Chapter3

Dislocation and strengthening mechanisms

강의명: 기계재료공학 (MFA9009)

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Recap

- Crystal structure
- Defects, point, lines, and bulk
- Dislocation
- Mechanical properties.
  - Yielding
  - Plasticity
  - Strain hardening.

Objectives

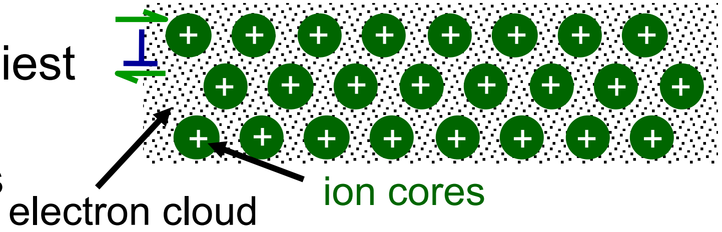
- 원자의 관점에서 살펴보는 전위 (edge, screw – 칼날 전위와 나사 전위)
- 전단 응력에 의한 전위의 이동 그에 따른 소성 변형
- Slip system
- 소성변형에 따른 금속의 입자 구조 변화
- 입계의 전위 이동 방해 – grain boundary acts as barrier to dislocations
- Substitutional solid solution strengthening – interaction between disl. And lattice distortion
- Interaction between dislocation and strain field – strain hardening (변형률 강화), cold working (냉간 가공)
- Heat treatment (열처리); Annealing, recovery, recrystallization and grain growth.

Theory of dislocation

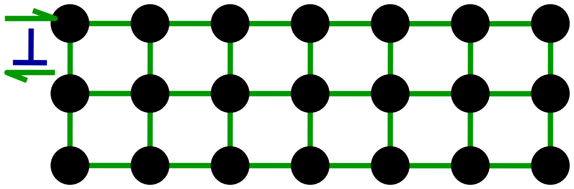
- 전위는 직접 발견되기 전에 이미 존재할 것으로 예상되었다.
  - 전위가 없는 완벽한 결정 구조의 강도의 계산치가 실제 실험치에 비교해 매우매우 컸다.
  - 전위가 있다고 가정한 후 계산하였더니, 실제 실험치와 근사 (1930)
  - 그 이후로 온갖 전위 이론들이 제시되었다.
- 차후 전자 현미경의 발달로 전위가 직접 관찰됨 (1950)
  - 위의 전위 이론들에 의해서 보였던 다양한 모델들을 전자 현미경으로 검증, 증명.

Dislocation and materials classes

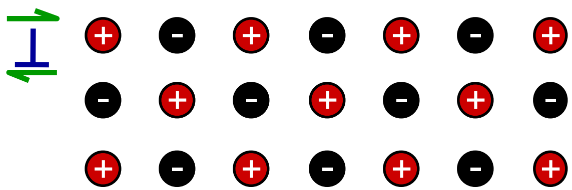
- Metals (Cu, Al):
  Dislocation motion easiest
  - non-directional bonding
  - close-packed directions for slip



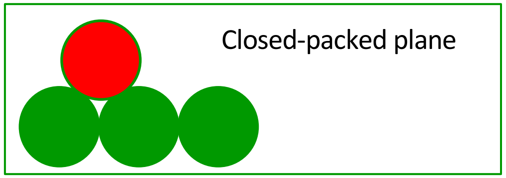
- Covalent Ceramics (Si, diamond): Motion difficult
  - directional (angular) bonding

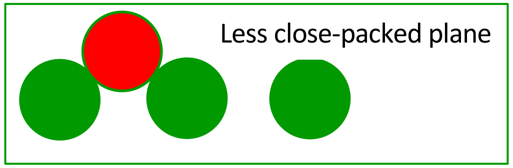


- Ionic Ceramics (NaCl):
  Motion difficult
  - need to avoid nearest neighbors of like sign (- and +)



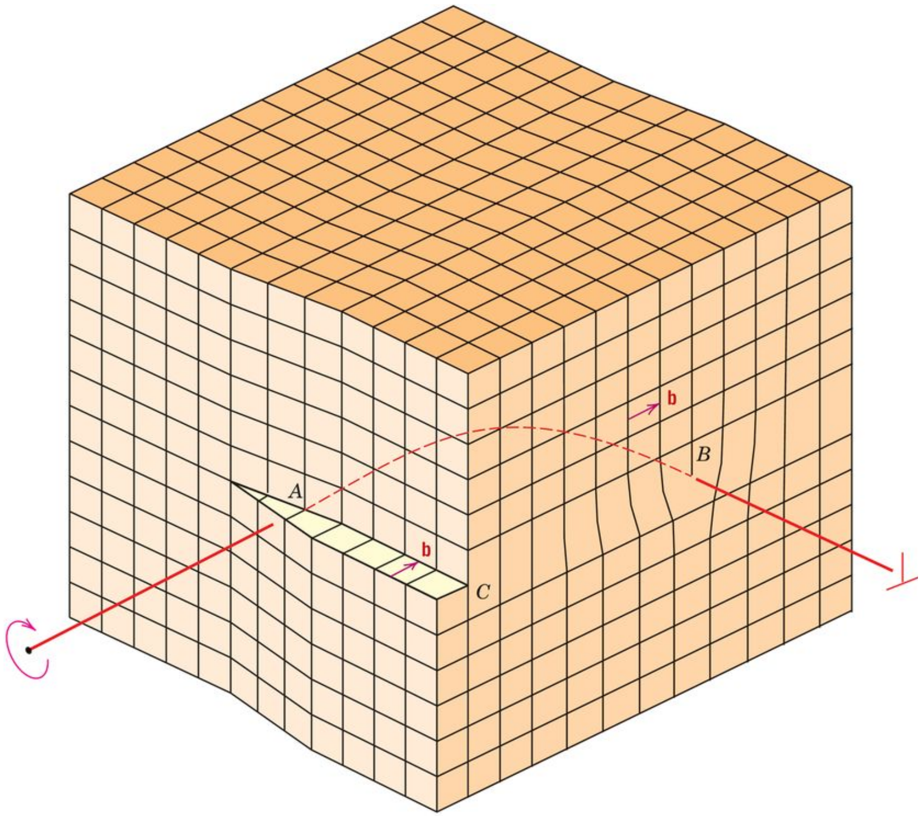
Q) Why does disl. move along close-packed direction?



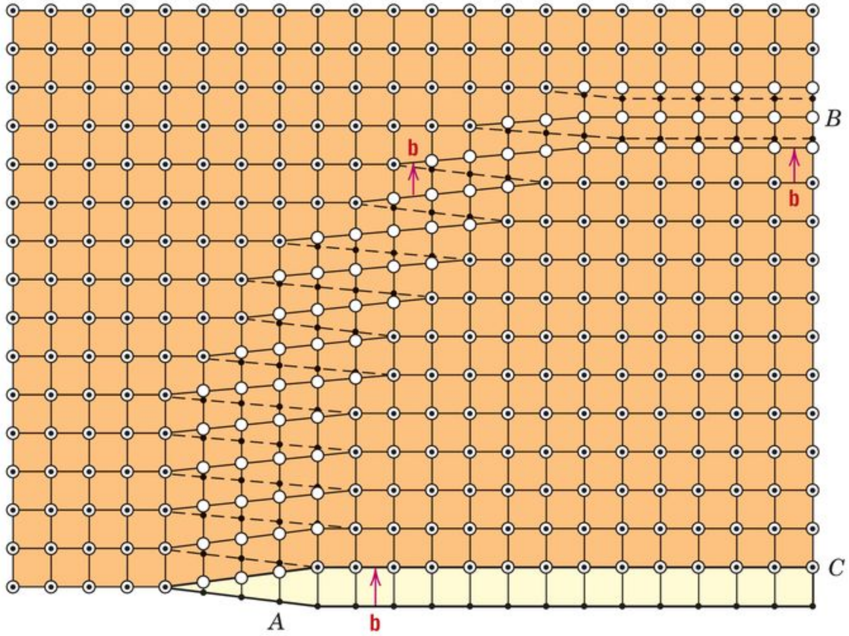


Q) Does slip only occurs on close-packed plane?
A) No. In case no close-packed plane exists, less closed-packed plane serves to accommodate dislocation slips.

Recap: dislocations



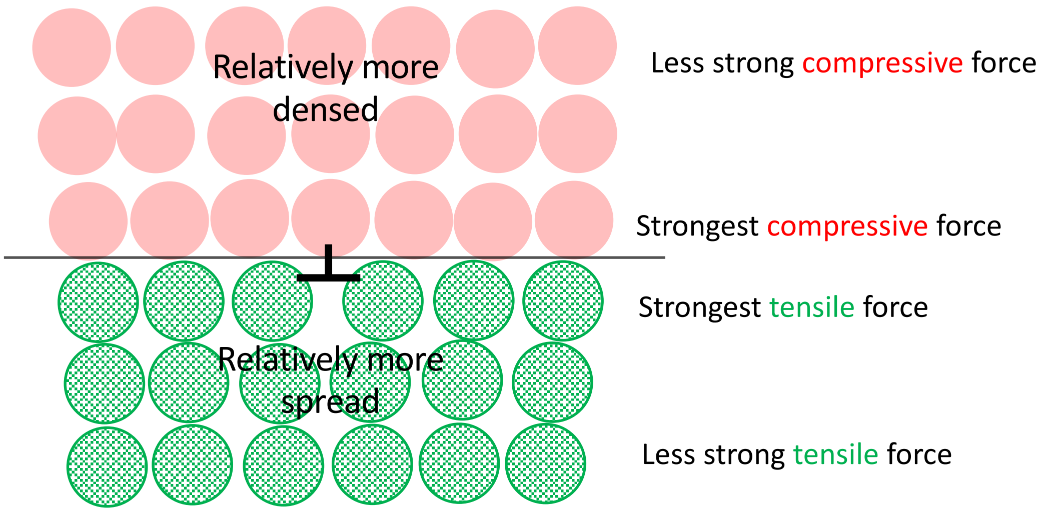
(a)



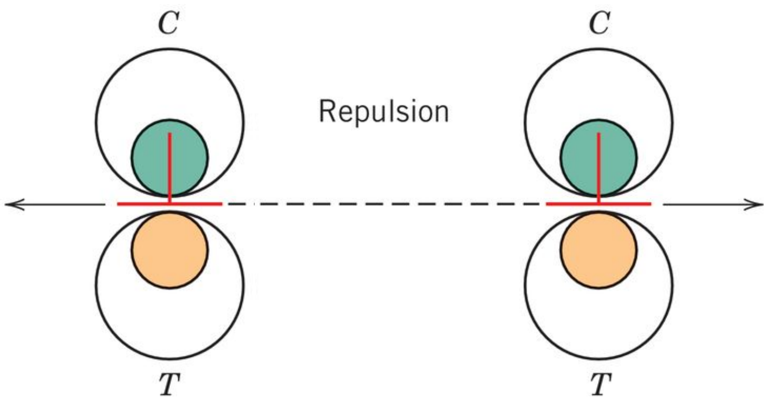
(b)

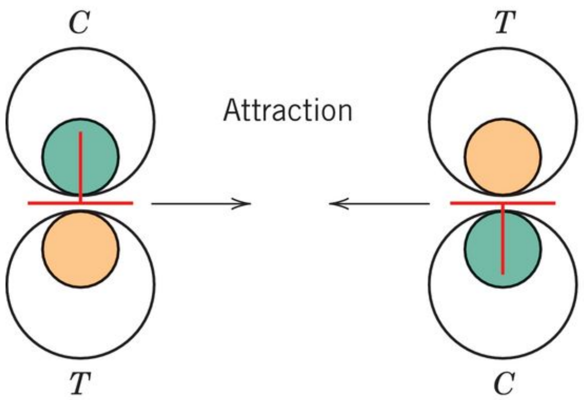
Dislocation and strain field

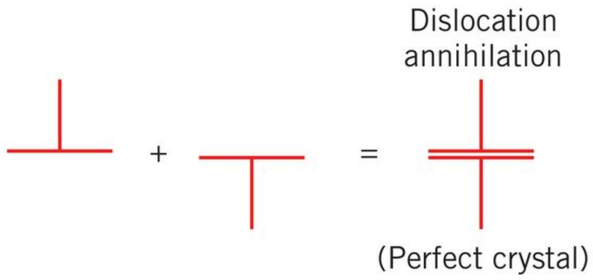
- Dislocation induces lattice distortion – 힘평형 상태에서 벗어난 원자간의 거리. 따라서 격자의 뒤틀림 변형률 (lattice distortion; lattice distortion strain) 그리고 그에 따라 뒤틀림 응력장 (stress field).



Interactions between dislocations



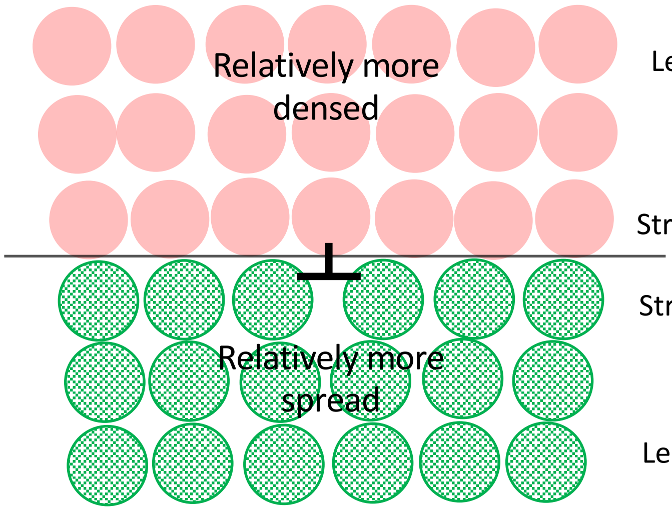


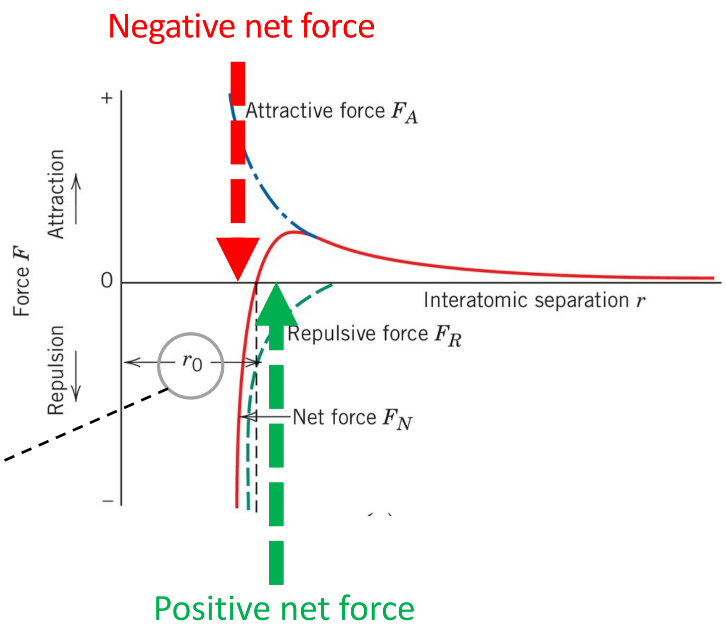


Dislocation density

- Dislocation density is quantified as
  - The length of total dislocations $[mm]$/ volume $[mm]^3$
  - Its unit is then $[mm]^{-2}$ (or m^{-2}).
- Dislocation increase as plastic deformation is applied. After certain plastic deformation, the dislocation density can increase to $10^{10}mm^{-2}$;
- Frank-Read dislocation source →

Lattice distortion induced by dislocation





Remember $\sigma = \mathbb{E}\varepsilon$, that is the Hooke's law in the elastic regime

Presence of dislocation causes 'elastic' strains to the neighboring atoms

In the scale of crystal lattice

$\sigma = \mathbb{E}\frac{\Delta a}{a_0}$

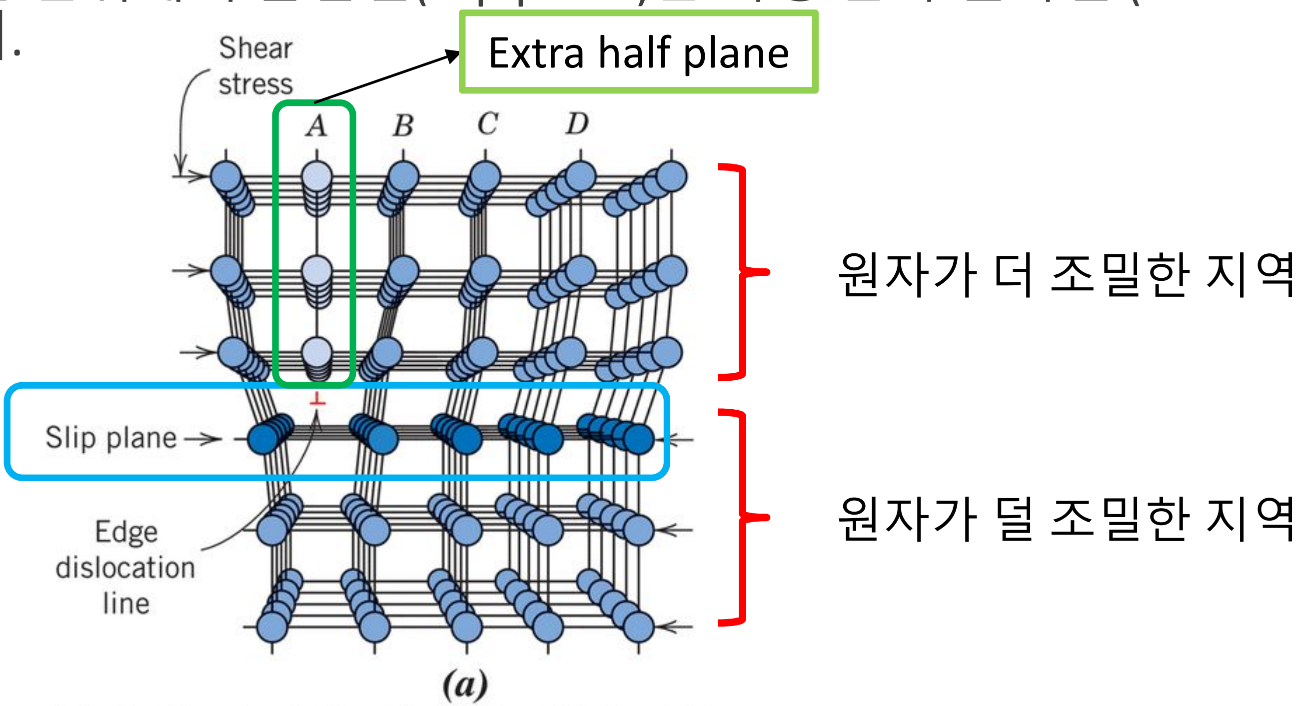
$\frac{\Delta a}{a_0}$ is the engineering strain from lattice strain; where a_0 is the lattice parameter when the net force between atoms is zero (force equilibrium)

Compressive force means σ<0; thus $\frac{\Delta a}{a_0}$<0; That again means Δa<0 so that $a_f < a_0$; Compressive strain

Tensile force means σ>0; thus $\frac{\Delta a}{a_0}$>0; That again means Δa>0 so that $a_f > a_0$; Tensile strain

Dislocation slip

- 전위의 의한 소성변형: 슬립 (slip) – 전위면이 서로 '미끄러지듯' 층층이 움직이는 것을 빗대어.
- 이렇게 전위선이 (전위는 '선' 결함임을 잊지말자) 가로지르는 면을 슬립면 (slip plane)이라고 한다.
- 전단 전위에서 슬립면(slip plane)은 과잉 반쪽 원자면 (extra half plane)의 끝에 위치.



Adapted from A. G. Guy, Essentials of Materials Sc

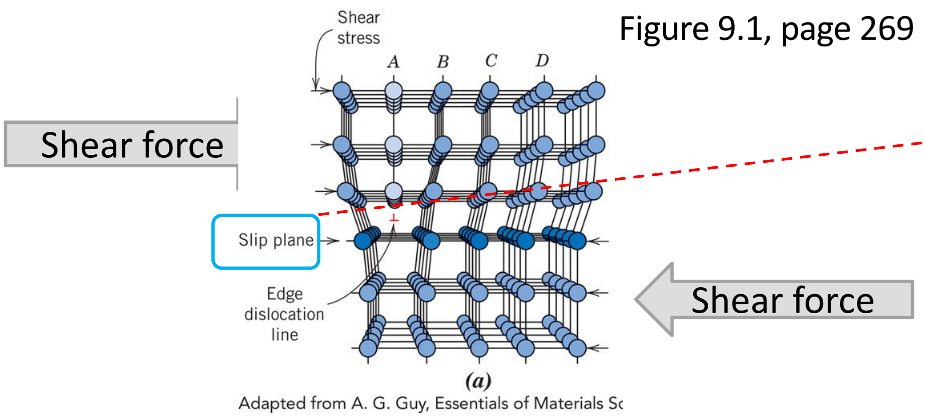
Dislocation motion

Dislocation motion & plastic deformation

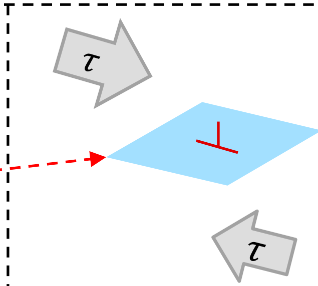
- Metals - plastic deformation occurs by slip – an edge dislocation (extra half-plane of atoms) slides through lattice.

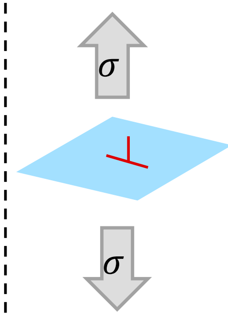
- 전위의 의한 소성변형: 슬립 – 전위면이 서로 '미끄러지듯' 층층이 움직이는 것을 빗대어.

Figure 9.1, page 269

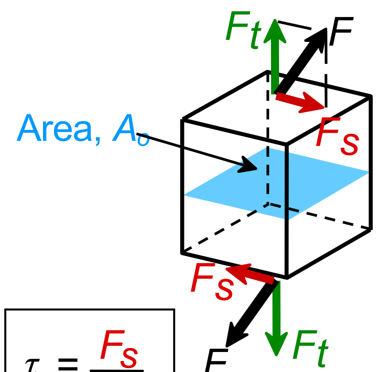


Dislocation moves by the shear force acting on the plane where dislocations are gliding



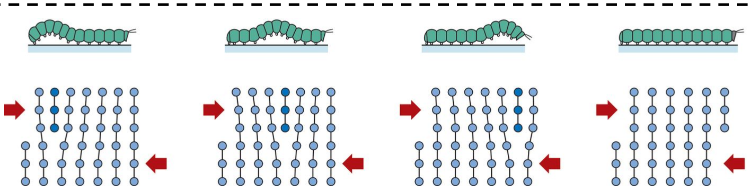


Normal stress cannot move dislocations



$$\tau = \frac{F_s}{A_o}$$

Slip 면에 대해 기울어진 힘의 경우 decompose



자벌레의 움직임에 비유-> Figure 9.1에서 A->B->C->D로 edge dislocation이 움직이는 것을 비유

Dislocation glide movie

Slip system and dislocation motion

- A dislocation moves on a slip plane in a slip direction perpendicular to the dislocation line
- The slip direction is the same as the Burgers vector direction

Slip system: a set of slip plane and slip direction
Usually denoted as {hkl}<uvw>;
slip plane family; slip direction family

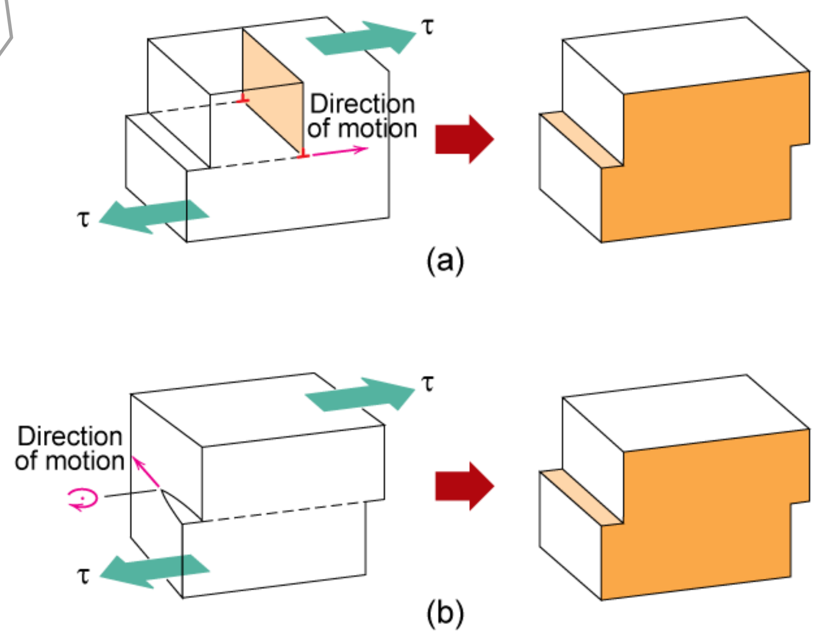
Slip systems are usually a set of close-packed plane and close-packed direction

There are exceptions to this rule

Crystal structure	Slip system	No.
FCC	{111}<110>	12
BCC	{110} *pencil glide*	..
HCP	{0001}<1120>	3

*{110} Pencil glide means that any direction on {110} plane may operate as a slip direction

{110}<111>, {110}<112>, {110}<123> ...



Edge dislocation

Screw dislocation

Fig. 9.2, *Callister & Rethwisch 9e.* (Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, The Structure and Properties of Materials, Vol. III, Mechanical Behavior, p. 70. Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Deformation mechanisms

Slip System

- Slip plane - plane on which the easiest slippage occurs
  - Highest planar densities (and large interplanar spacings)
- Slip directions - directions of movement
  - Highest linear densities

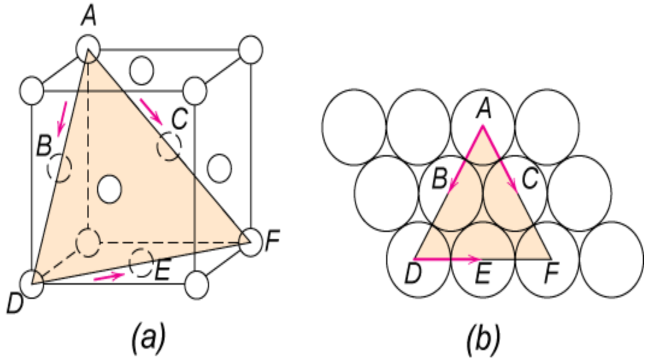
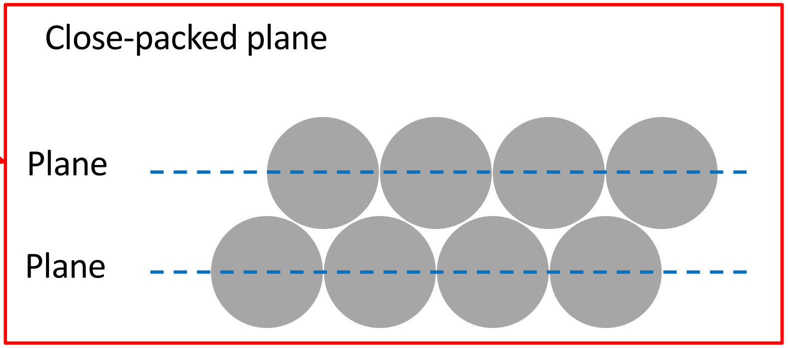


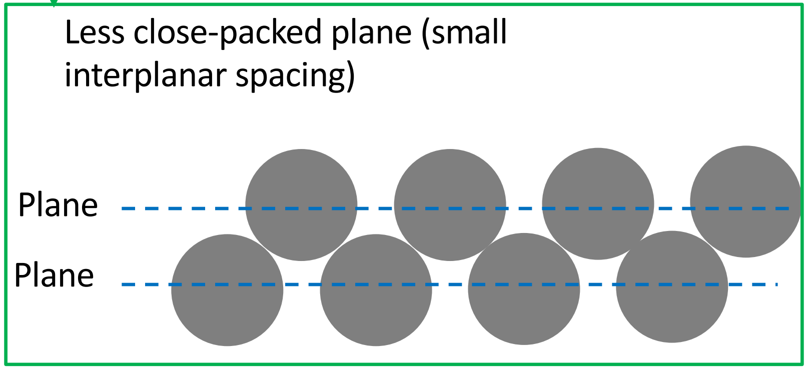
Fig. 9.6, *Callister & Rethwisch 9e.*

FCC Slip occurs on {111} planes (close-packed) in <110> directions (close-packed)
=> total of 12 slip systems in FCC

– For BCC & HCP, there are other slip systems.

Note: BCC does not have closed-packed plane
HCP has both slips and twinning



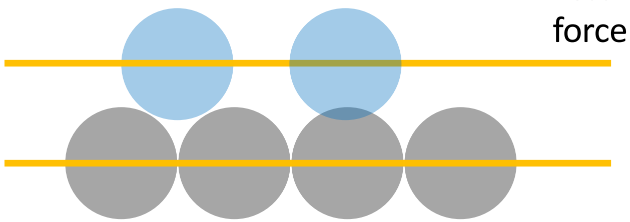


Higher planar density, larger interplanar spacing

Larger interplanar spacing means less energy barrier for dislocation to overcome to slip

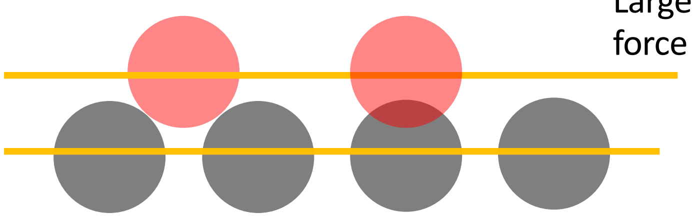
Close-packed plane

Close-packed plane

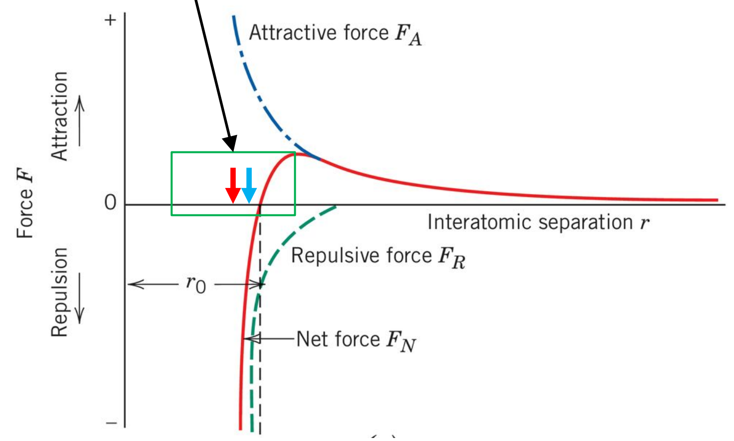


Comparison

Less packed plane (small interplanar spacing)



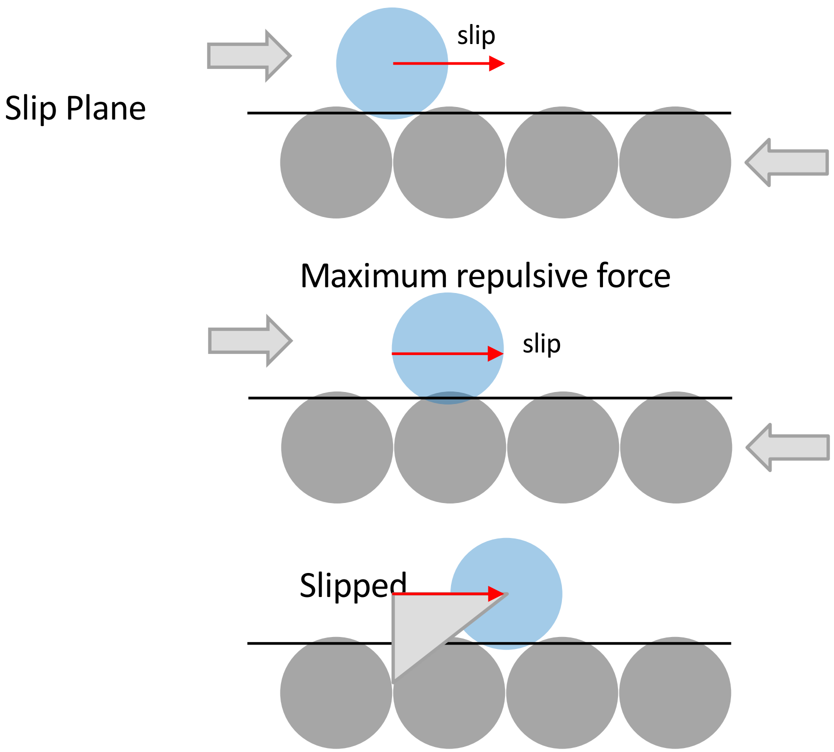
Repulsive force occurs when disl. (atom) slips; the amount of repulsive force is less for close-packed planes



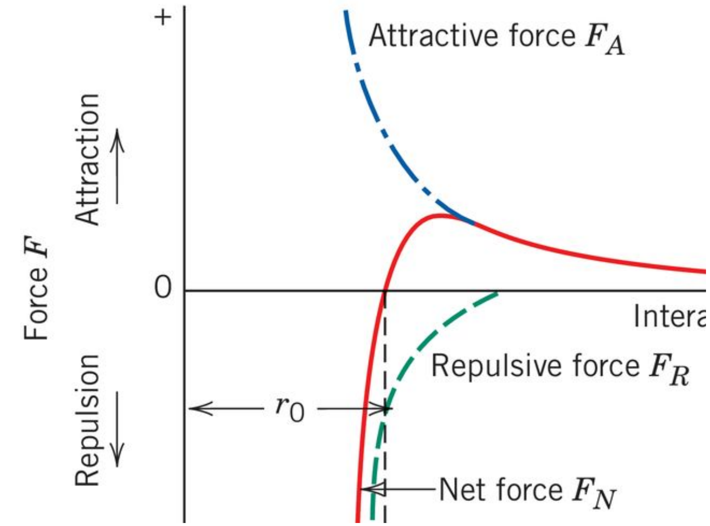
Easier to move on the close-packed crystallographic plane; The same reasoning is applied to easier motion along close-packed crystallographic direction

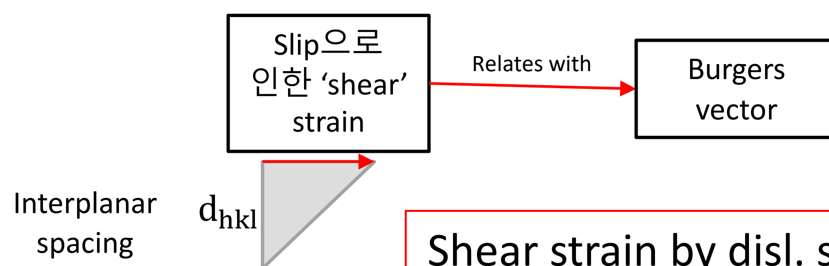
Shear force

For a dislocation to slip, a critical amount of force is necessary



Shear force acting on the slip plane moves the dislocation





Shear strain by disl. slip:

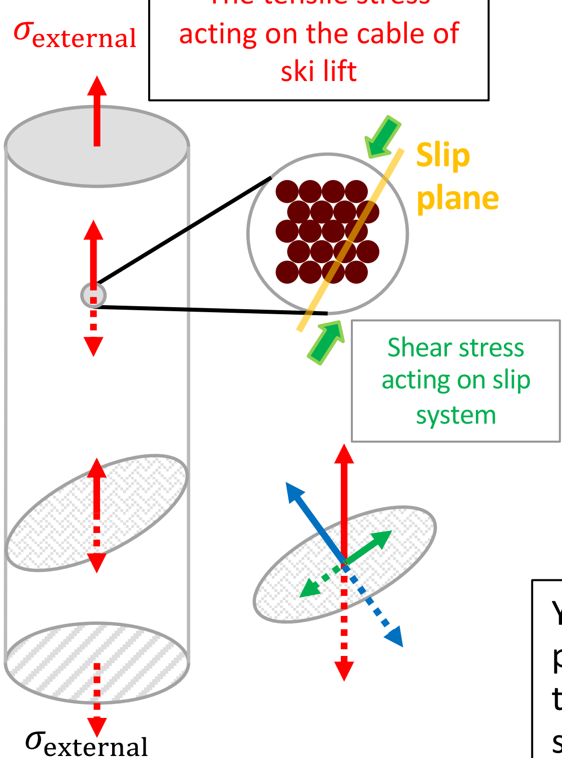
$$\gamma = \frac{b}{d_{hkl}}$$

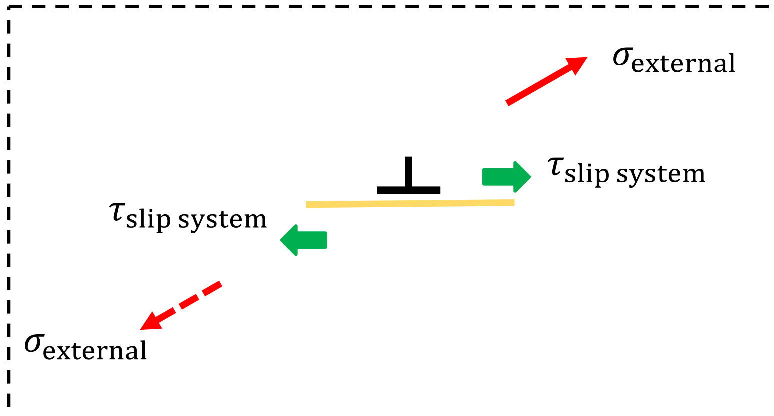
External load to shear force on dislocation

Shear force acting on the slip plane makes the dislocation move

In reality, we do not apply the force to individual dislocations

Remember cable of ski lift under tensile load



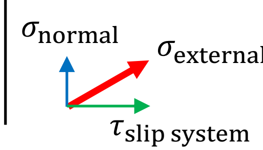


You can find what shear stress (τ) is acting on the slip plane along slip direction, provided that you know 1) the external stress (σ_{external}); 2) orientation of the slip system with respect to external loading

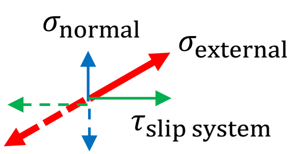
How?

By **resolving** the external load to slip system

여기서 resolve의 뜻은, 성분으로 '분해'하다.



Stress and Dislocation Motion

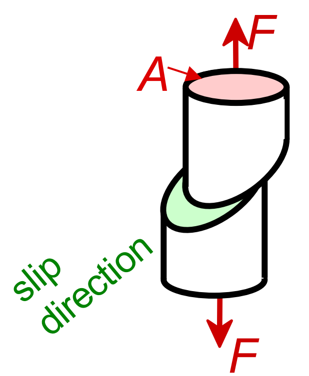


σ_{normal} does not contribute to dislocation slip;
$\tau_{slip\ system}$ does;
$\tau_{slip\ system}$ is called resolved shear stress

- Resolved shear stress, τ_{RSS} is obtained by resolving the externally applied stress on the slip system (plane/direction)

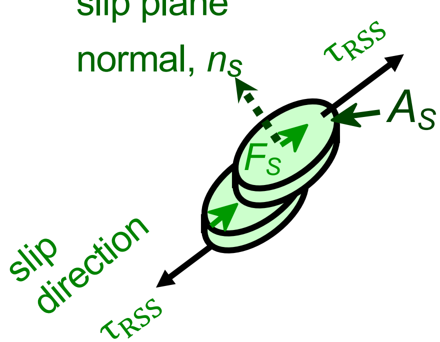
Applied tensile stress:

$\sigma_{external} = F/A$



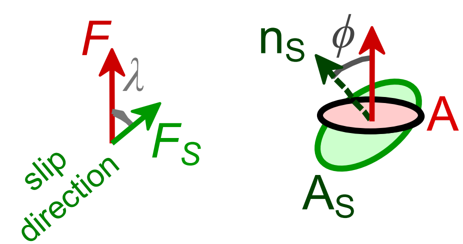
Resolved shear stress:

$\tau_{RSS} = F_s/A_s$



Relation between τ_{RSS} and $\sigma_{external}$

$F_s = F\cos\lambda \qquad A_s = \dfrac{A}{\cos\phi}$



$$\tau_{RSS} = \frac{F_s}{A_s} = \frac{F\cos\lambda}{A/\cos\phi} = \frac{F}{A}\cos\lambda\cos\phi$$

$$\tau_{RSS} = \sigma\cos\lambda\cos\phi$$

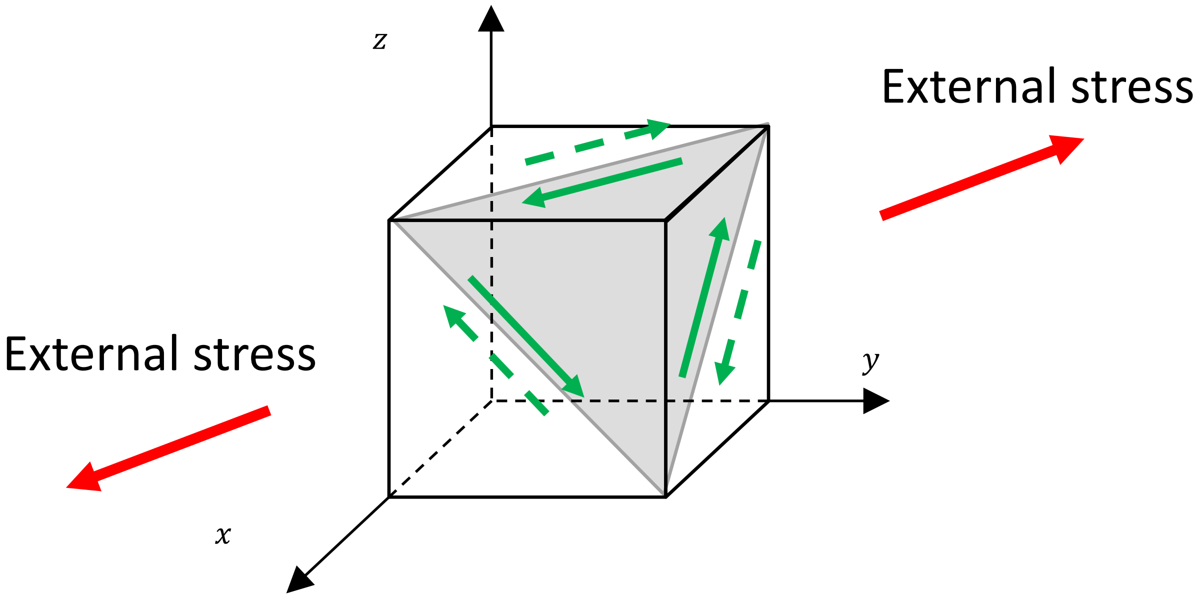
F: externally applied force
A: the cross sectional area of the external plane, on which F is operative
F_s: Force that acts on the slip system
A_s: the area of plane on which F_s is operative.
n_s: normal direction of the crystallographic slip plane
τ_{RSS}: shear stress acting on the slip system (slip direction/plane)
$\cos\lambda$: direction cosine between F and F_s
$\cos\phi$: direction cosine between normals of slip plane and the external plane.

There can be many slip systems due to (rotational) crystallographic symmetry

Among them, the one that exhibits the maximum RSS will preferably slip.

An inverse question: How to determine RSS? (to be discussed later)

Many potential slip systems exist.

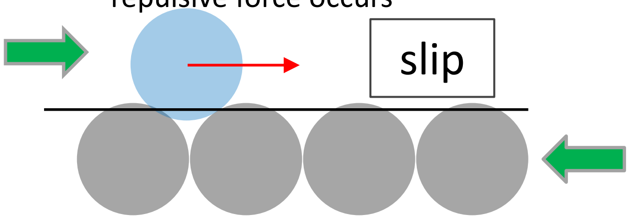


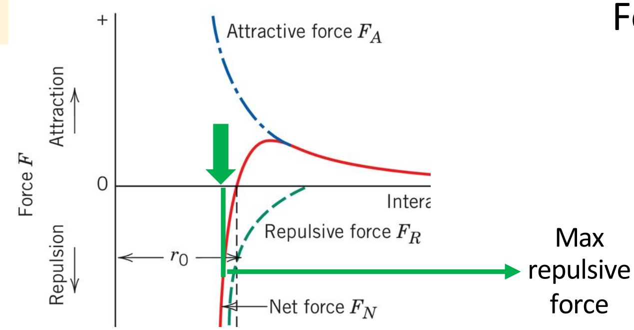
Among potential slip systems, find the one that has the maximum RSS

Where coordinate system transformation is required?

Critical Resolved Shear Stress

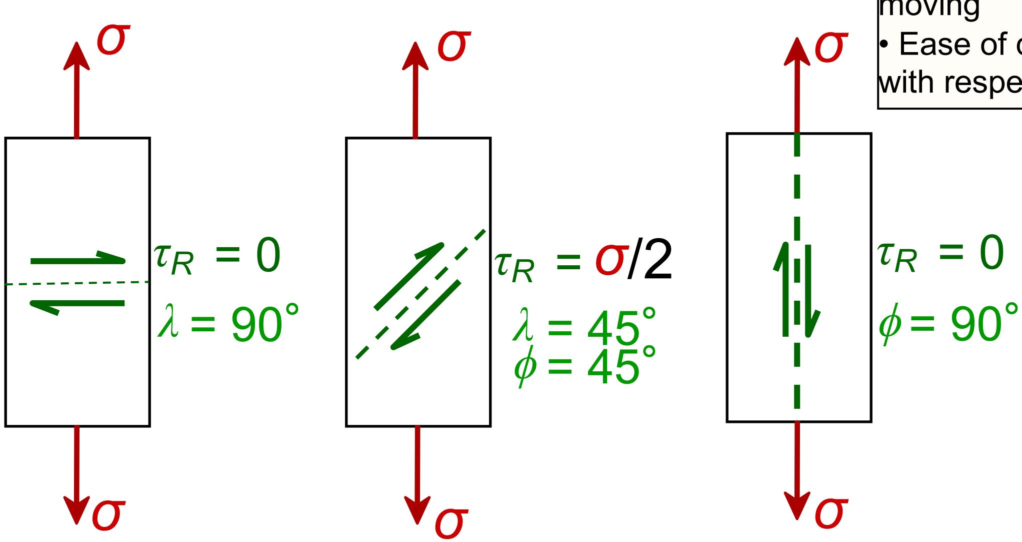
Atom position when maximum repulsive force occurs





For dislocation to slip, this max. force should be overcome.

Max. repulsive force is closely related with the CRSS



- Condition for dislocation motion (= condition for plastic yielding):
  If RSS reaches a certain (critical) value, the dislocation will start moving
- Ease of dislocation motion depends on crystallographic orientation with respect to the external loading direction

$$\tau_{RSS} = \sigma \cos\lambda \cos\phi$$

$\cos\lambda \cos\phi$: Schmid's (orientation) factor

Dislocation slip condition (≈ atomic yield condition)

$$\tau_{RSS} \geq \tau_{CRSS}$$

Example: yield of single crystal

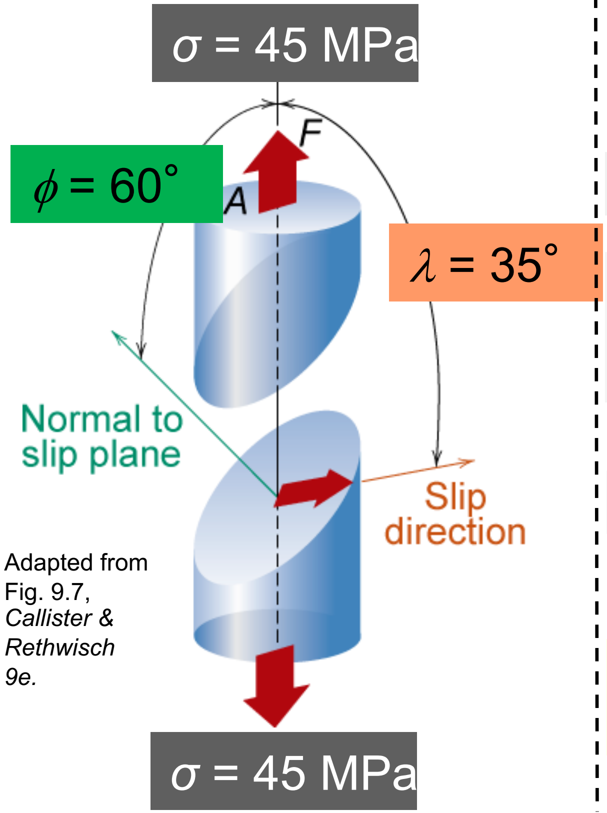
a) Will the single crystal yield?
b) If not, what stress is needed?

$\tau_{RSS} = \sigma \cos\lambda \cos\phi$

We learned this equation that correlates the external loading (σ) and the orientation of slip system (λ, ϕ).

Condition 1. External load of 45 MPa

Condition 2. Slip system characterized by $\lambda = 35°, \phi = 60°$



Adapted from Fig. 9.7, *Callister & Rethwisch 9e.*

Condition for dislocation to slip? → $\tau_{RSS} \geq \tau_{CRSS}$

Condition 1. $\tau_{CRSS} = 20.7$ MPa

Condition 2. $\tau_{RSS} = \sigma \cos\lambda \cos\phi$
$= 45 \cos 35° \cos 60°$ [MPa]
$\approx 45 \times 0.819 \times 0.5 \approx 18.4$ [MPa]

Check $\tau_{RSS} \geq \tau_{CRSS}$

45 MPa is not sufficient enough to activate this slip system ($\lambda = 35°, \phi = 60°$)

Example: yield of single crystal

What external stress should be applied for a slip system to yield?

Dislocation slip condition:

$$\tau_{CRSS} = \tau_{RSS}$$

Dislocation slips when

$$\tau_{CRSS} \leq \tau_{RSS} = \sigma \cos\lambda \cos\phi$$

The yield stress (σ_Y) to this single crystal is:

$$\sigma_Y = \frac{\tau_{CRSS}}{\cos\lambda \cos\phi}$$

A single crystal is characterized by its orientation with respect to the external loading (λ, ϕ) and CRSS (τ_{CRSS})

Exercise 1.
For dislocation on $(111)[1\bar{1}0]$ slip system to slip, what tensile stress should be applied? The slip system's orientation w.r.t. the tensile stress is characterized by two angles ($\phi = 30°, \lambda = 25°$) and its CRSS ($\tau_{CRSS} = 30\text{MPa}$)

$$\sigma_Y = \frac{\tau_{CRSS}}{\cos\lambda \cos\phi} = \frac{30\ [\text{MPa}]}{\cos 30° \cos 25°} \approx 38.2\ [MPa]$$

Therefore, for deformation to occur the applied stress must be greater than or equal to the yield stress of 38.2 [MPa]

Example

- 단결정 BCC iron의 [010] 방향으로 일축 인장 응력이 가해진다.
  - A) 52 MPa의 인장 응력이 가해질때, (110) 면의 $[\bar{1}11]$ 방향으로의 RSS?
  - B) 만약 A)의 슬립 시스템의 CRSS가 30 MPa 이라면 소성 변형을 위해 필요한 인장응력은 얼마나 되어야 하나?

- (풀이) $\sigma_Y = \frac{\tau_{CRSS}}{\cos\lambda\cos\phi}$ 와 $\tau_{RSS} = \sigma^{tensile}\cos\lambda\cos\phi$를 각각 사용하되, 해당 문제를 풀기위해 λ와 ϕ 결정할 필요있다. λ와 ϕ는 벡터의 내적을 통해 구할 수 있다. 즉 $\mathbf{v}\cdot\mathbf{u} = v_1u_1 + v_2u_2 + v_3u_3 = |\mathbf{v}||\mathbf{u}|\cos\theta$ 따라서 $\theta = \cos^{-1}\left[\frac{v_1u_1+v_2u_2+v_3u_3}{|\mathbf{v}||\mathbf{u}|}\right]$

- [010]과 (110)를 나타내는 벡터를 사용하여 ϕ, [010]과 $[\bar{1}11]$ 를 나타내는 벡터를 사용하여 λ를 구하고, 이를 이용하여 A)와 B)를 풀 수 있다.

Slips of single crystal and polycrystal

Fig. 9.8, *Callister & Rethwisch 9e.*

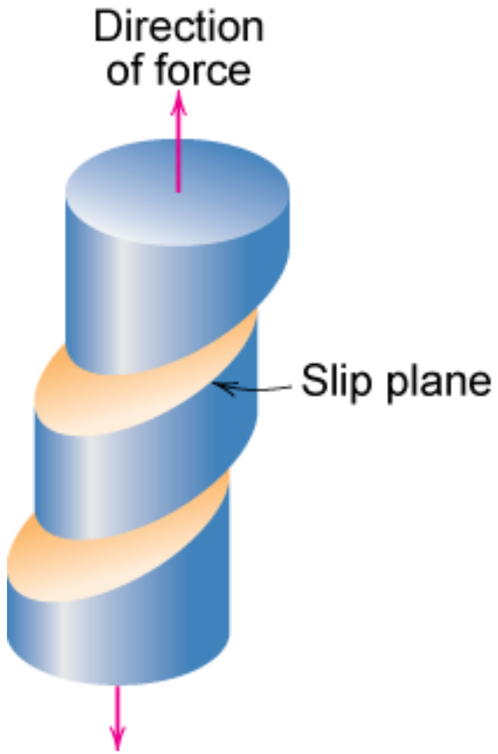


Fig. 9.9, *Callister & Rethwisch 9e.* (From C. F. Elam, *The Distortion of Metal Crystals*, Oxford University Press, London, 1935.)

Comparison

Adapted from Fig. 9.10, *Callister & Rethwisch 9e.* (Photomicrograph courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

A single slip system is active.
Orientation of that slip system to external force is the same.

Orientations of grains are different from each other;
Active slip system in each grain depends on the orientation of each grain

Slip in polycrystals

- Polycrystals stronger than single crystals – grain boundaries are barriers to dislocation motion.
- Orientation of slip system (λ, ϕ) of a grain may differ from one to another.
- For a given external load, τ_{RSS} of a particular slip system will vary from one grain to another.
- Among various slip systems of many grains, the slip system with the largest τ_R yields first.
- Other (less favorably oriented) grains yield later.

Important conclusions:
If you make grains oriented in a particular way, you would be able to make the material stronger (by increasing the necessary σ_Y)

$$\sigma_Y = \frac{\tau_{CRSS}}{\cos\lambda \cos\phi}$$

Most of strengthening mechanisms focus on increasing τ_{CRSS}

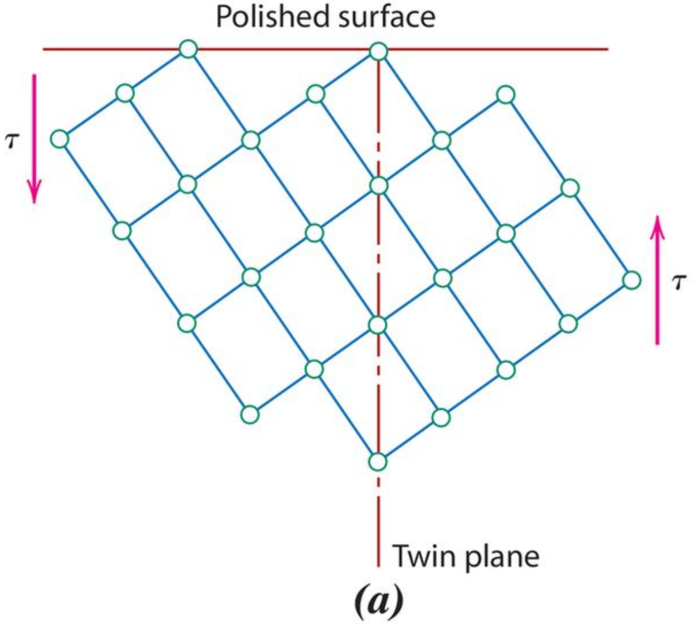
Strengthening by crystal texture is limited for crystal structures with high crystallographic symmetry; why?

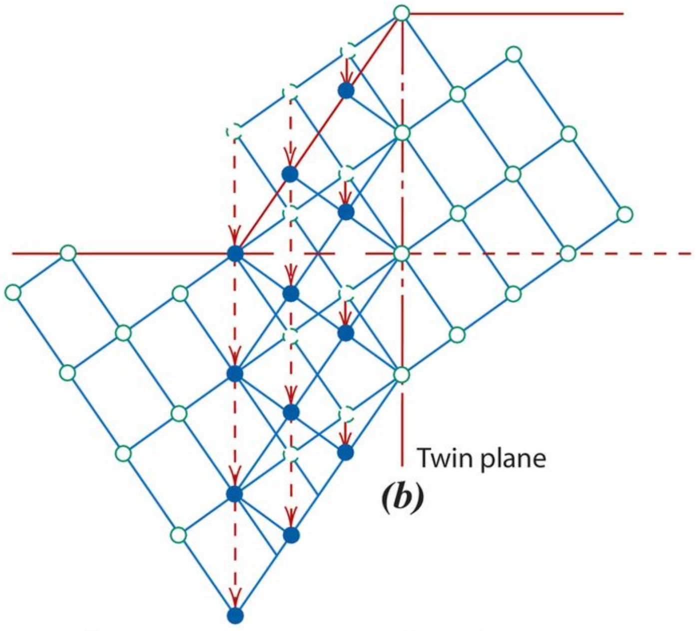
Because other members of the slip system family will become active if the orientation of grain is changed

Adapted from Fig. 9.10, *Callister & Rethwisch 9e.* (Photomicrograph courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

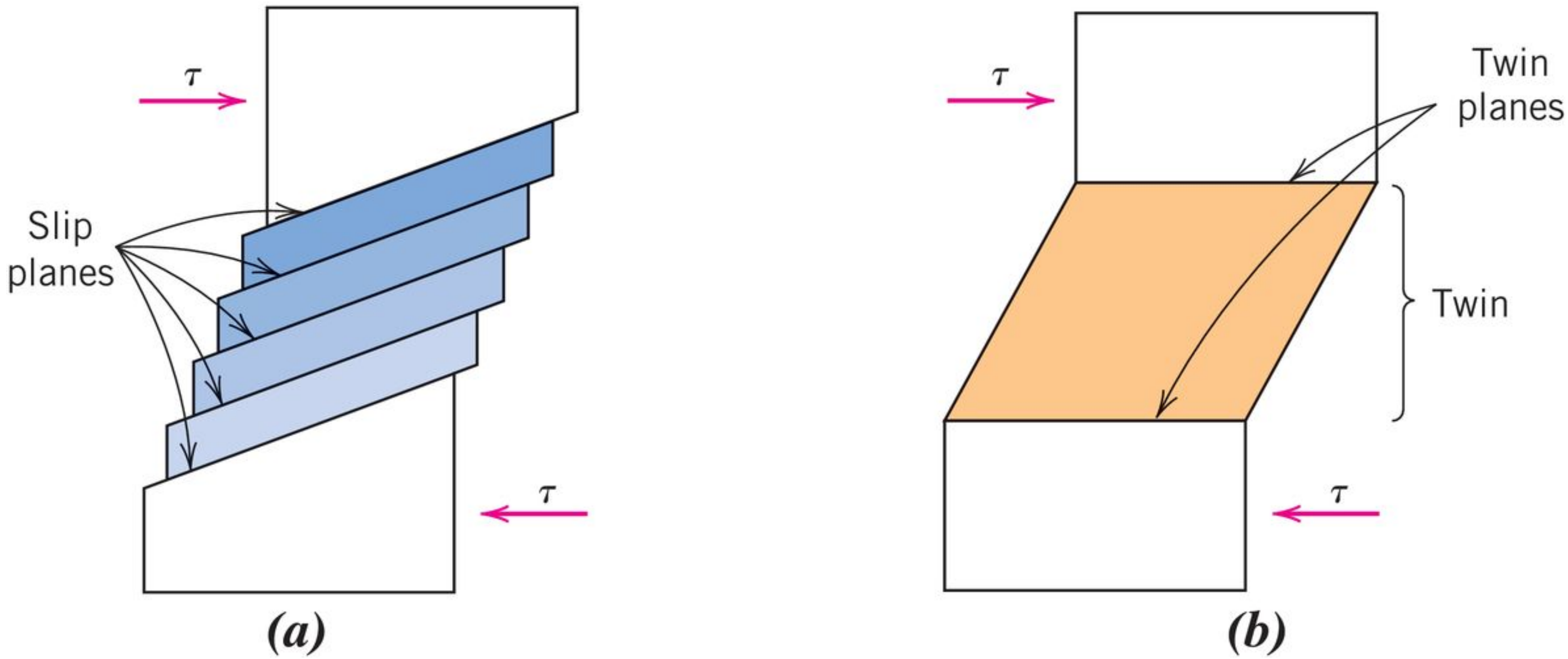
Twinning

- 지금까지 우리는 전위(dislocation)와 전위에 의한 소성변형 메카니즘인 슬립에 대해 배웠다.
- 사실 결정 상태의 금속이 소성변형을 일으키는 방법은 슬립만 있는 것은 아니다.
- 전단 응력을 받아 한 결정면을 중심으로 맞은 편의 원자들이 '거울'로 대칭이 되게 재정렬 (rearrangement)을 하는 경우가 있다. 이를 우리는 twinning이라고 한다.





Compare twinned region with the slipped region



Slip 이 발생한 경우 Slipped region에서의 결정 방위가 일어나지 않은 곳과 동일하다.

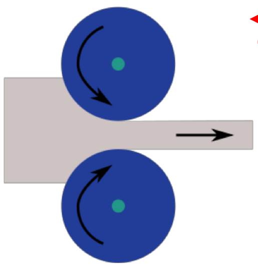
Twin 이 발생한 경우 Twinned region에서의 결정 방위가 일어나지 않은 곳과 다르다. – 단순히 다를 뿐만 아니라, mother region과 특정한 방위 관계를 가진다.

Anisotropy in σ_Y

Strengthening by crystal texture is limited for crystal structures with high crystallographic symmetry; why?

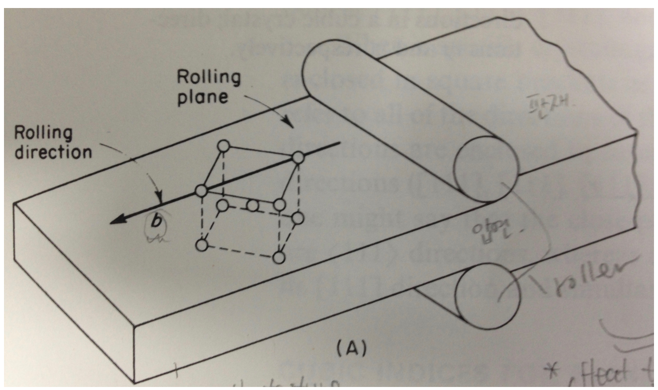
Because other members of the slip system family will become active if the orientation of grain is changed

Yet, the anisotropy on yield stress is shown in polycrystalline metal alloys; particularly crystal structures with relatively low-symmetry



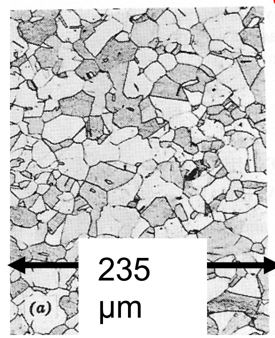
Rolling direction

A certain crystal orientation is preferably aligned along a particular direction



- Can be induced by rolling a polycrystalline metal

- before rolling



- after rolling

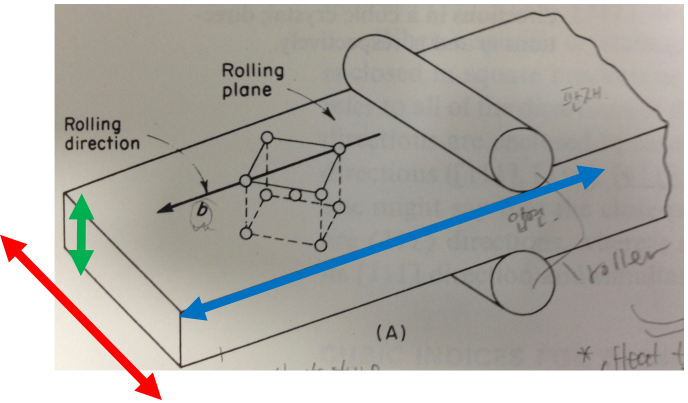
Adapted from Fig. 9.11, *Callister & Rethwisch 9e.* (from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

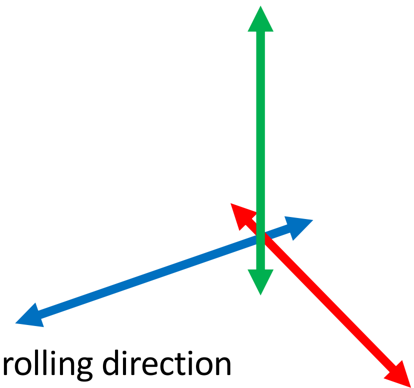
Isotropic
because grains are equiaxed and randomly oriented.

Anisotropic because rolling affects gra

Anisotropy in σ_Y

Image from Olaf Engler, MSEA Vol. 618 p654-662, 2014

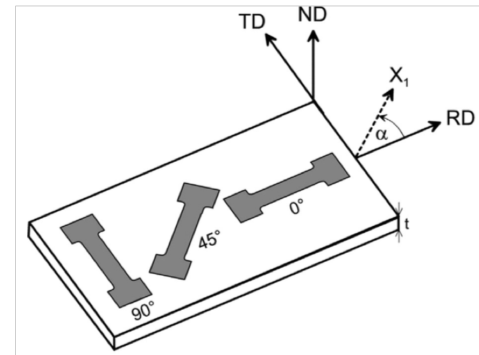




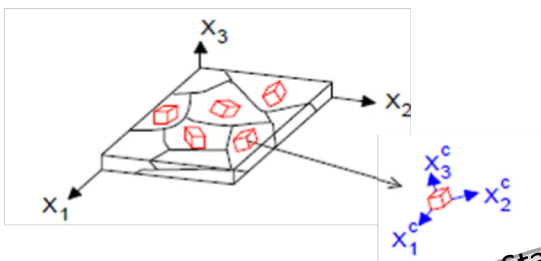
ND; normal direction

RD; rolling direction

TD; transverse direction



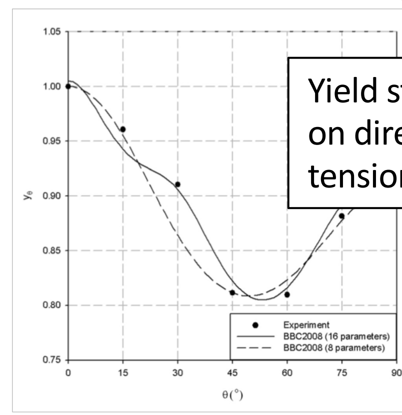
Cutting-off tensile specimens at various degrees from RD



Each grain has a difference crystal orientation

Statistically random → **Isotropy**

Statistically meaningful trend → **Anisotropy**



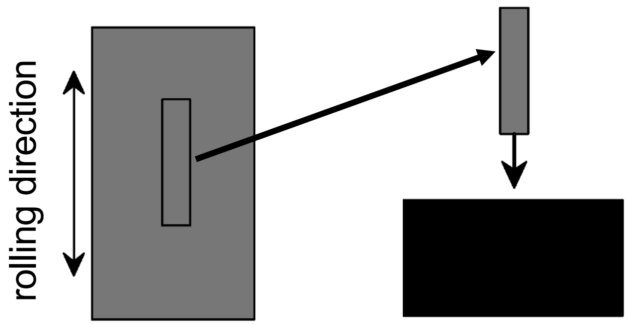
Yield stress depends on direction of tension

Anisotropy in Deformation

1. Cylinder of tantalum machined from a rolled plate:

2. Fire cylinder at a target.

3. Deformed cylinder



Photos courtesy of G.T. Gray III, Los Alamos National Labs. Used with permission.

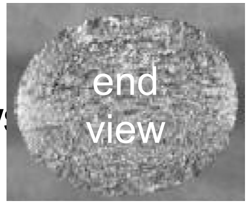


plate thickness direction

- The noncircular (ellipsoidal) end view shows anisotropic deformation of rolled material.

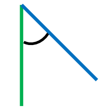
Earring profile of deep-drawn cups

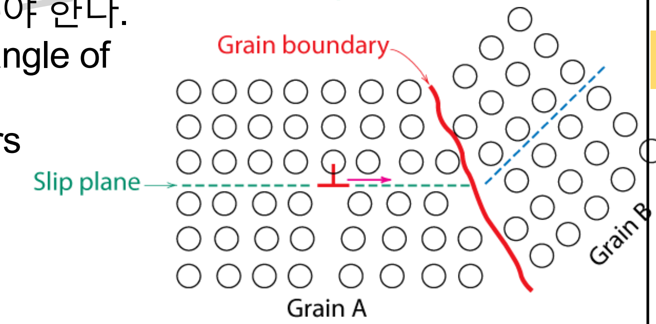
금속 재료의 Strengthening mechanisms (강화기구)

- Reduction of grain size (grain size reduction; Hall-Petch equation)
- Solid solution strengthening (고용체 강화)
- Precipitation hardening
- Cold-work (Strain hardening; work hardening)

Four Strategies for Strengthening:
1: Reduce Grain Size

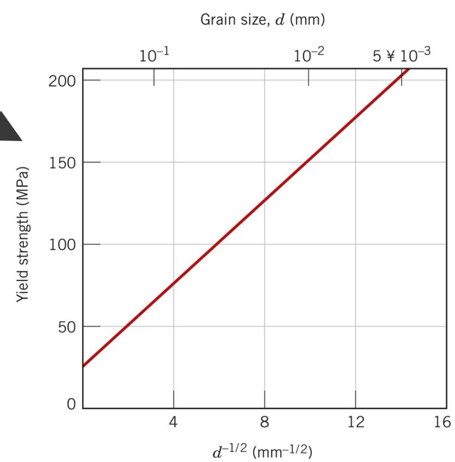
- ❑ GB가 slip 방해할 수 있는 이유:
  - ○ Discontinuous lattice; 같은 슬립면/슬립방향으로 이동 불가
  - ○ 따라서 전위가 GB 통과위해서는 방향을 바꿔야 한다.
- ❑ Barrier "strength” increases with increasing angle of misorientation
  - ○ Smaller grain size = more g.b. = more barriers
  - ○ Hall-Petch Equation:





$$\sigma_{yield} = \sigma_0 + k_y d^{-1/2}$$

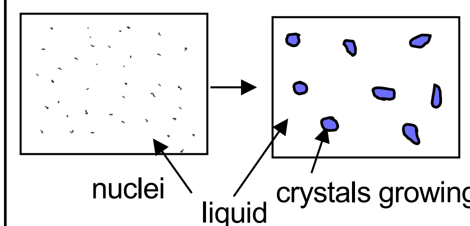
σ_{yield}: 항복 강도
σ_0, k_y 재료 상수 (material constants)
d: average grain size (diameter)



Methods to reduce grain size

1. Rapid cooling from liquid state

Inducing more nuclei to grow



2. Cold work

SPD; Grain fragmentation

Smaller grain size: more barriers to overcome → material strengthening

Four Strategies for Strengthening:
2: Solid Solutions Strengthening

Before discussing the solid solution hardening, we will briefly discuss what is a solid solution.

In chemistry, a solution is a homogeneous mixture of one or more solutes in a solvent.

Solute (용질): minor component
Solvent (용매): solute를 녹이는 물질 (host)

You all might be familiar with liquid solution such as saline water (소금물).
Saline water is a mixture of NaCl and H_2O. H_2O is the solvent, which is in its liquid state.
Notice that 1) NaCl is the minor component, whose amount is less than the solvent water and 2) NaCl is 'homogeneously' distributed in the solvent.

There are different types of solutions, where the solvent exists in its gaseous or solidus state. For example, the air you inhale in the class room is a solution, which is a mixture of oxygen, nitrogen and others. Carbonated water (탄산수) is also a solution where the solute is a gaseous substance (dioxide; 이산화탄소) and the solvent is water.

Solid solution is a type of solution where solvent is in its solidus state. A good example is the steel, where Fe atoms are the solvent and carbons are dissolved in Fe. Development of hydrogen storage alloy is actively studied, which can serve to 'store' hydrogen safely.

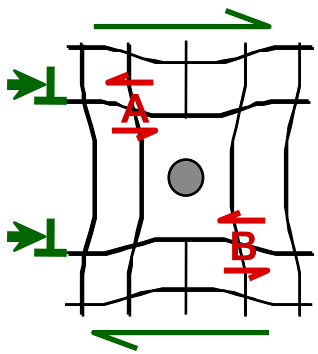
Four Strategies for Strengthening:
2: Solid Solutions Strengthening

Impurity atoms distort the lattice & generate lattice stress (strains).

$$\tau = E\frac{\Delta a}{a_0}$$

•(Stress) strain fields act as barriers to dislocation motion (either repulsive or attractive).

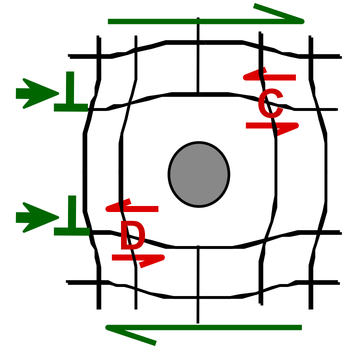
- Smaller substitutional impurity



Repulsive force:
다가오는
dislocation을
막는다

Impurity generates local stress at **A** and **B** that opposes dislocation motion to the right.

- Larger substitutional impurity



Attractive force:
떠나가는
dislocation을 잡는다

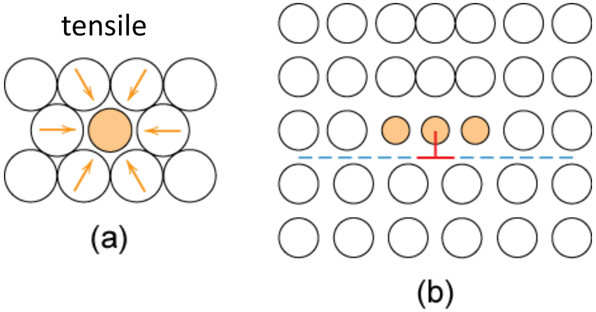
Impurity generates local stress at **C** and **D** that opposes dislocation motion to the right.

Lattice distortion (either compressive or tensile) prohibits dislocation motion

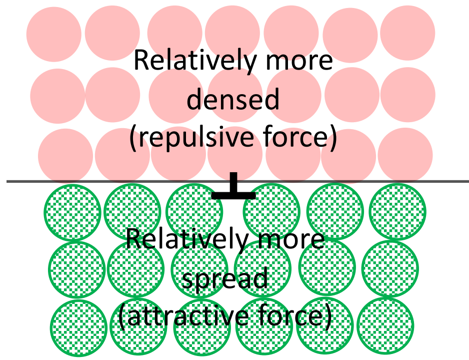
material strengthening

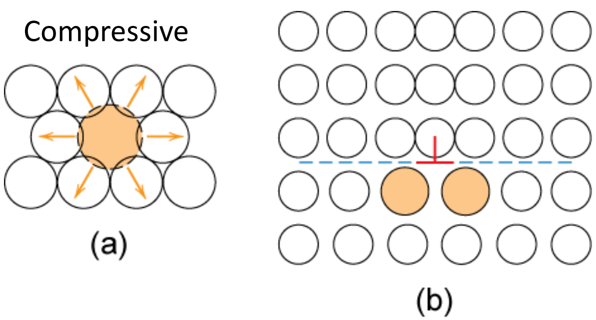
Four Strategies for Strengthening:
2: Solid Solutions Strengthening

- Large impurities tend to concentrate at dislocations (regions of tensile strains)



- Small impurities tend to concentrate at dislocations (regions of compressive strains) - partial cancellation of dislocation compressive strains and impurity atom tensile strains





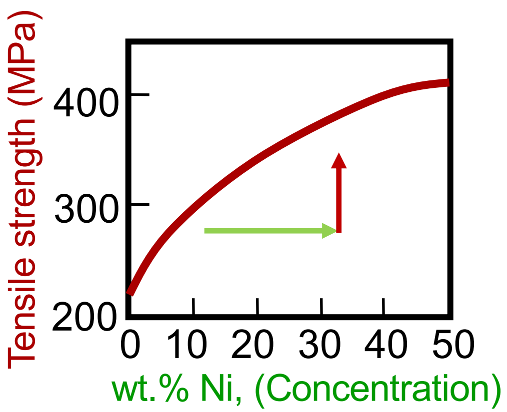
- Large impurities also tend to concentrate at dislocations (regions of tensile strains) - partial cancellation of dislocation tensile strains and impurity atom compressive strains

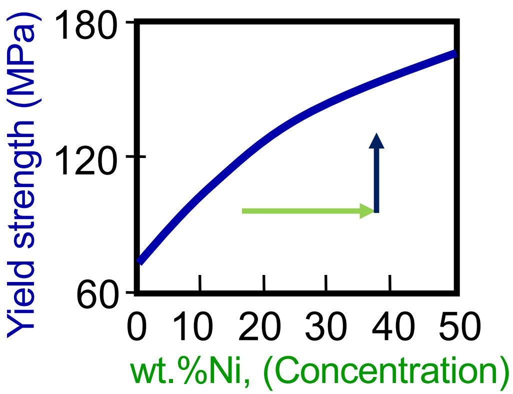
Dislocations are 'pinned' by solutes (either big or small) → material strengthening

Example of Solid Solution Strengthening: Cu-Ni alloy

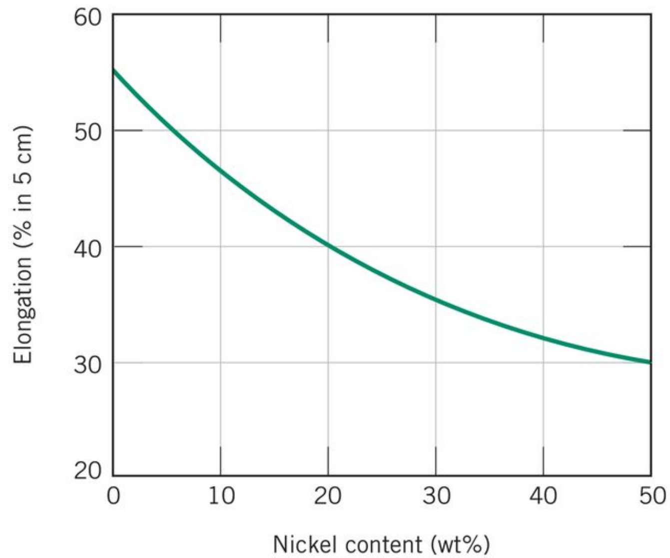
Pure metals are usually ductile and weak → alloying → Strength ↑ Hardness ↑ Ductility ↓

- Tensile strength & yield strength increase with wt% Ni





강도/경도의 증가는 연성의 감소로 이어진다.



(c)

- Strength: 강도
- Hardness: 경도
- Concentration: 농도
- wt (%): weight percent; 무게비 (농도 단위); cf. at%; 원자비

Four Strategies for Strengthening:
3: Precipitation Strengthening (Age hardening)

온도

High temp.

Air can dissolve **A** amount of water

냉각

Low temp.

Air can dissolve a bit less amount (**B**) of water

얼음 알갱이 석출 (구름, 눈, 이슬, 우박)

온도, 압력등의 시간에 따른 변화 (history)에 의해 다른 size의 알갱이가 석출된다.

Metal solid can dissolve **C** amount of solutes

1. Solution heat treatment

2. Fast Cool down (Quenching)

Metal can dissolve a bit less amount (**D**) of solutes

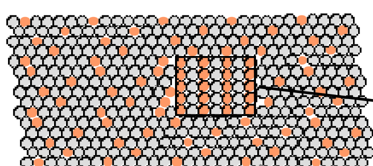
C is still 'dissolved' (과포화)

3. Heated to intermediate temp.

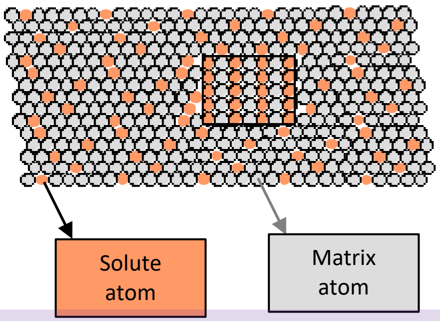
Giving no time for C to diffuse

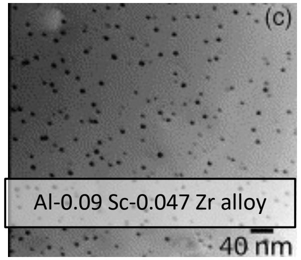
4. Aging (holding temperature)

- Let the chemical compounds of metal/solutes form -> 2nd phase particles
- Size of the particle depend on the temp and the time



Four Strategies for Strengthening:
3: Precipitation Strengthening (Age hardening)

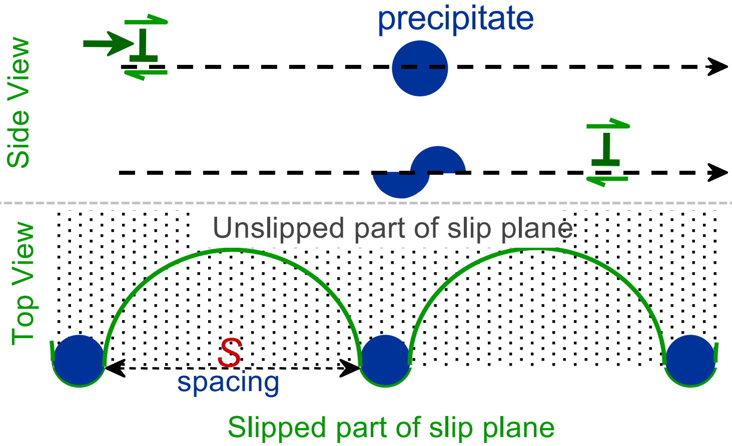




Fuller et al. Acta Mat. 51 (2003)

Precipitates: finely dispersed second phase particle

- Hard precipitates are difficult to shear.
  Ex: Ceramics in metals (SiC in Iron or Aluminum).

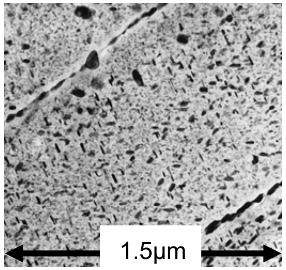


Large shear stress needed to move dislocation toward precipitate and shear it

Dislocation advances but precipitates act as 'pinning' sites with spacing S.

Applications

Internal wing structure on Boeing 767



Aluminum is strengthened with precipitates formed by alloying.

Chapter-opening photograph, Chapter 11, *Callister & Rethwisch 3e.*
(Courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

Adapted from Fig. 17.20, *Callister & Rethwisch 9e.* (Courtesy of G.H Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

Dislocation Pinning Points

Dislocation pinning mechanisms provide strengthening by hindering dislocation motion

3 main sources of pinning points are discussed below

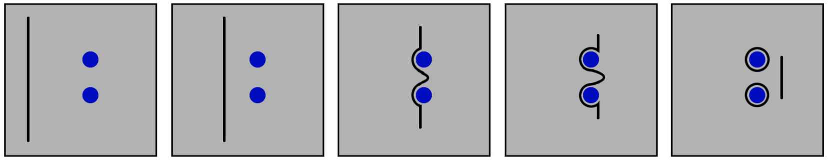
Point defects

Another dislocation; Dislocation jogs, Dislocation kinks

Alloying elements

Alloying element is ‘foreign’ to matrix; thus forming point defects which arise stress to the adjacent lattice

(2nd phase) Precipitates

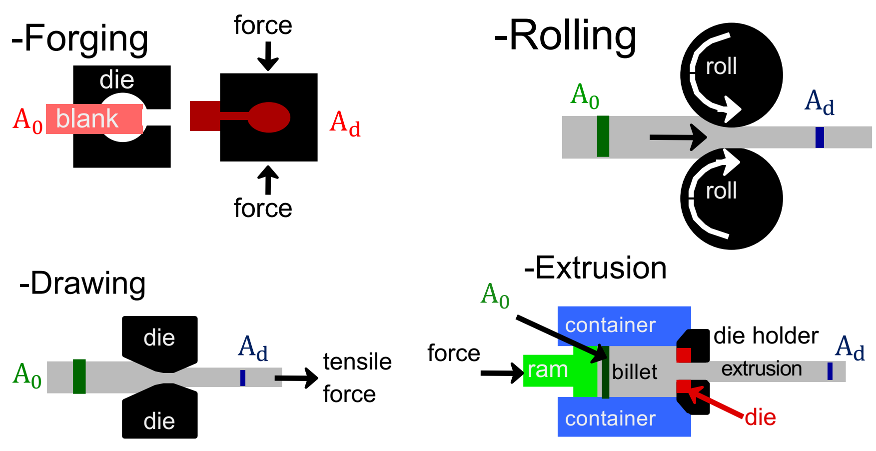


Four Strategies for Strengthening: 4: Cold Work (Strain Hardening)

Cold Work (냉간 가공): plastic deformation at room temperature (for most metals).

→ Dislocation ↑ / Grain size ↓ (HP eq.) → Material Strengthening

Conventional cold-work process usually reduces cross sectional area



Adapted from Fig. 17.2, *Callister & Rethwisch 9e.*

Amount of cold-work is estimated by %CW

$$\%CW = \frac{A_0 - A_d}{A_0} \times 100$$

A_0: initial cross section area
A_d: final cross section area

Hot forging4m 40s

Cold-Rolling4m 27s

Cold drawing 1m 28s

Cold extrusion 1m 49s

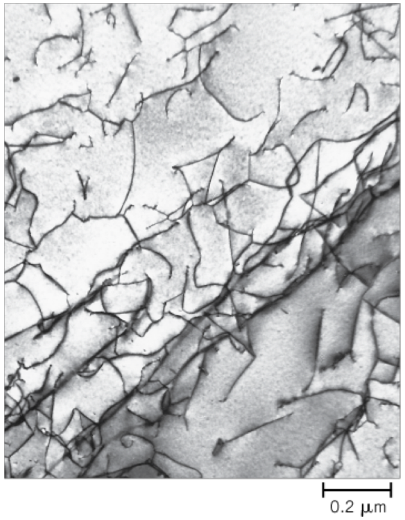
Dislocation Structures Change During Cold Working

Plastic deformation that occurs during cold-work generates more dislocations, which means that the space between dislocations decreases (disl. density increase)

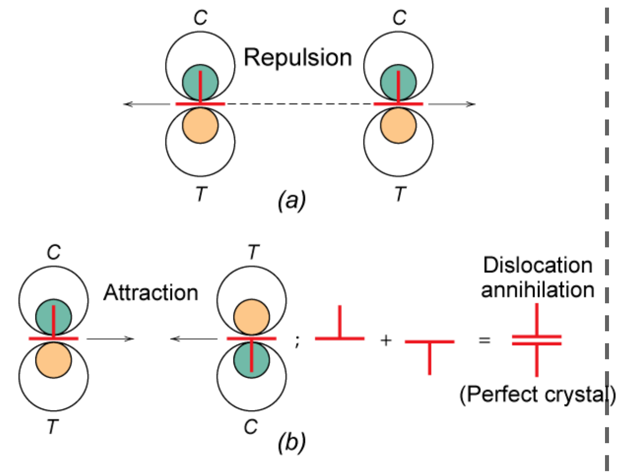
Dislocation density 전위밀도 (ρ_d)=

- Carefully grown single crystals
  → 10^3 mm^{-2}
- Deforming sample increases density
  → 10^9-10^{10} mm^{-2}
- Heat treatment reduces density
  → 10^5-10^6 mm^{-2}

Yield strength increases as ρ_d increases



Dislocation structure in Ti after cold working.



- Dislocations **entangle** with one another during cold work.
- Dislocation motion becomes more difficult (strengthening)

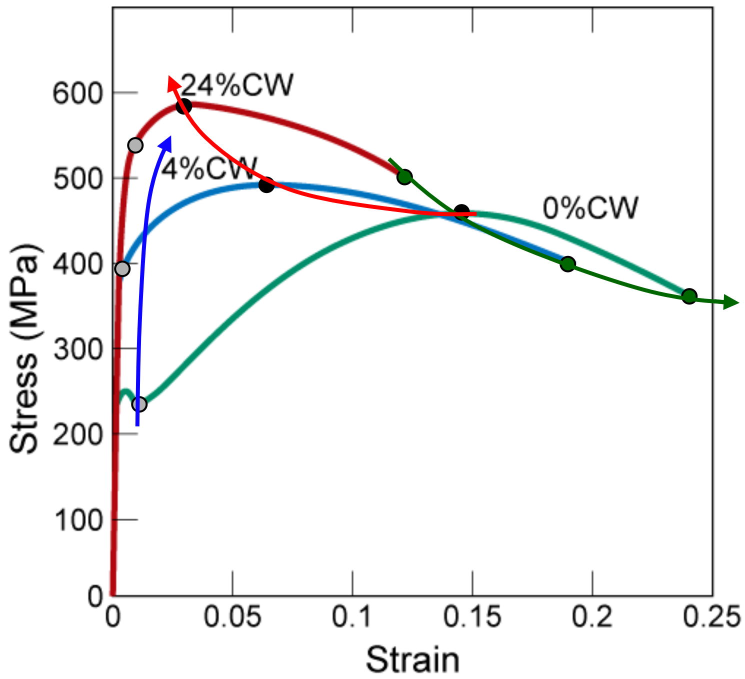
Impact of Cold Work

As cold-work is increased

- Yield strength (σ_y) increases.
- Tensile strength (TS) increases.
- Ductility (%EL) decreases.

보통 강도와 연성이 모두 높은 재료가 선호된다. 강도를 높이기 위해 냉간가공을 높이면 연성이 자연스럽게 낮아짐에 유의

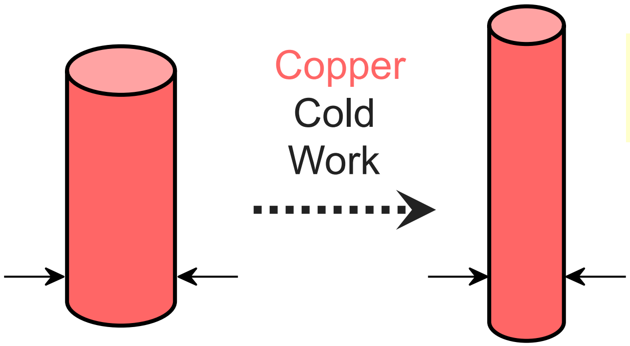
Changes in stress-strain curves of low carbon steels with increasing cold-work



냉간 가공에 의한 강도 증가는 응력-변형률 곡선으로 설명할 수 있다.

Mechanical Property Alterations Due to Cold Working

- What are the values of yield strength, tensile strength and ductility after cold working Cu?



$D_0 = 15.2$ mm

$D_d = 12.2\ mm$

$$\%CW = \frac{A_0 - A_d}{A_0} \times 100\ (\%) = \frac{\frac{\pi D_0^2}{4} - \frac{\pi D_d^2}{4}}{\frac{\pi D_0^2}{4}} \times 100 = \frac{D_0^2 - D_d^2}{D_0^2} \times 100$$

$$\%CW = \frac{15.2^2 - 12.2^2}{15.2^2} \times 100 \approx 35.6\%$$

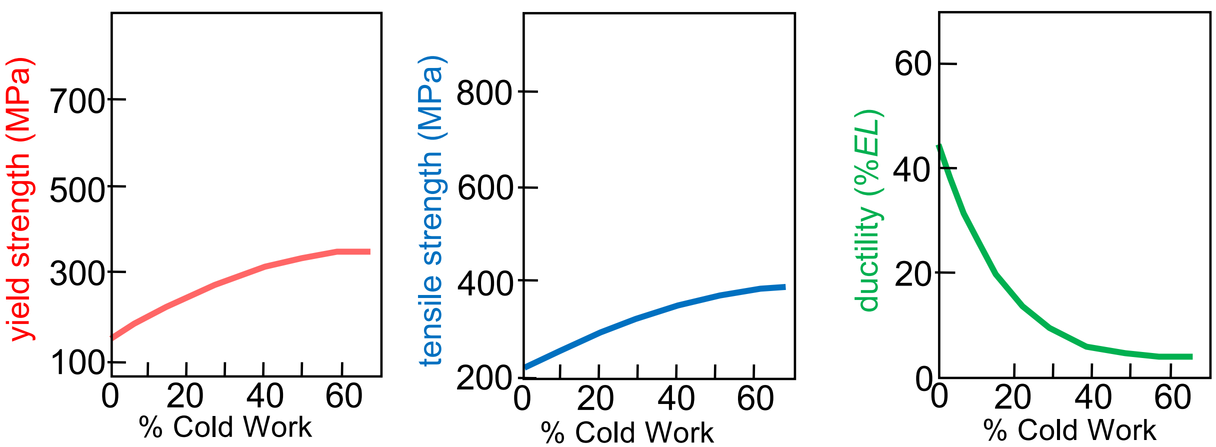


Fig. 9.19, *Callister & Rethwisch 9e.* [Adapted from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), 1978; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker (Managing Editor), 1979. Reproduced by permission of ASM International, Materials Park, OH.]

Heat Treatment (열처리)

재료에 열을 가해 미세 조직을 변화시켜 원하는 물성 변화를 최종적으로 다듬는 과정

다양한 열처리 기술이 존재한다 (시간과 온도 control)

Aging (Precipitation heat treatment): 석출물을 적절한 시간동안의 열처리를 통해 인위적으로 만들어내어 강도 증가: over-aging may reduce strength.

Annealing (풀림): 고온에 장시간 노출시킨후 천천히 냉각하는 공정. (상온->고온->상온)

Recovery: cold-work을 통해 얻어진 전위를 감소시키고, 내부 변형률 에너지 감소

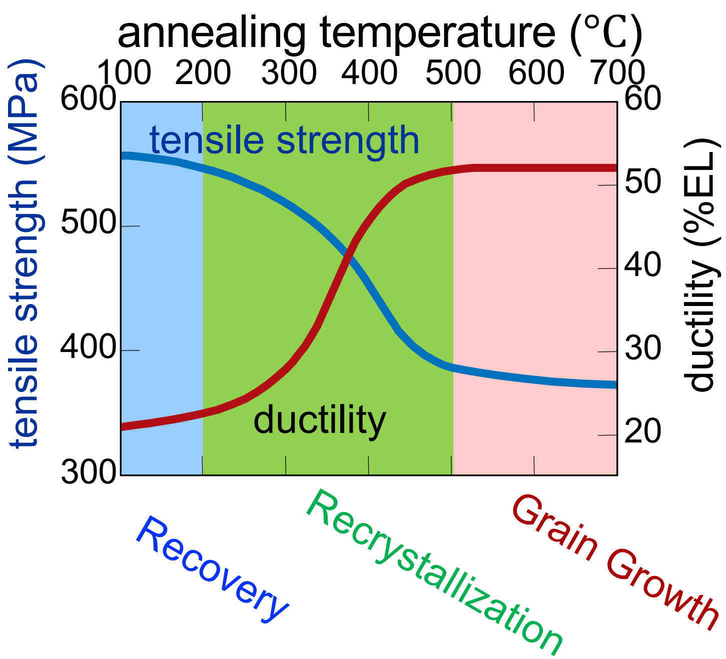
Recrystallization (재결정): cold-work 동안 dislocation과 내부 변형률 가득한 grain이 없어지고 새로운 grain (dislocation-free, strain-free)이 형성

Grain-growth; Grains created during recrystallization grows

Quenching (급속 냉각): 고온에 노출되어 있는 금속을 급속하게 냉각하는 공정; Steel의 경우 Martensite라는 불안정하지만 매우 강한 상(phase)을 얻을 수 있다.

Effect of Heat Treating After Cold Working

- 1 hour treatment at T_{anneal} decreases *TS* and increases *%EL*.
- Effects of cold work (strength & hardness) are nullified!



- Three Annealing stages:
  1. Recovery
  2. Recrystallization
  3. Grain Growth

Anneal: (구워) 풀림하다
Nullify: 헛되게 하다

Three Stages During Heat Treatment: 1. Recovery

- Three Annealing stages:
  1. Recovery
  2. Recrystallization
  3. Grain Growth

Material is exposed to high temperature ($T>T_{Room}$) during annealing

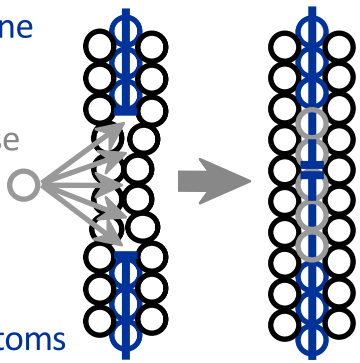
Note that **diffusion** (확산) of atoms are promoted at elevated temperature

*Diffusion is discussed in Chapter 7

Reduction of dislocation density by annihilation.

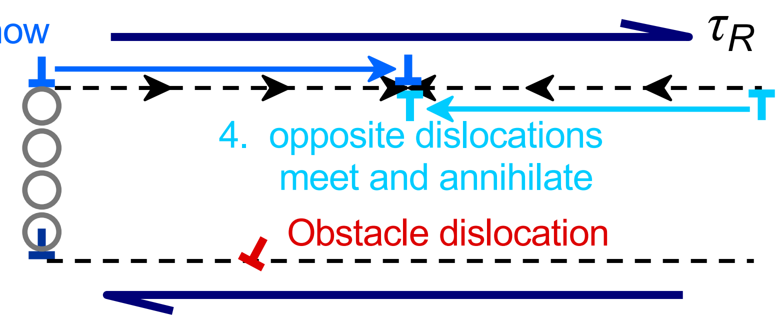
- Scenario 1

Results from diffusion



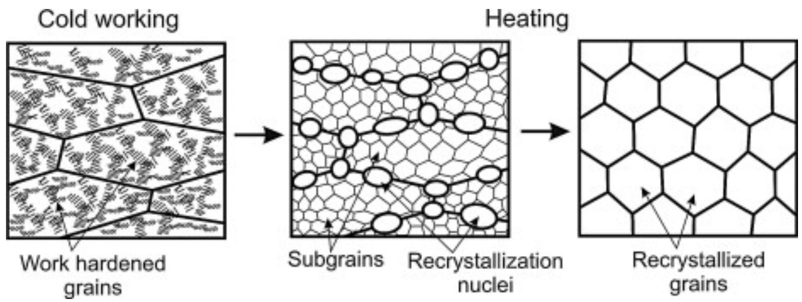
- Scenario 2

3. "Climbed" disl. can now move on new slip plane
2. grey atoms leave by vacancy diffusion allowing disl. to "climb"
1. dislocation blocked; can't move to the right



Three Stages During Heat Treatment: 2. Recrystallization

- Three Annealing stages:
  1. Recovery
  2. Recrystallization
  3. Grain Growth



Energy state comparison

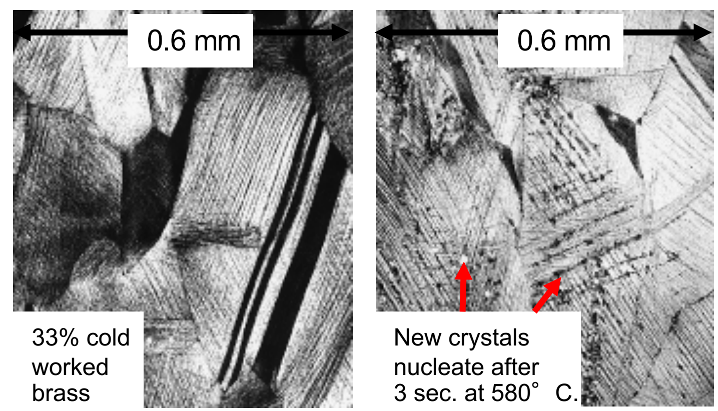
Grains with high dislocation density > Grains without dislocation

Grains without dislocation is energetically more preferred.

Heat assists grains with high energy to become new grains with low energy

See Fig. 9.21 Page 288

- New grains are formed that:
  -- have **low dislocation densities**
  -- are **small in size**
  -- consume and replace parent cold-worked grains.



황동 (brass) Cu-Zn alloy

Adapted from Fig. 9.21 (a),(b), *Callister & Rethwisch 9e.* (Photomicrographs courtesy of J.E. Burke, General Electric Company.)

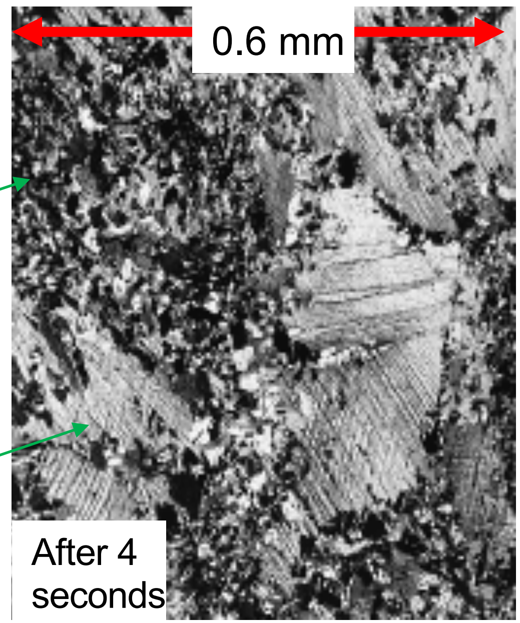
As Recrystallization Continues...

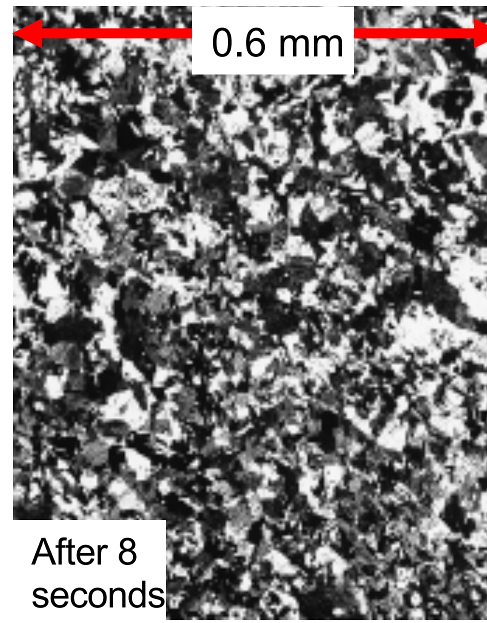
- Three Annealing stages:
  1. Recovery
  2. Recrystallization
  3. Grain Growth

- All cold-worked grains are eventually consumed/replaced.

하�-거나, 까만 작은 알갱이들(재결정된 grain)

냉간가공(cold-work) 동안 변형이 많이 발생한 기존의 결정립





Adapted from Fig. 9.21 (c),(d), *Callister & Rethwisch 9e.* (Photomicrographs courtesy of J.E. Burke, General Electric Company.)

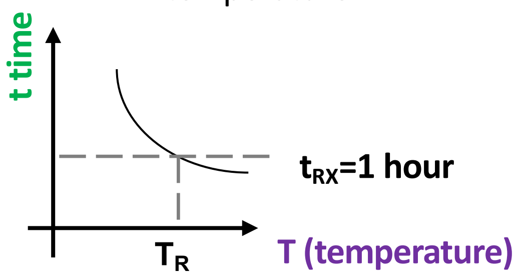
Recrystallization

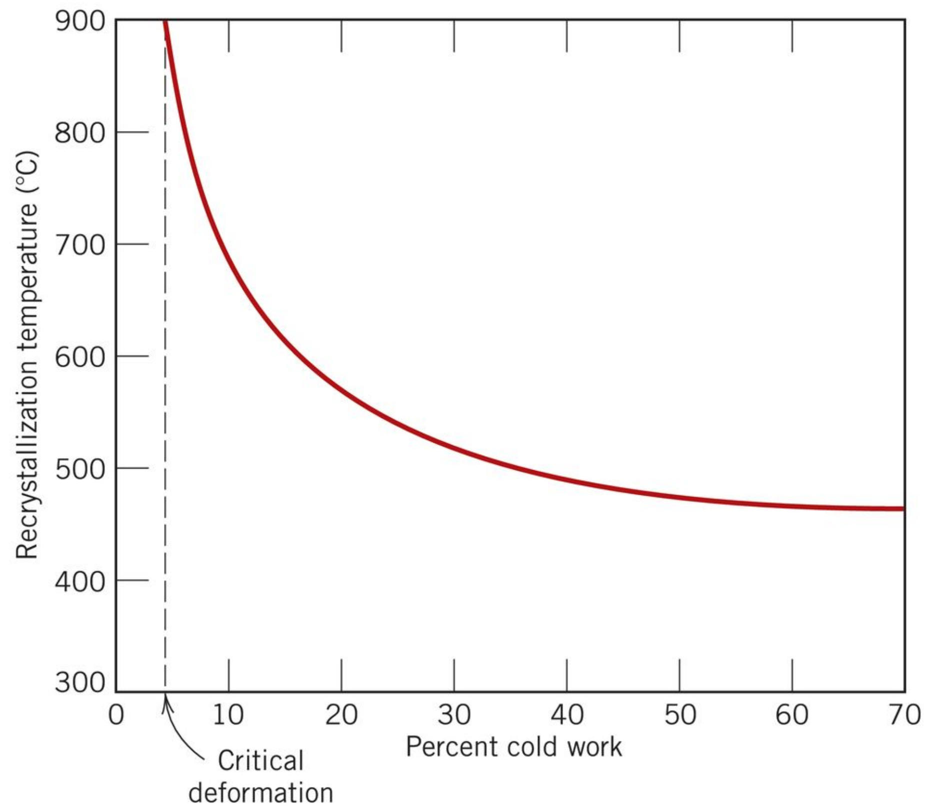
Recrystallization rate depends on temperature and time.

Recrystallization process

elapsed time t

t varies depending on temperature T





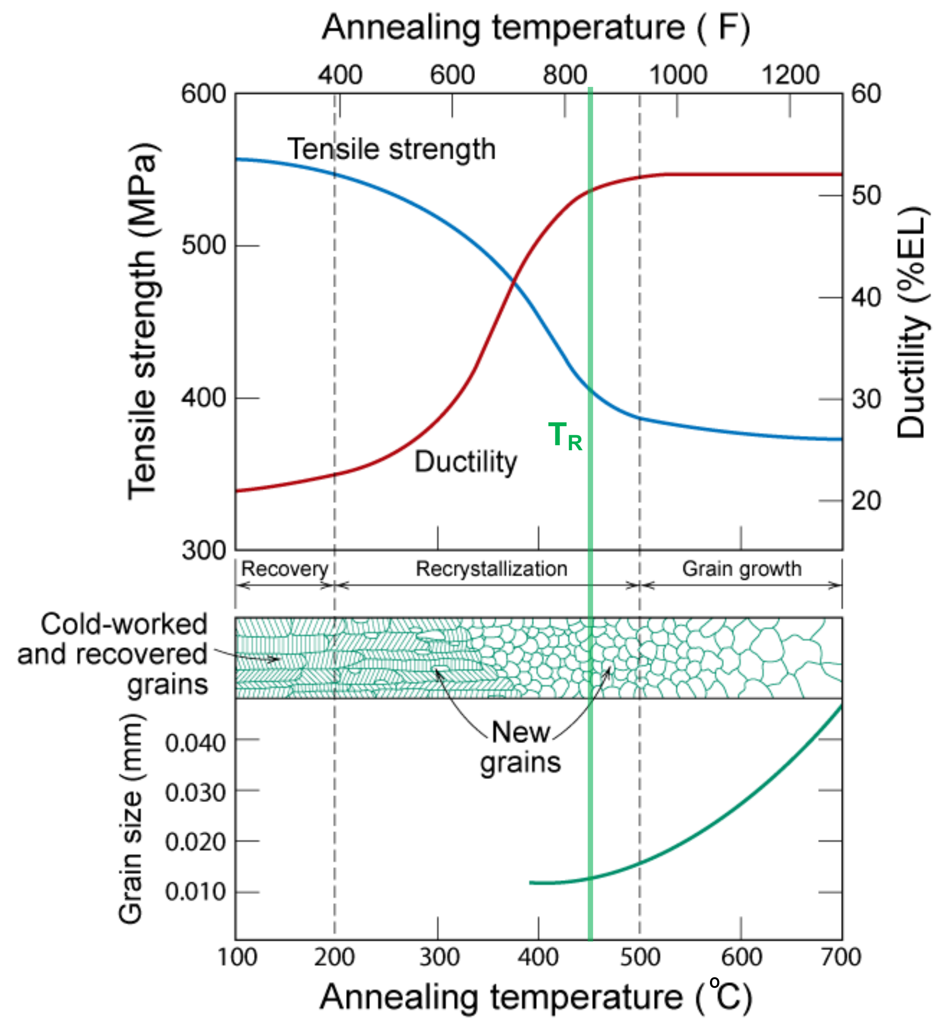
There's a certain amount of deformation needed for recrystallization to occur.

Recrystallization temperature

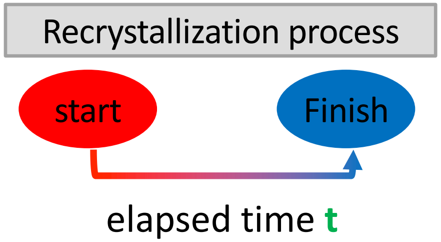
Changes in cold-worked brass during 1 hour of annealing at various temperatures

Changes in mechanical properties

Changes in grain size



Recrystallization temperature; Summary



T_R = recrystallization temperature = temperature at which recrystallization just reaches completion in 1 hour.

$0.3T_m < T_R < 0.6T_m$ $\qquad$ T_m: melting temperature

For a specific metal/alloy, T_R depends on:

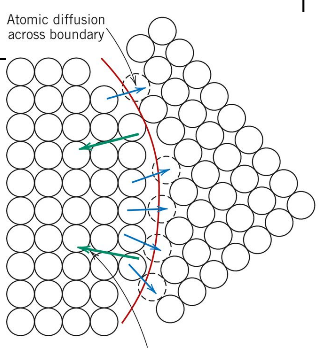
- The amount of cold work (%CW): T_R decreases with increasing %CW
- Purity of metal: T_R decreases with increasing purity; Adding alloying elements will delay completion of recrystallization.

Three Stages During Heat Treatment: 3. Grain Growth

- Three Annealing stages:
  1. Recovery
  2. Recrystallization
  3. Grain Growth

After recrystallization, the grains are dislocation-free. However, if exposed to heat, grains further grow.

The driving force for grains to grow comes from grain boundaries (the energy state of g.b. is higher than that of grain). Therefore, by growing grains (=reducing g.b.), the total energy reduces.

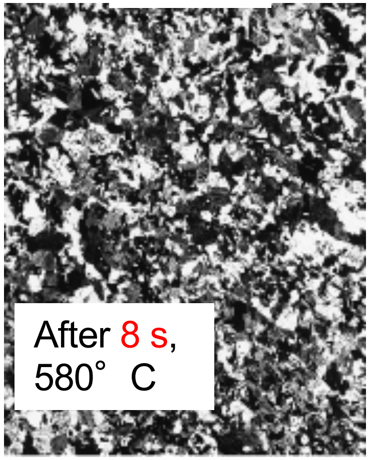


Adapted from L. H. Van Vlack, Elements of Materials Science and Engineering, 6th edition. © 1989 by Addison-Wesley Publishing Company, Inc.

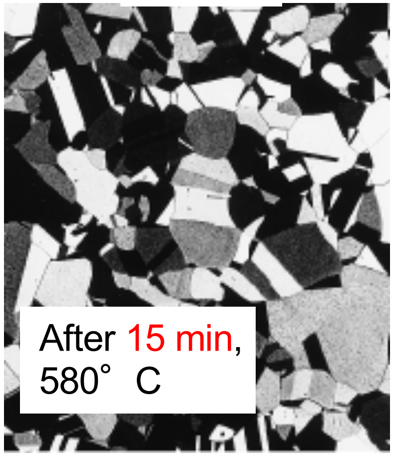
- At longer annealing time, average grain size increases.

-- Small grains shrink (and ultimately disappear)
-- Large grains continue to grow

0.6 mm



0.6 mm



Adapted from Fig. 11.21 (d),(e), *Callister & Rethwisch 9e.* (Photomicrographs courtesy of J.E. Burke, General Electric Company.)

- Empirical Relation (eq. 9.9):

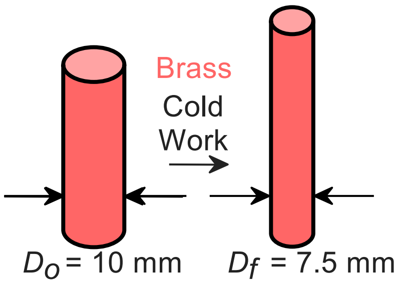
$$d^n - d_o^n = Kt$$

- exponent typ. ~ 2 (n)
- grain diam. at time t (d)
- coefficient dependent on material and *T*. (K)
- elapsed time (t)

Diameter Reduction Procedure

A cylindrical rod of **brass** originally 10 mm in diameter is to be cold worked by drawing. The circular cross section will be maintained during deformation. A cold-worked tensile strength in excess of 380 MPa and a ductility of at least 15 %*EL* are desired. Furthermore, the final diameter must be 7.5 mm. Explain how this may be accomplished.

What are the consequences of directly drawing to the final diameter?



$$\%CW = \left(\frac{A_0 - A_f}{A_0}\right) \times 100 = \left(1 - \frac{A_f}{A_0}\right) \times 100$$

$$= \left(1 - \frac{\pi D_f^2/4}{\pi D_0^2/4}\right) \times 100 = \left(1 - \left(\frac{7.5}{10}\right)^2\right) \times 100$$

$$= 43.8\%$$

The influence of cold-work on mechanical properties should be found from database.

Diameter Reduction Procedure – Solution (cont.)

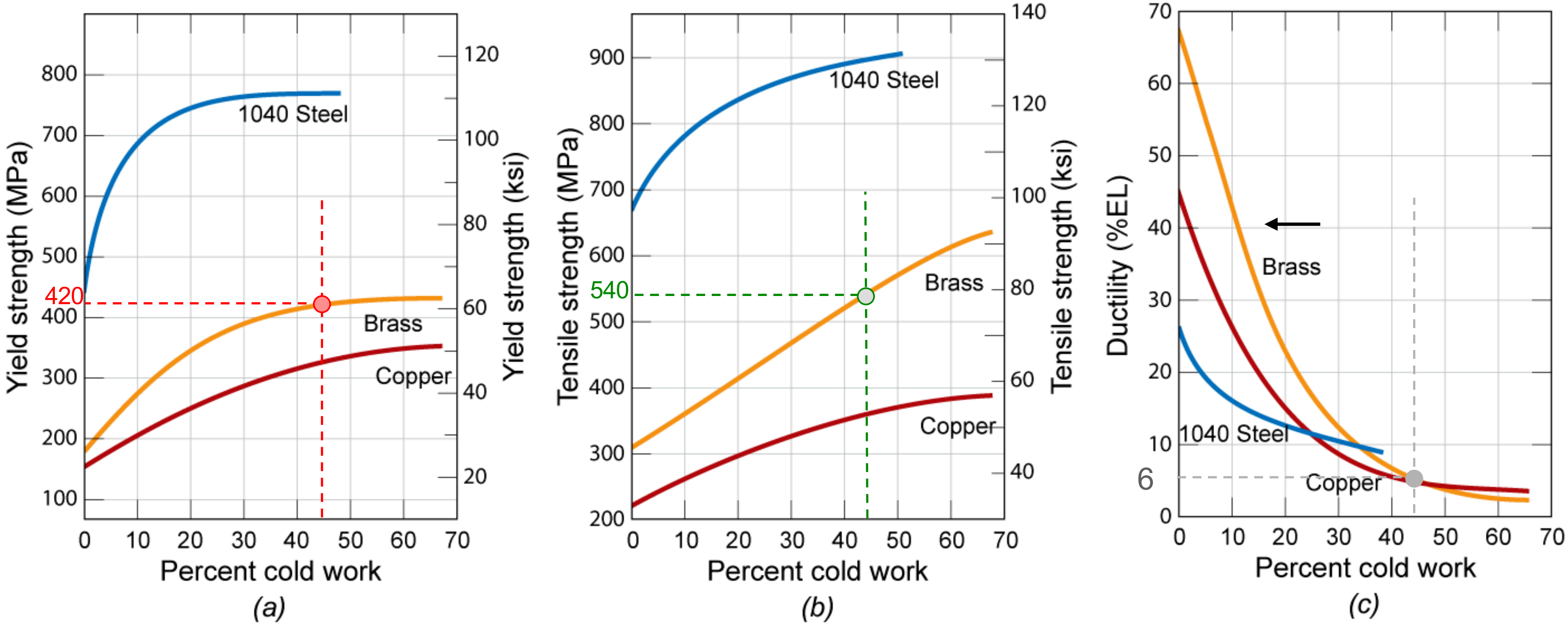


Fig. 9.19, Callister & Rethwisch 9e.
[Adapted from Metals Handbook: Properties and Selection: Irons and Steels, Vol. 1, 9th edition, B. Bardes (Editor), 1978; and Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals, Vol. 2, 9th edition, H. Baker (Managing Editor), 1979. Reproduced by permission of ASM International, Materials Park, OH.]

- For %CW = 43.8%
  - σ_y = 420 MPa
  - TS = 540 MPa > 380 MPa
  - %EL = 6 < 15
- This doesn't satisfy criteria… what other options are possible?

Diameter Reduction Procedure – Solution (cont.)

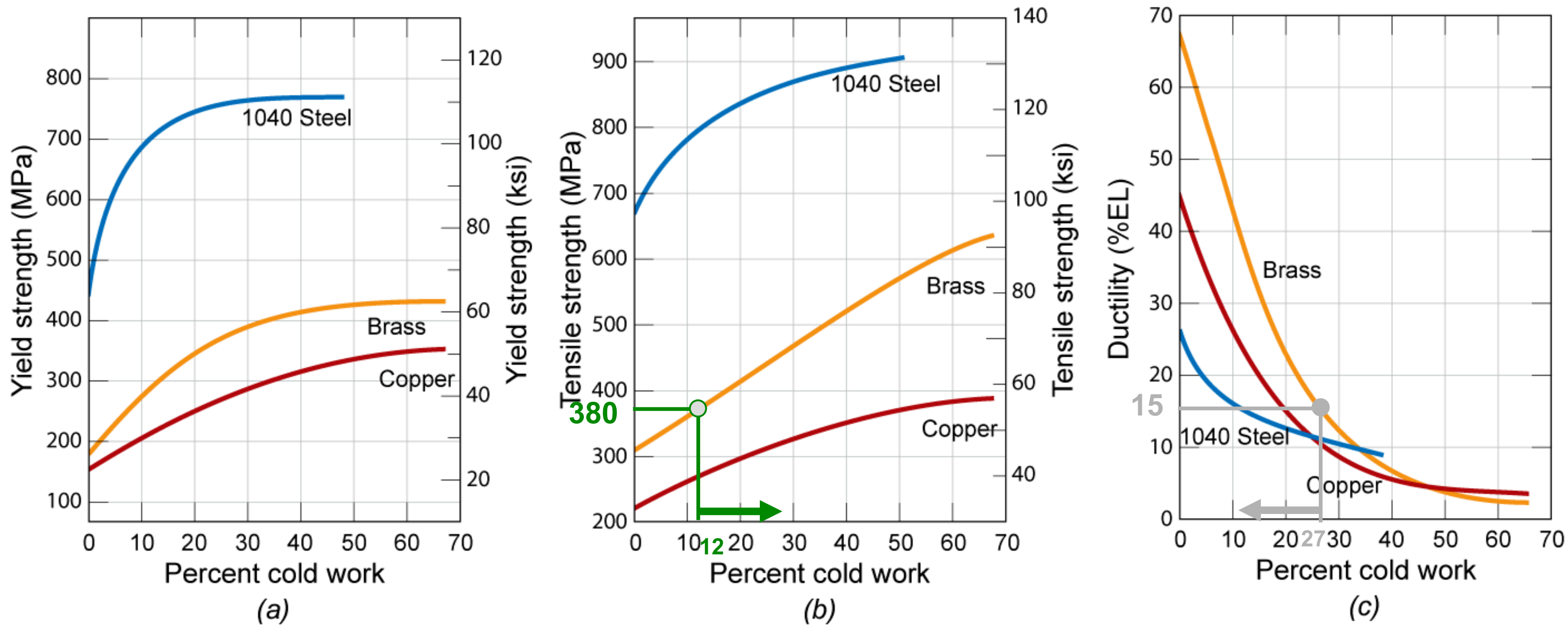


Fig. 9.19, *Callister & Rethwisch 9e.* [Adapted from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), 1978; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker (Managing Editor), 1979. Reproduced by permission of ASM International, Materials Park, OH.]

For *TS* > 380 MPa → > 12 %CW

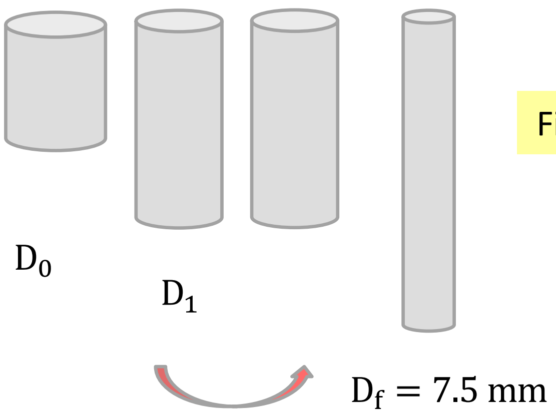
For *%EL* > 15 → < 27 %CW

∴ our working range is limited to 12 < %CW < 27 ≪ 43.8%

Diameter Reduction Procedure – Solution (cont.)

Suggested solution: 1) Cold-work, 2) then anneal (RX), then 3) cold-work again

- For objective we need a cold-work of 12 < %CW < 27
  - We'll use 20 %CW
- Diameter after 1st cold work stage (but before 2nd cold work stage) is calculated as follows:



Find what value of the intermediate diameter D_1 will allow us to have the CW% of 20.

$$\left(1 - D_f^2/D_1^2\right)\times 100 = 20$$

$$(1 - 7.5/D_1^2)\times 100 = 20$$

$$D_1 = 8.39\ [\text{mm}]$$

Anneal (RX) – nullify the effects of CW

Diameter Reduction Procedure – Summary

Stage 1: Cold work – reduce diameter from 10 mm to 8.39 mm

$$\%CW = \left(1 - \left(\frac{8.39\ \text{mm}}{10\ \text{mm}}\right)^2\right) \times 100 = 29.6\%$$

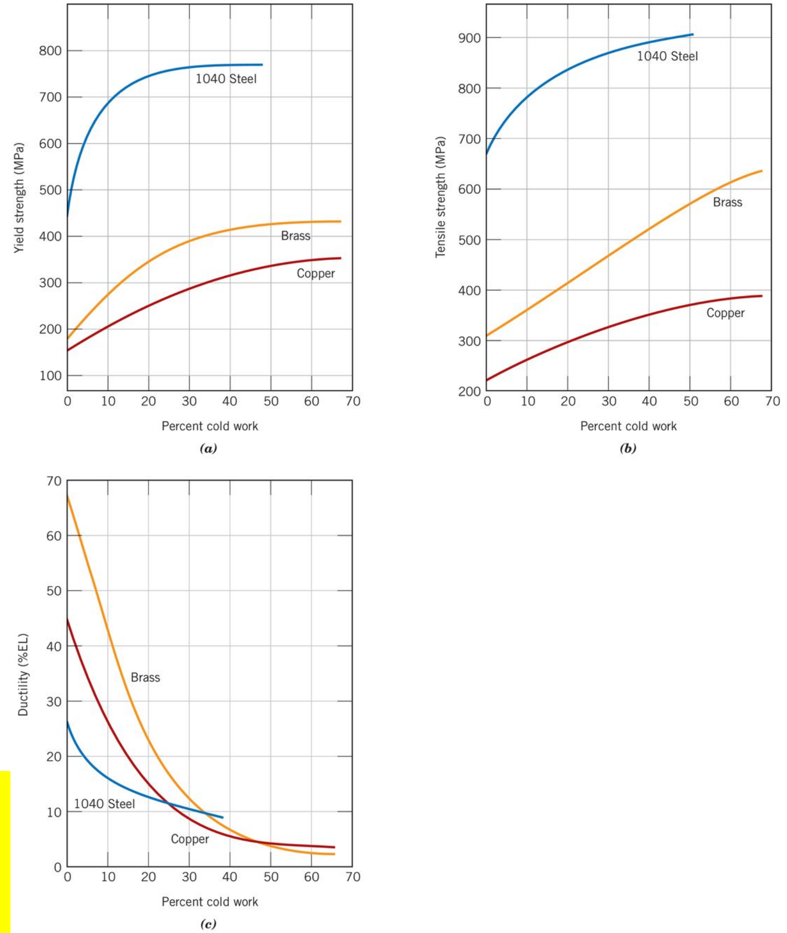
Stage 2: Heat treat (allow recrystallization) -> recover to properties before cold-work

Stage 3: Cold work – reduce diameter from 8.39 mm to 7.5 mm

Fig 9.19

$$(1 - 7.5^2/8.39^2) \times 100 = 20\ [\%CW] \Rightarrow$$

$$\sigma_Y \approx 340\ \text{MPa}$$
$$\sigma_{TS} \approx 410\ \text{MPa}$$
$$\%EL \approx 23\%$$



Therefore, all criteria satisfied.

Recap

- 전단 응력에 의한 전위의 이동 그에 따른 소성 변형
- Dislocation and lattice distortion
  - Interaction between dislocations
- Slip system – closed-packed plane and close-packed direction.
- Twinning. Difference between twinning and slip.
- 입계의 전위 이동 방해 – grain boundary acts as barrier to dislocations
- Interaction between dislocation and strain field – strain hardening (변형률 강화), cold working (냉간 가공)
- Heat treatment (열처리); Annealing, recovery, recrystallization and grain growth.