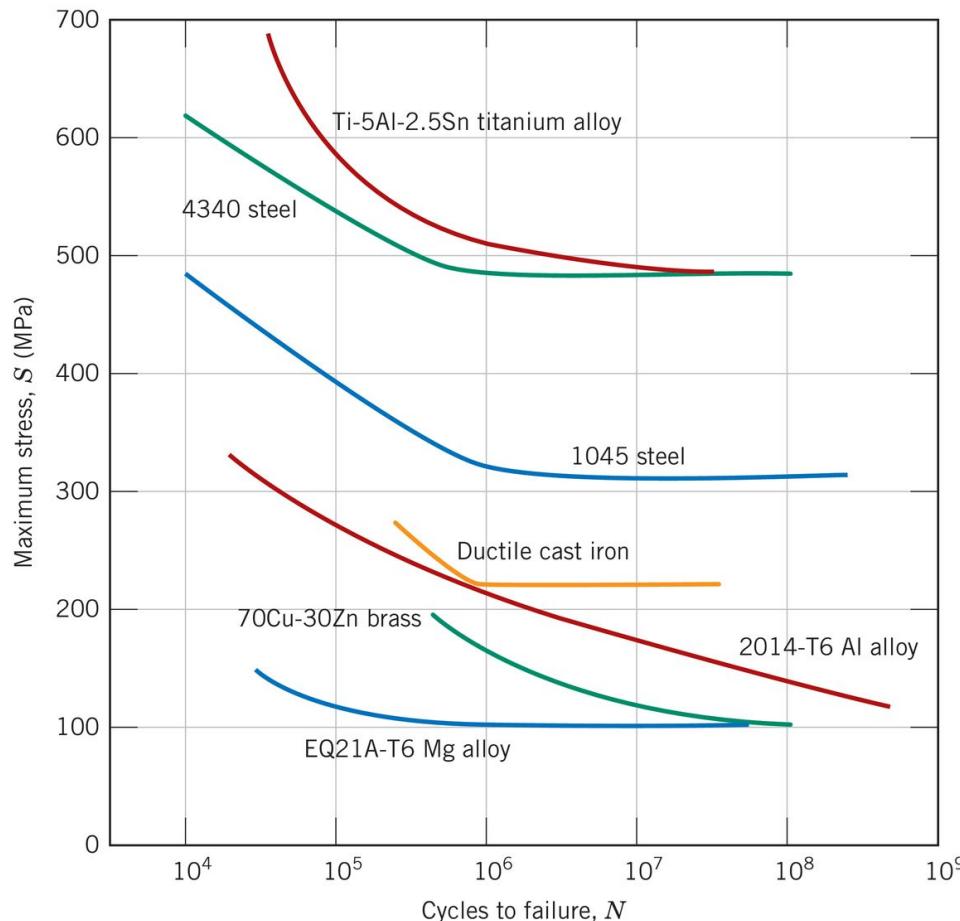
- For some materials, there is no fatigue limit!



case for
Al, Cu, Mg...

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

S-N curves for various materials

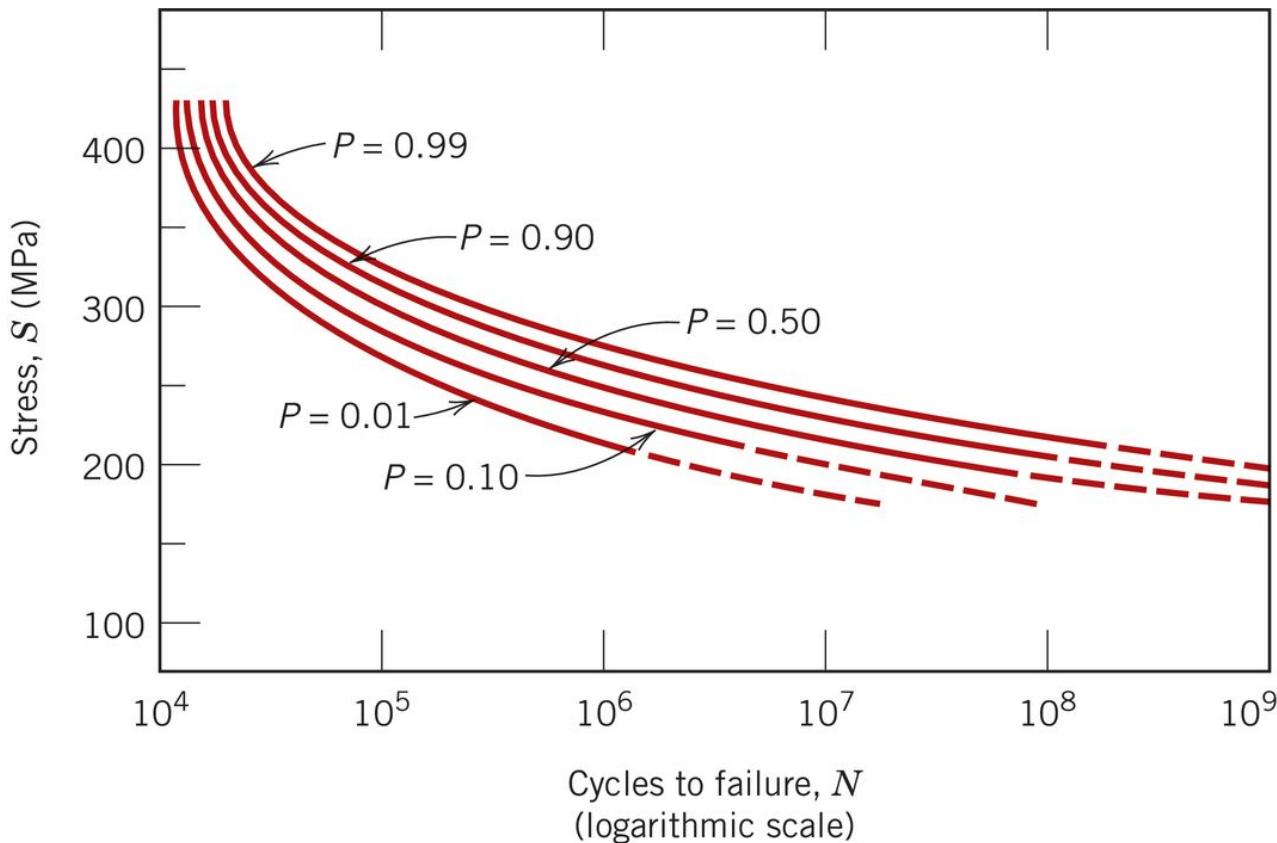


- 교번 응력 실험으로 얻어진 다양한 금속 재료의 S-N 곡선
- Fatigue limit을 보여주는 재료를 찾아보자.

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

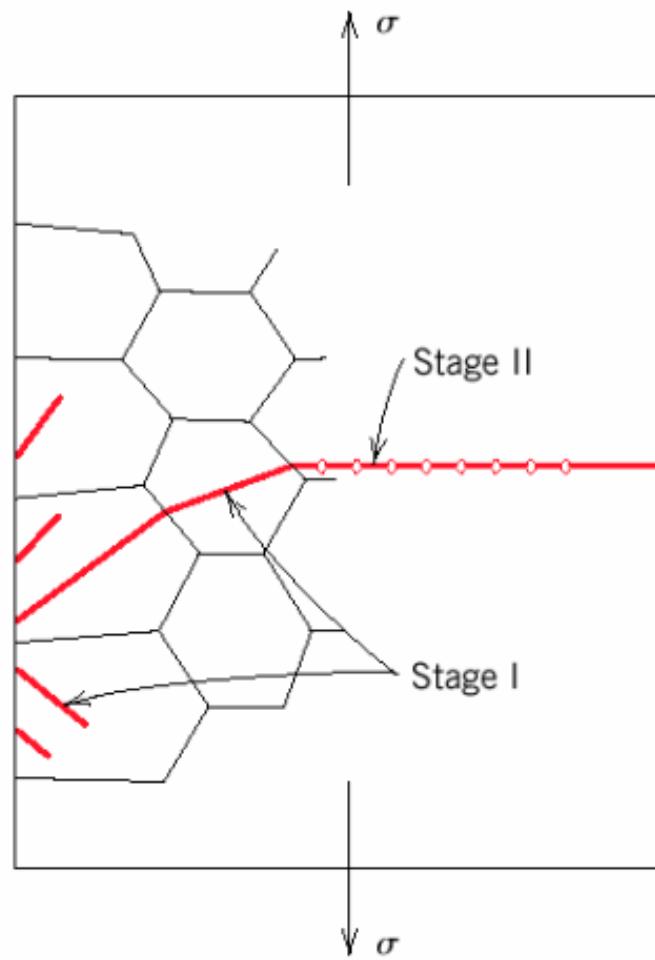
- 1) Crack initiation (균열 생성)
 - Small crack is created where the stress is ‘concentrated’.
- 2) Crack propagation (균열 전파)
 - Crack advances incrementally with each stress cycle
- 3) Final failure
 - When crack reaches the ‘critical’ size, failure rapidly occurs
- Cyclic loading can produce ‘steps’ caused 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

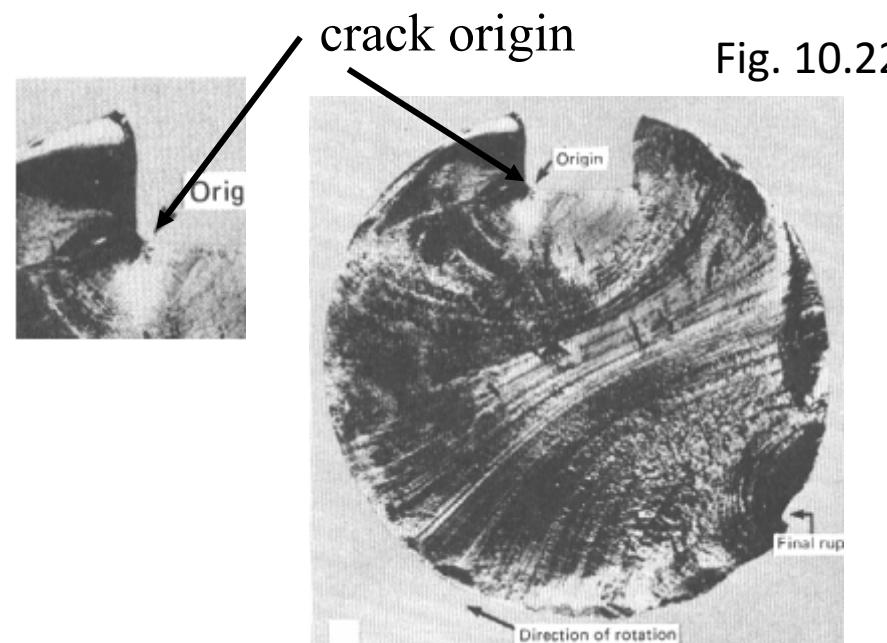


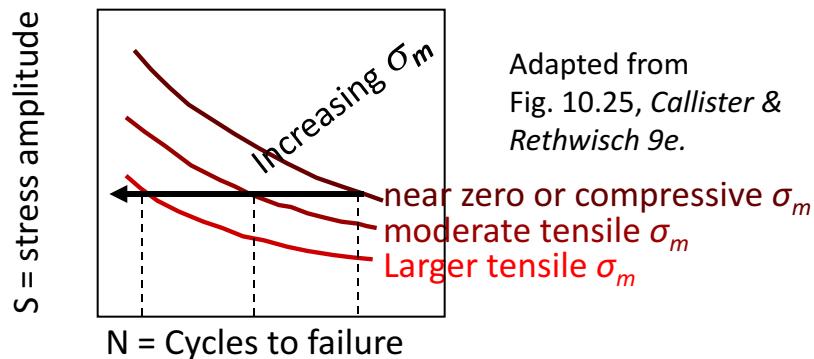
Fig. 10.22

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

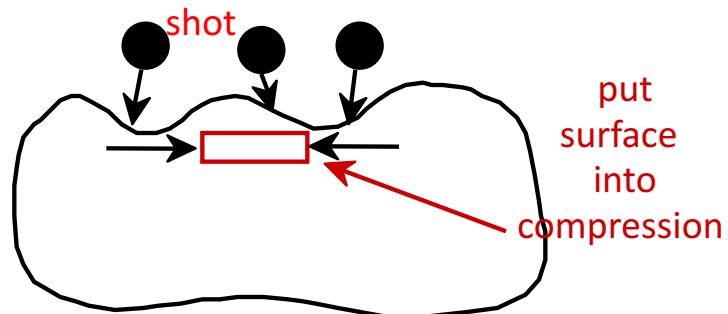
How to Improve Fatigue Life (Read Ch 10.10)

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

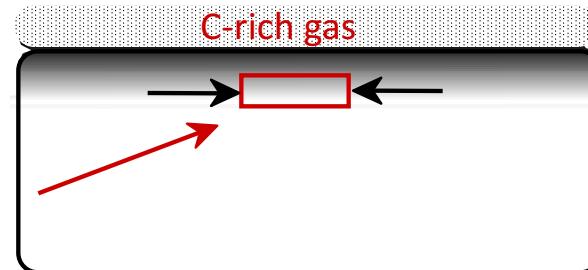
Adapted from Fig. 10.25, Callister & Rethwisch 9e.



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



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



2. Remove stress concentrators.

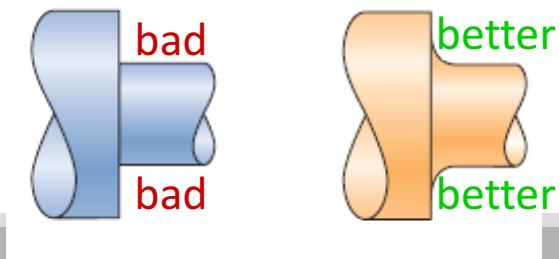
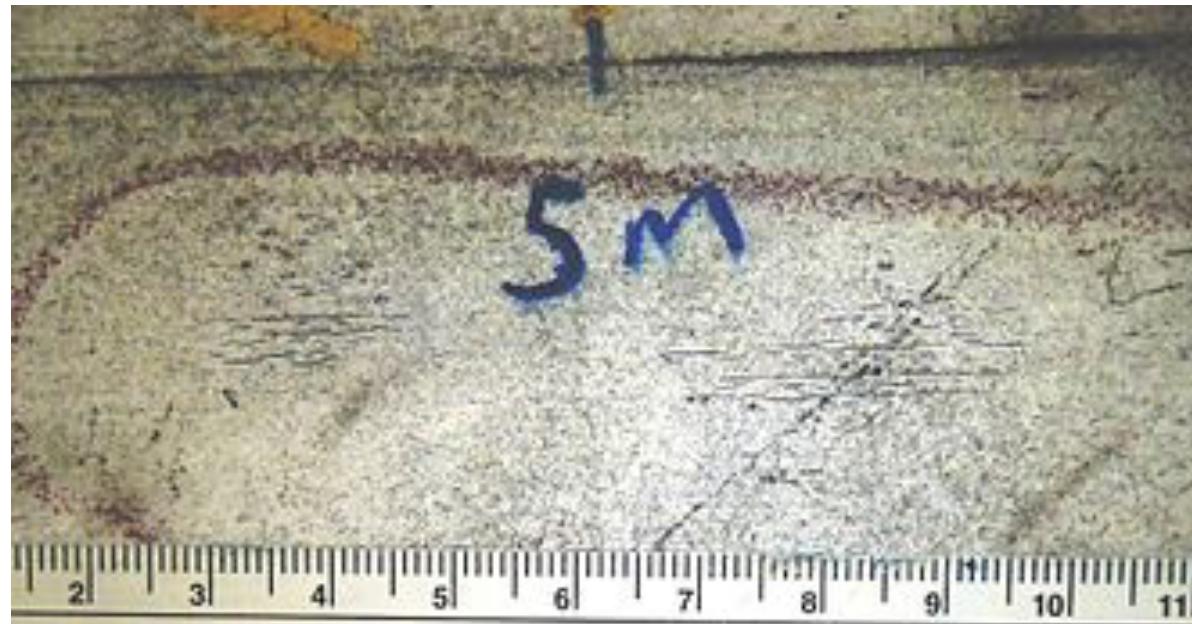


Fig. 10.26, Callister & Rethwisch 9e.

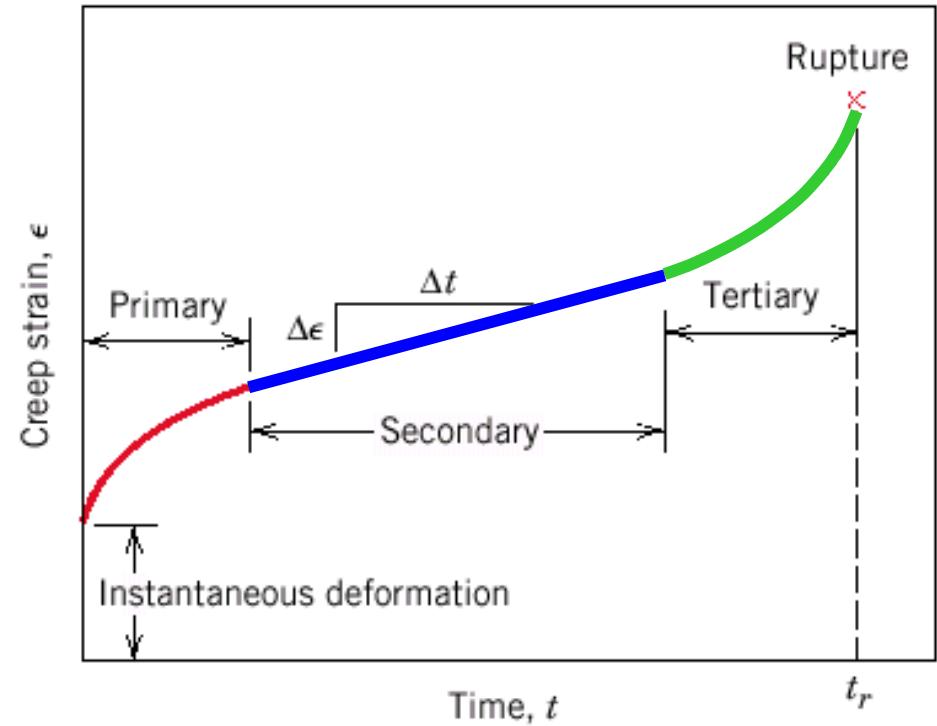
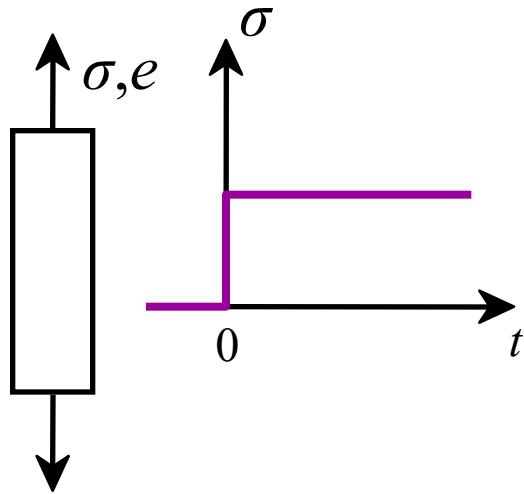
Other factors

- 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 (σ) vs. time



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

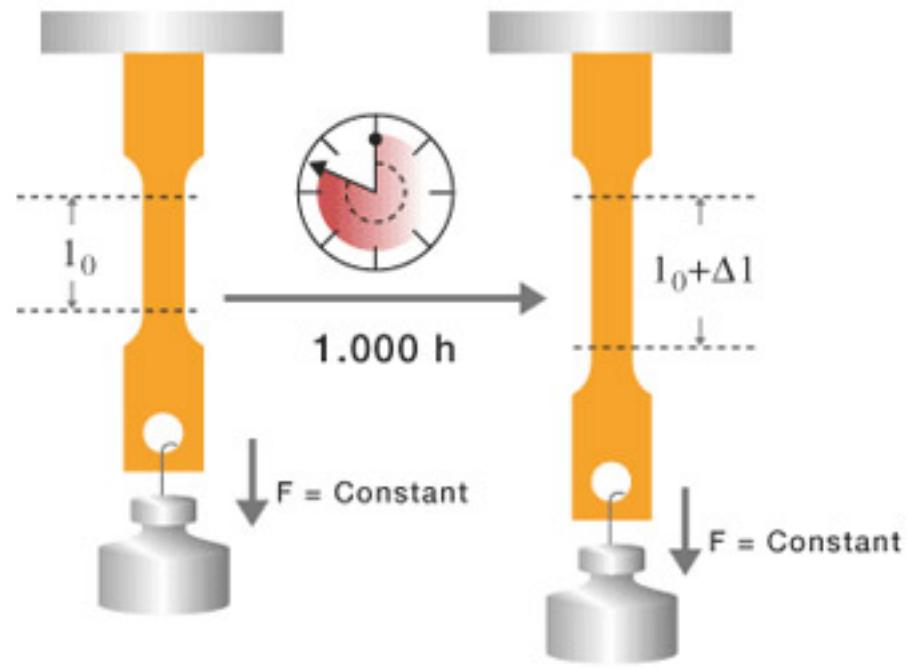
Secondary Creep: steady-state i.e., constant slope ($\Delta\epsilon / \Delta t$).

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

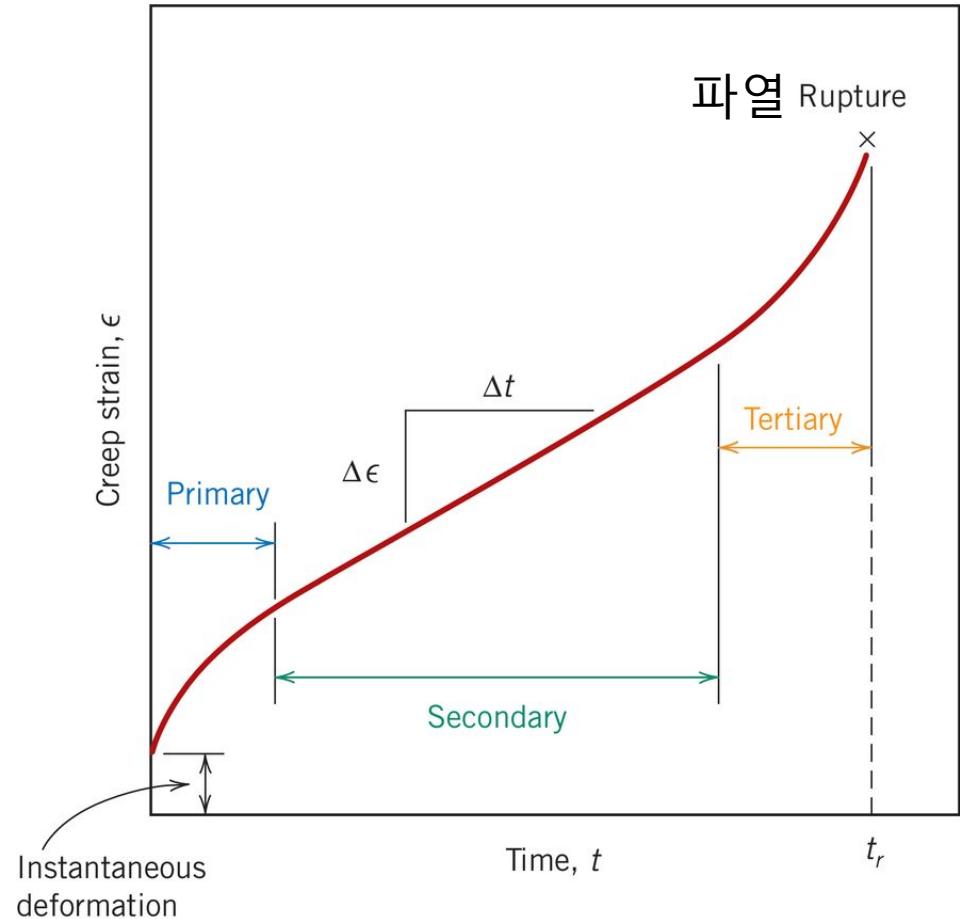
Adapted from
Fig. 10.29, Callister & Rethwisch 9e.

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 ($0.4 > T_m$)

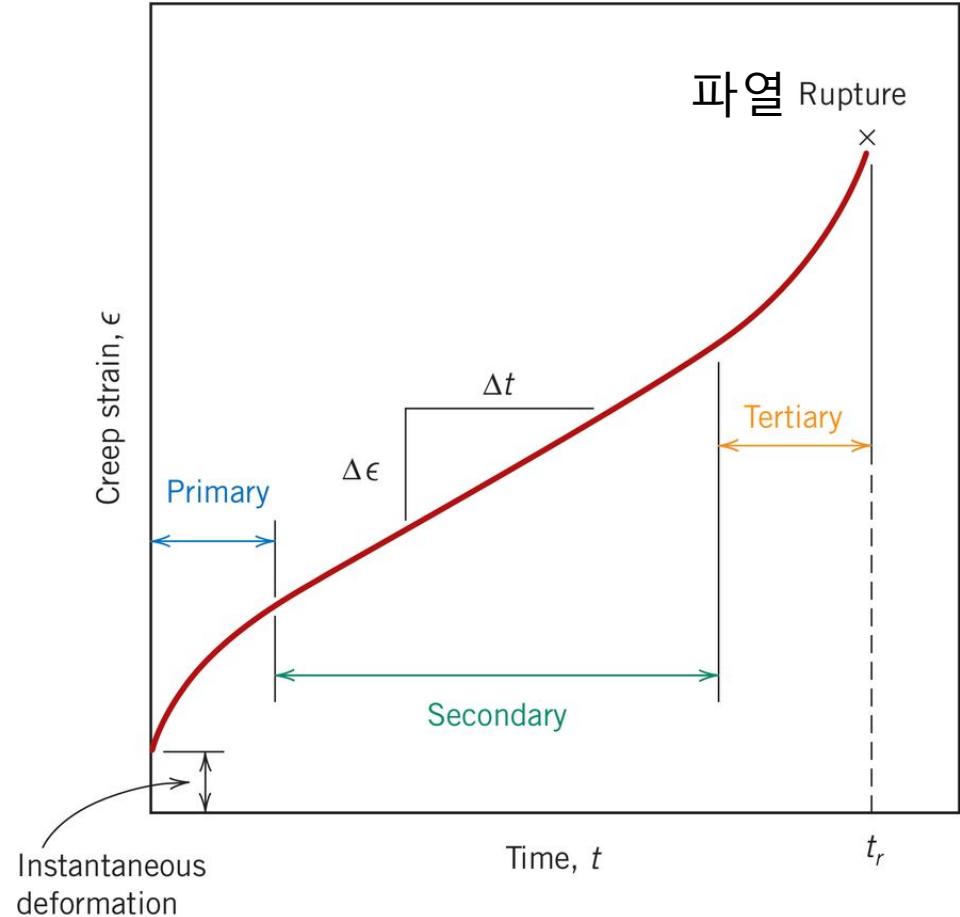


Creep test under constant load



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;

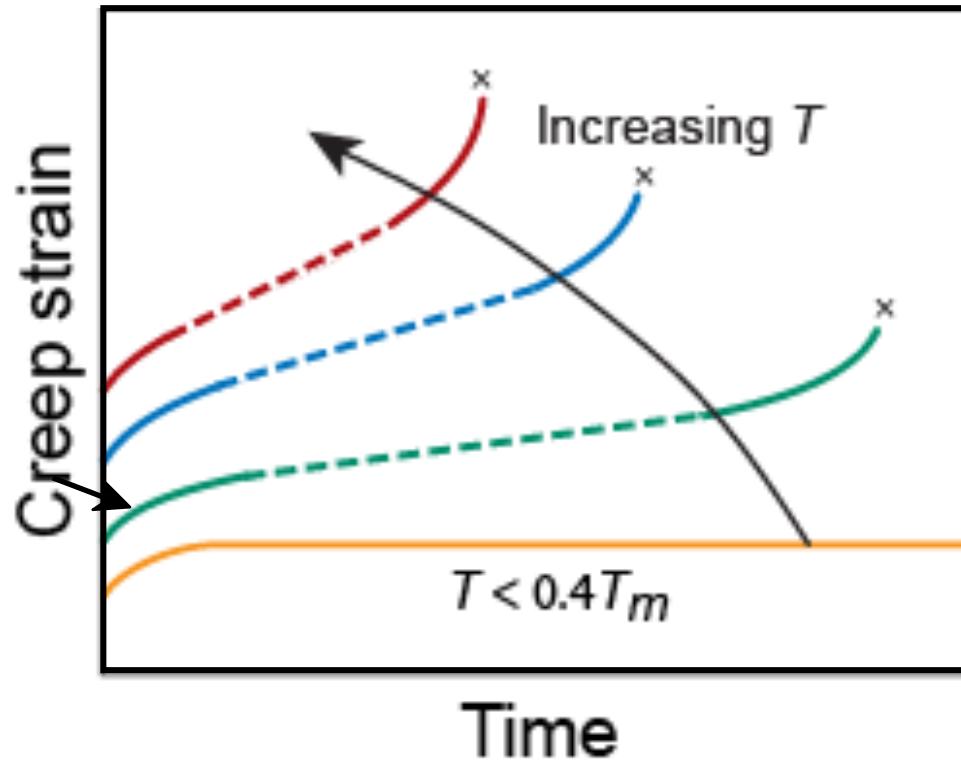
Two parameters from creep test



- 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

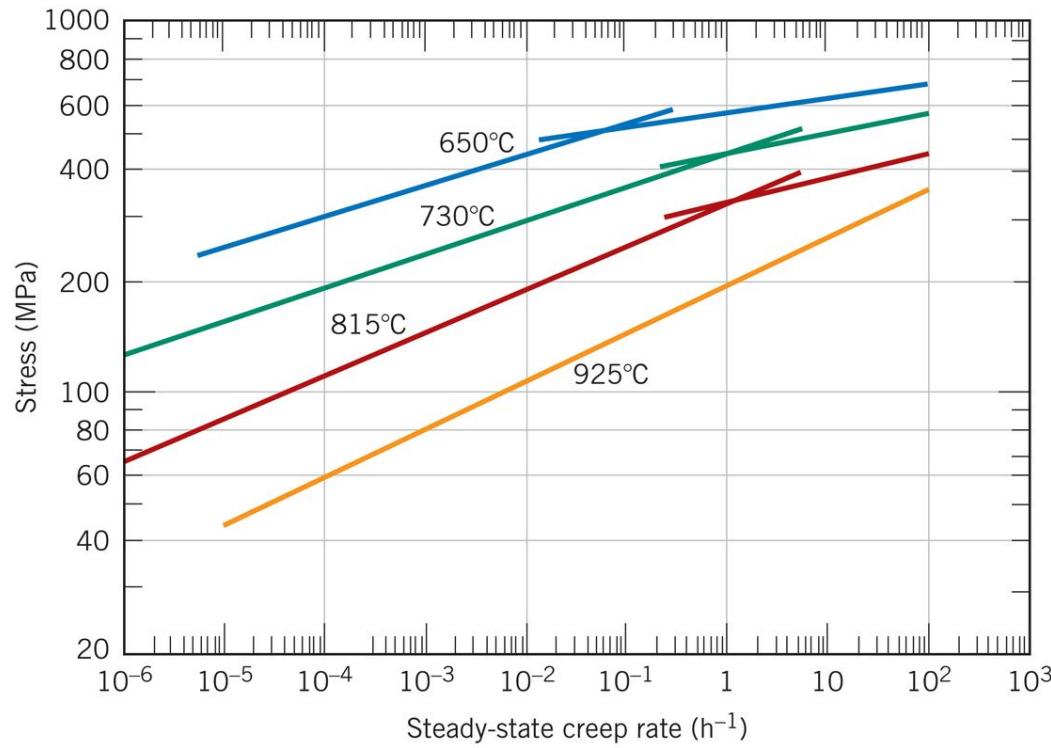


Figs. 10.30, Callister &
Rethwisch 9e.

Creep characteristic affected by stress

- $\dot{\epsilon}_s = K_1 \sigma^n$

- 정상 크리프 속도의應력 의존성을 power-law type 의 실험식으로 설명



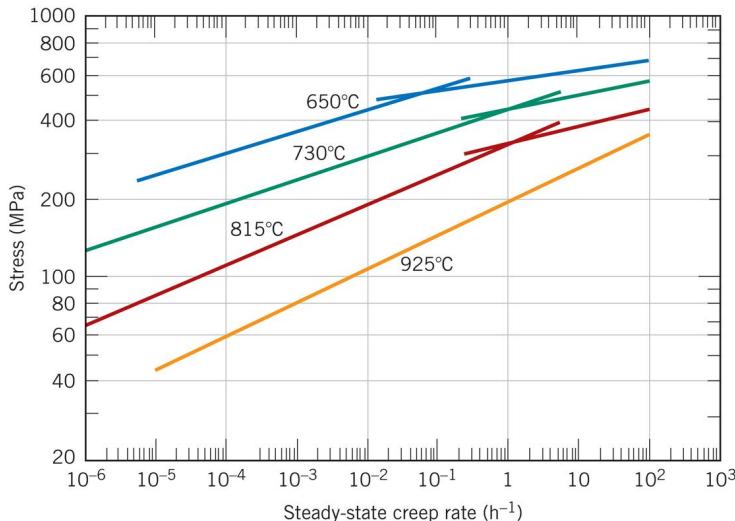
$$\ln \dot{\epsilon}_s = n \ln \sigma + \ln K_1$$

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

$y=ax+b$ 的 형태 (즉, 선형 관계)

Creep characteristic affected by stress and temperature

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



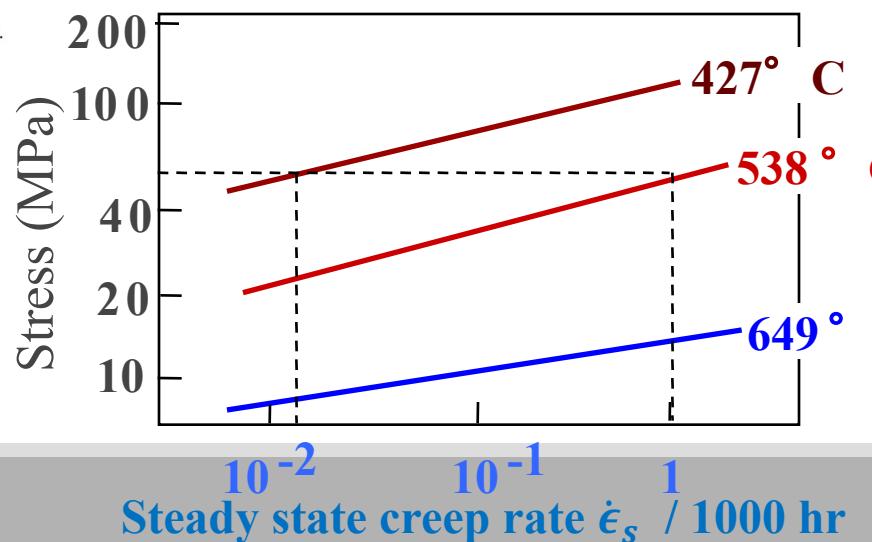
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온도 구간에 따라 다른 '기울기'. 이는 온도에 따라 n, Q_c 값이 달라지기 때문.

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

- 기공확산
- 입계확산
- 전위 이동 및 입계 슬립

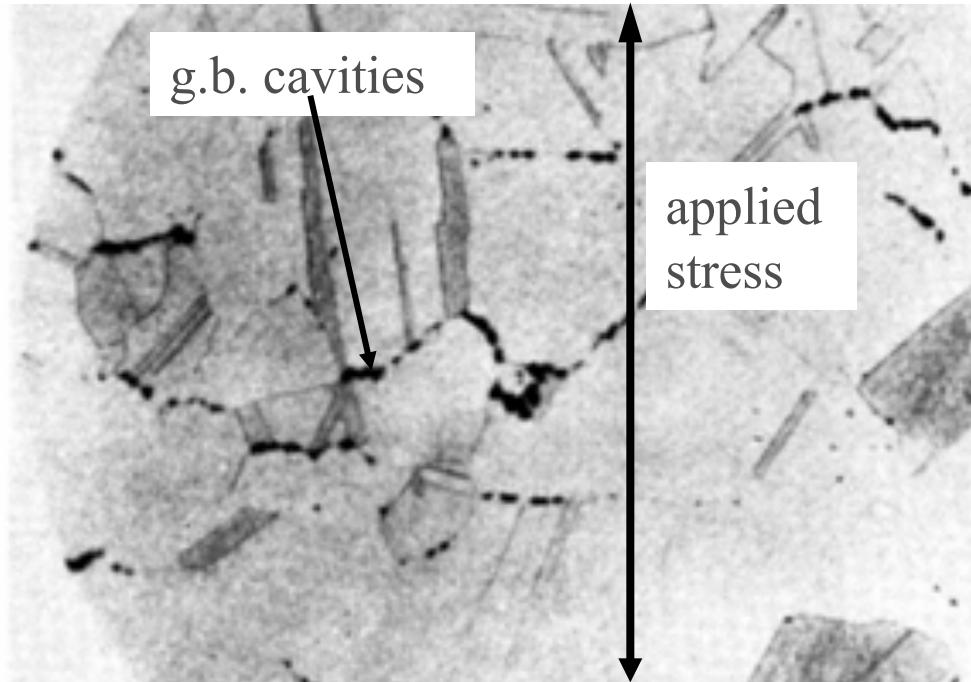
- Creep Strain rate increases with increasing T, σ



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.)

Data extrapolation methods

- 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

- 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 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.

References

- <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.