

# Chapter 8

## Strain Hardening & Annealing

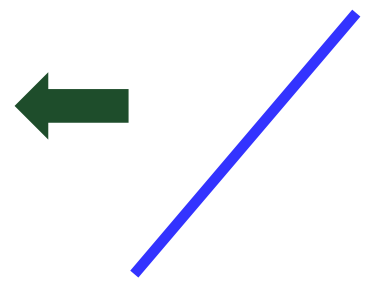
Dr. Zhe Cheng

# Strengthening of Metals by Impeding Dislocation Motion

## ➤ **Strain hardening**

- Entangled dislocations hamper dislocation motion

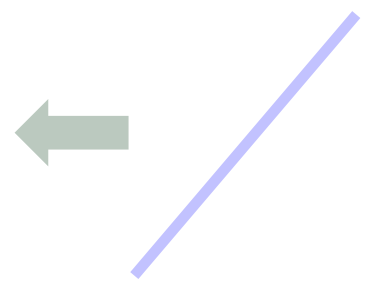
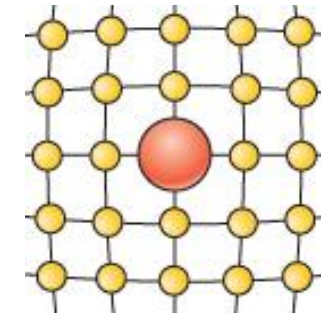
Entangled  
dislocations



## ➤ **Solid solution strengthening**

- Lattice distortion from impurity atoms hampers dislocation motion

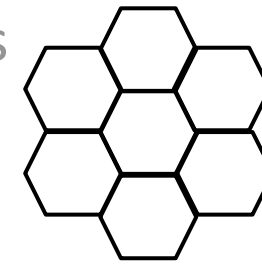
Impurity atom



## ➤ **Grain-size strengthening**

- Grain boundaries (& local distortion) hamper dislocation motion

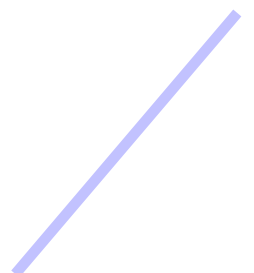
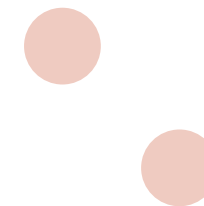
Grain  
boundaries



## ➤ **Secondary-phases or precipitation strengthening**

- Hard second phases or precipitates hamper dislocation motion

2nd phases



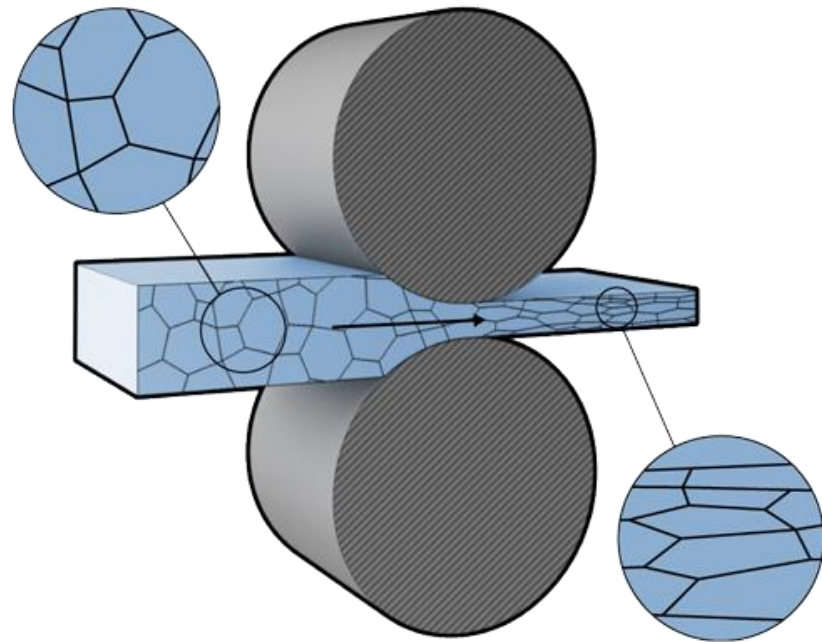
# What is Cold Working of Metals?

## ➤ Definition

Plastically (permanently) shape/deform metals to desired shape, often at around room temperature (or, technically, below recrystallization temperature)

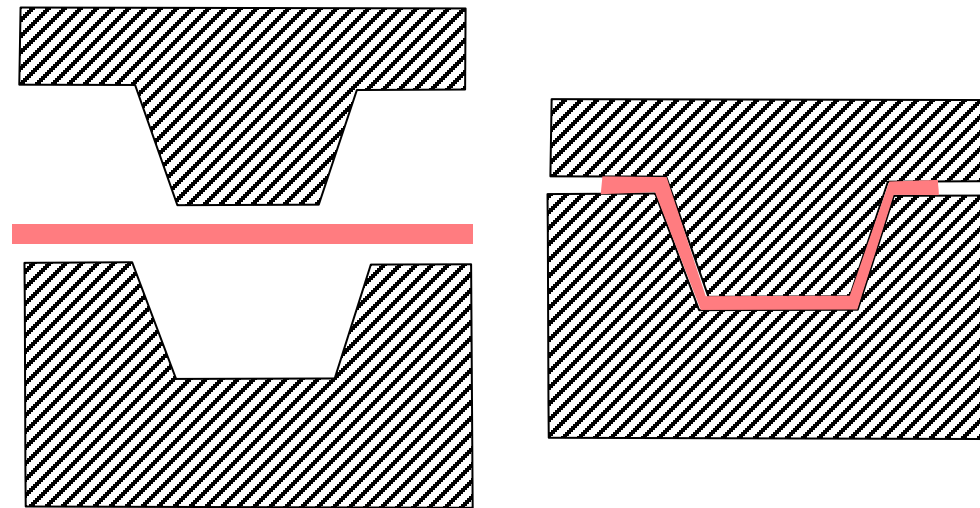
## ➤ Examples

### Cold Rolling



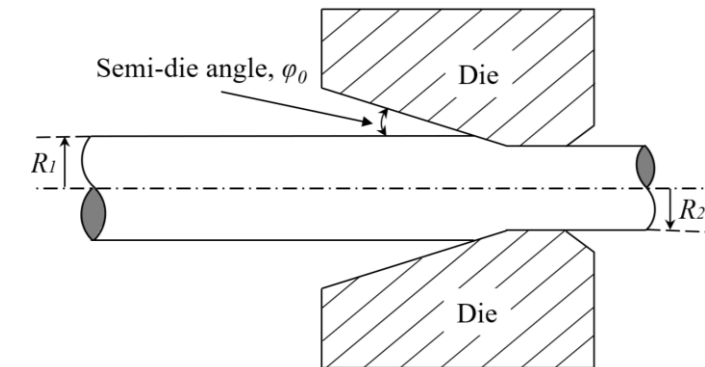
Sheet metal

### Cold Bending/Stamping



Sheet Metal

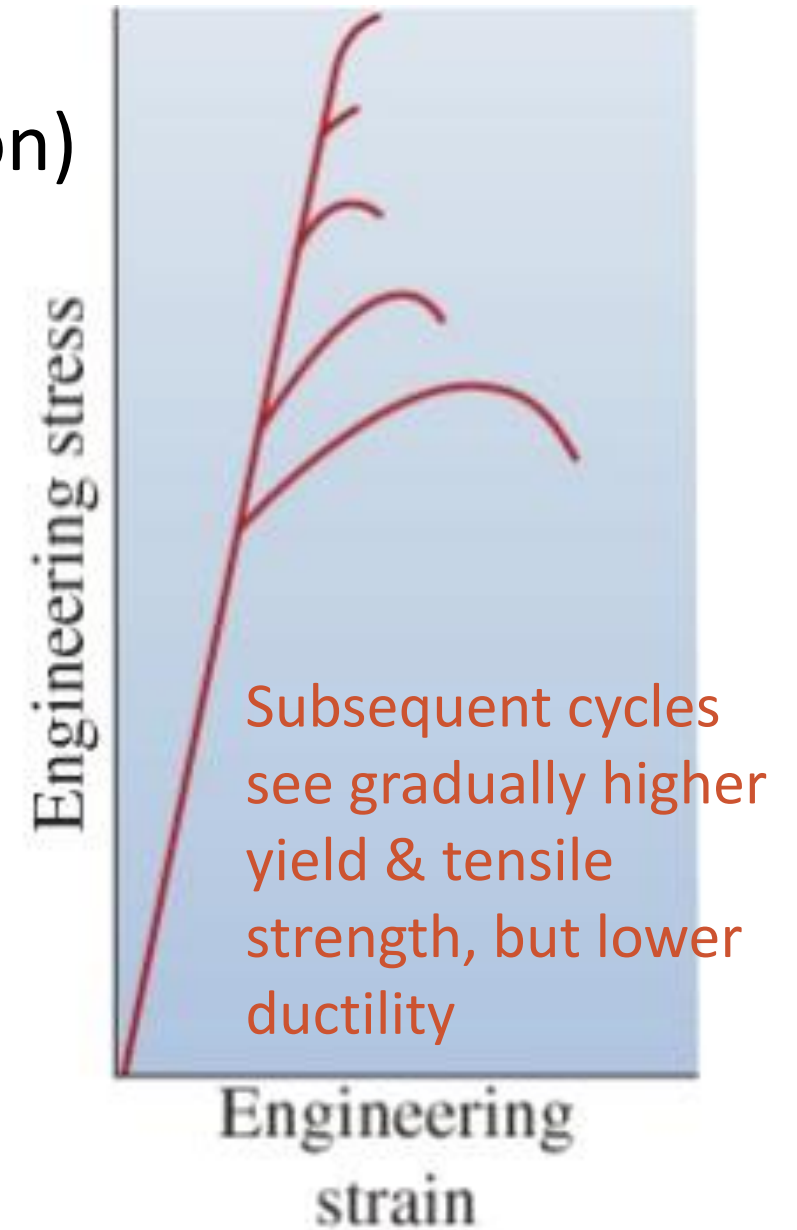
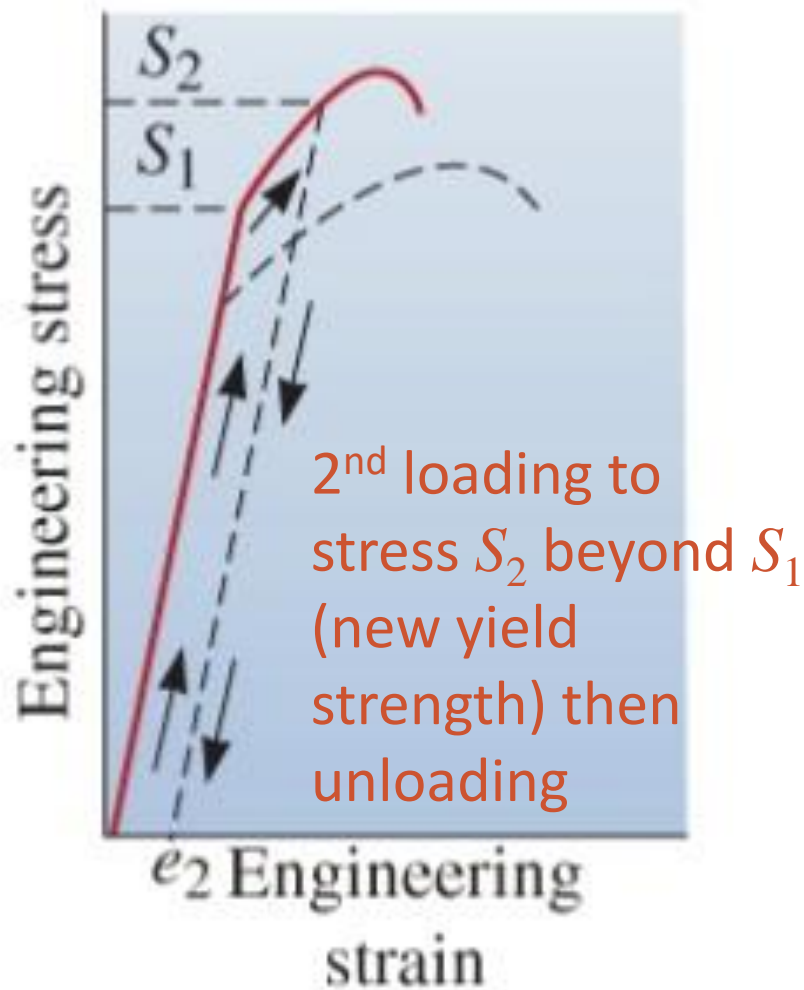
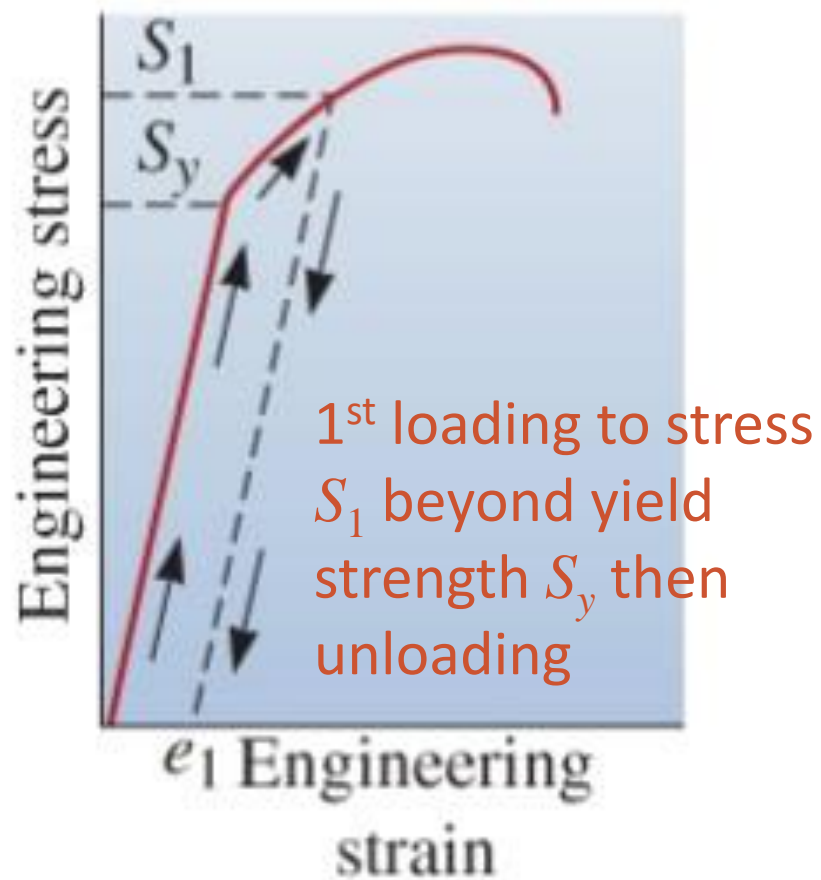
### Cold Drawing



Metal wire

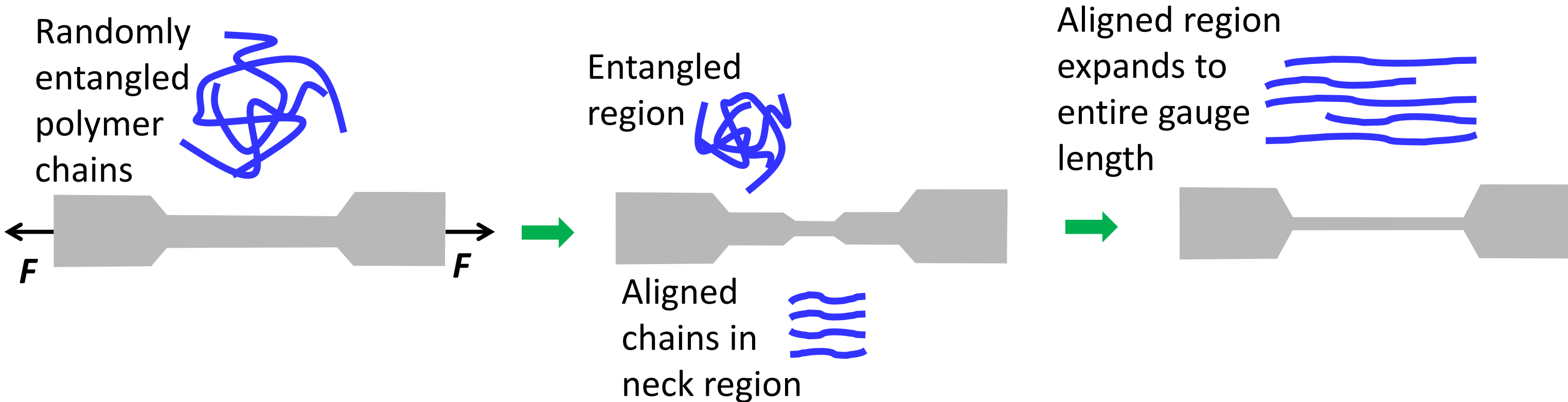
# (Cold) Work/Strain Hardening of Metals

- After a metal (pure or alloy) is **plastically deformed** and load/stress is removed, it often show **higher yield strength & tensile strength**, in subsequent loading, i.e., it appears to be “harder” or “stronger” after cold work or plastic strain, and such a phenomenon is called work hardening or strain hardening
- Hardening accompanied by **ductility drop** (e.g., % elongation)



# Work/Strain Hardening for Polymers

- Metal strain hardening due to entangled dislocations inhibiting dislocation motion
- As polymers are plastically deformed, some (thermoplastics) also display strain hardening, due to better alignment of polymer chains



# Mechanical Properties vs. Percentage Cold Work

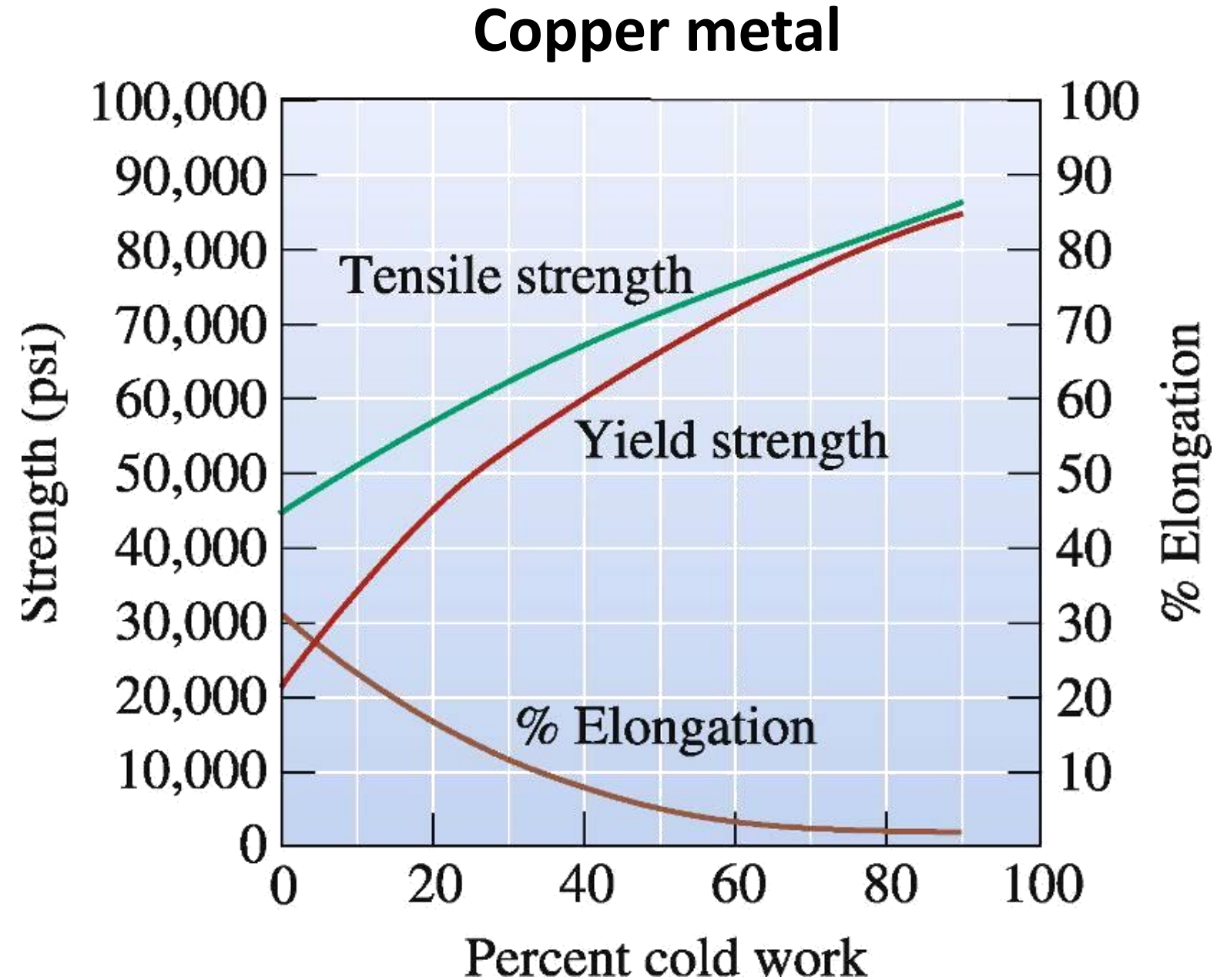
Percentage cold work often defined as:

$$\frac{A_0 - A_f}{A_0} \times 100\% = \%RA \quad \text{or}$$

$$\frac{t_0 - t_f}{t_0} \times 100\% \quad \text{\% reduction in thickness}$$

Cold work (plastic strain) leads to:

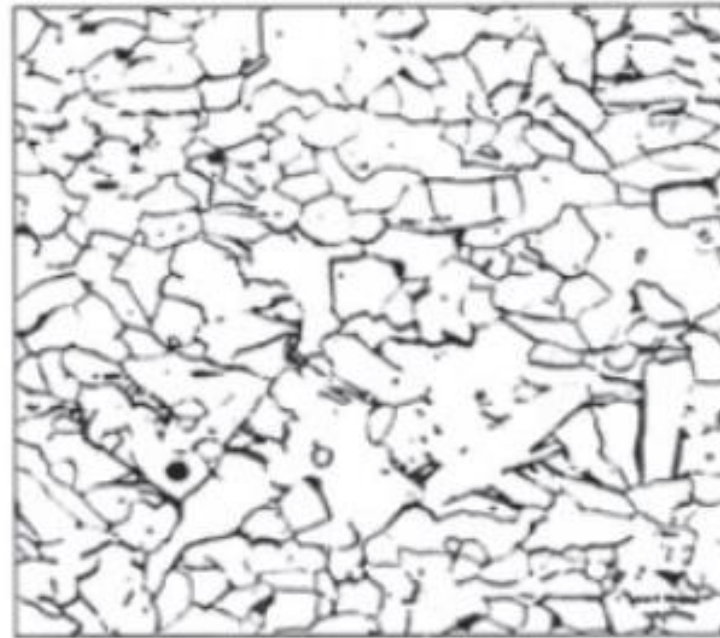
- Higher strength:  $\sigma_y$  and  $\sigma_U$
- Lower ductility (% *EL*)



# Microstructure Changes during Cold Work

Cold work changes microstructure:

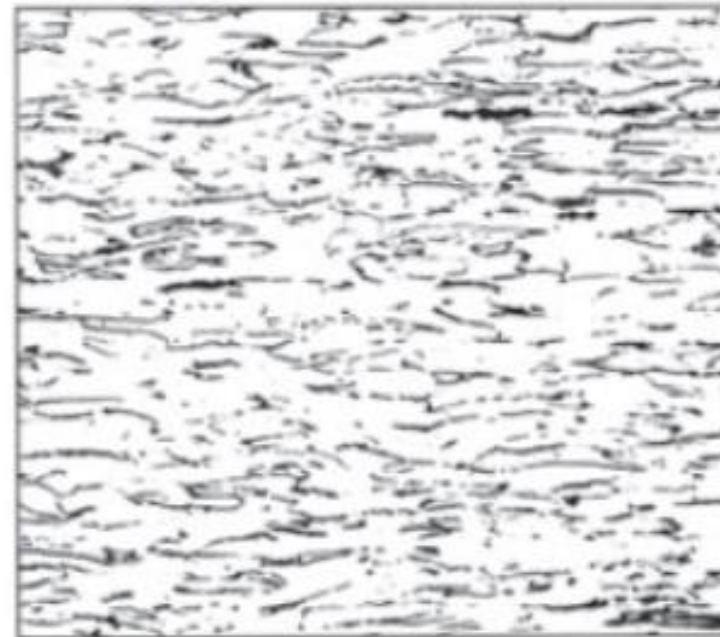
- Grains become longer/flatter
- More dislocations within grains - dislocation density (length per unit volume or # per unit area) increase by  $10^6$  times!



(a)



(b)



(c)



(d)

# Additional Notes about Cold Working

- Widely practiced due to forming the (precise) shape and strengthening material & structure at the same time
- Need to manage complications in cold working due to
  - Drop in ductility leading to defects such as cracks/holes
  - Residual stress leading to pre-mature failure
  - An-isotropy (non-uniformity) in mechanical properties

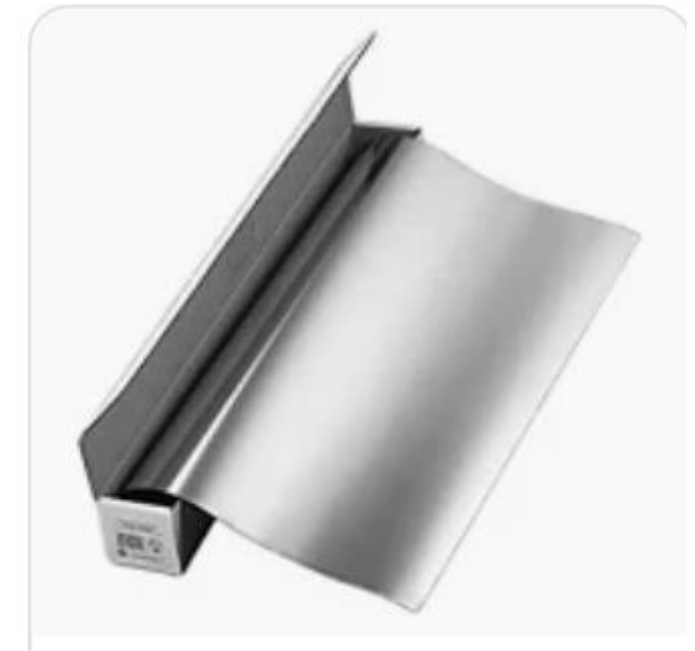
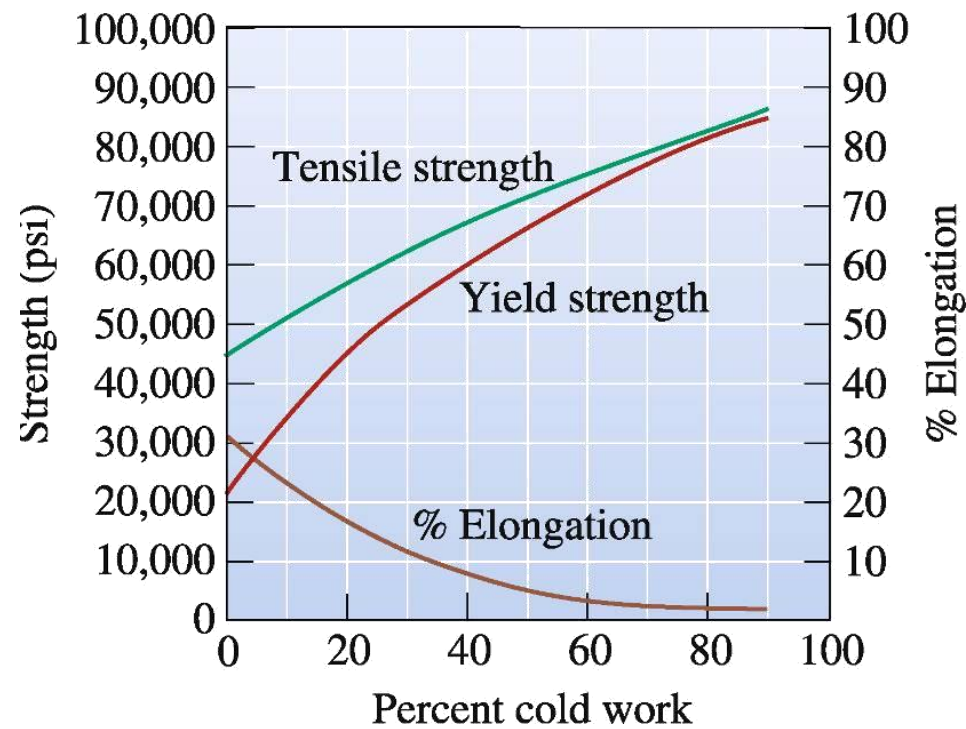


# Heat Treatment AFTER Cold Working

➤ Cold working “hardens” metals making them less ductile, sometime, may be even too brittle for needed subsequent deformation (e.g., via co-work)

- Example: rolling stainless steel from 1 inch (25.4 mm) sheet to 1 mil or 0.001” = 0.025 mm) foil

% thickness reduction ~99.9%



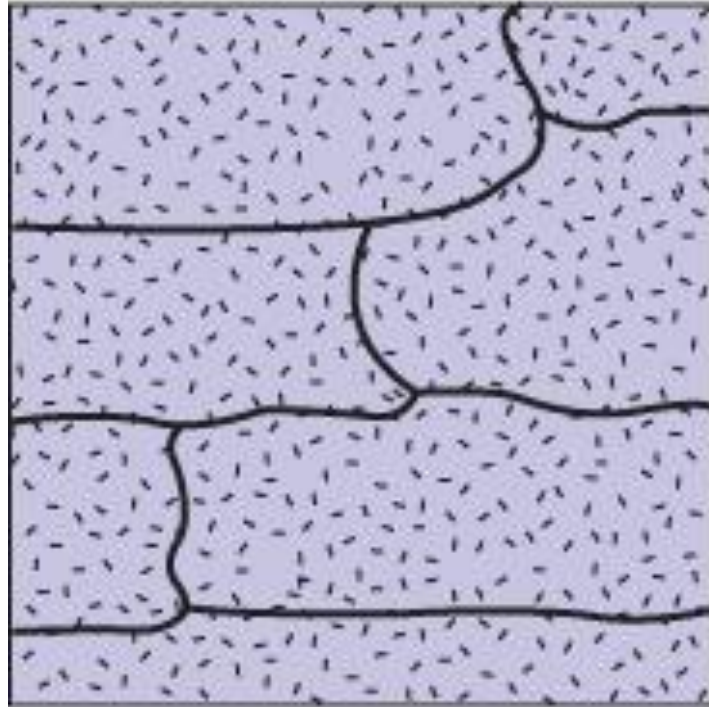
➤ **Heat treatment**, i.e., heating up the metal piece and hold, often called **annealing** of cold-worked metals, can **restore the mechanical properties**, meaning reduces strength, but increase **ductility**, which allows for more plastic deformation to the eventual shape needed

# THREE Stages of Heat Treatment/Annealing

Higher Temperature

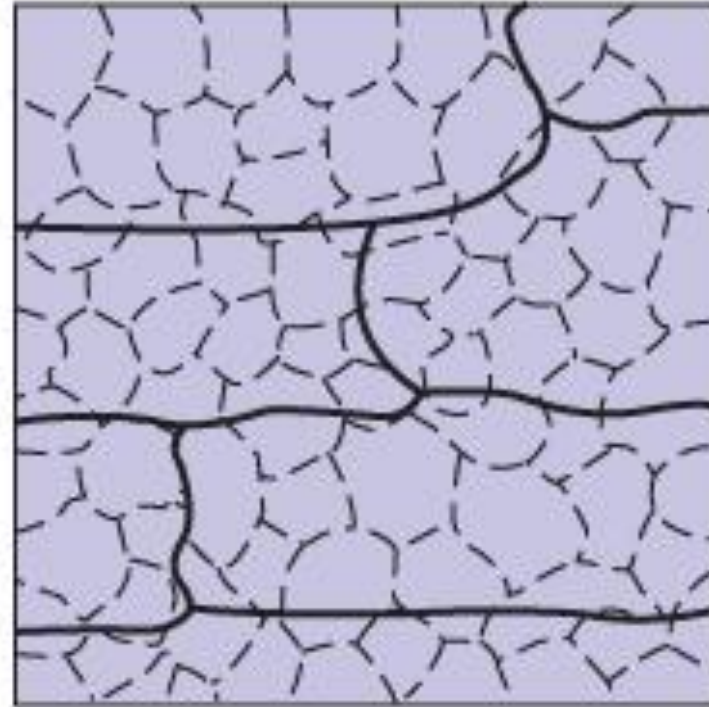


After cold-working



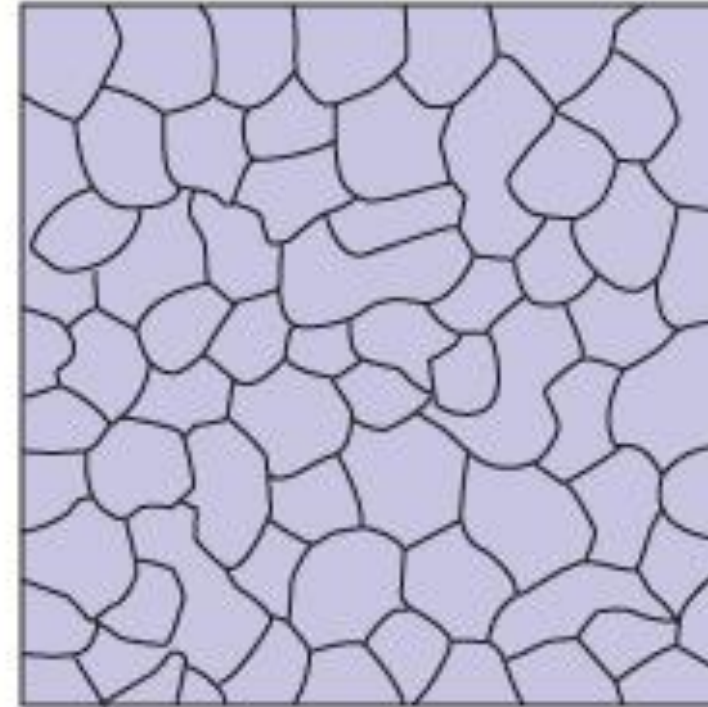
- Squeezed grain shape
- Very high defect (dislocation) density

(1) Recovery



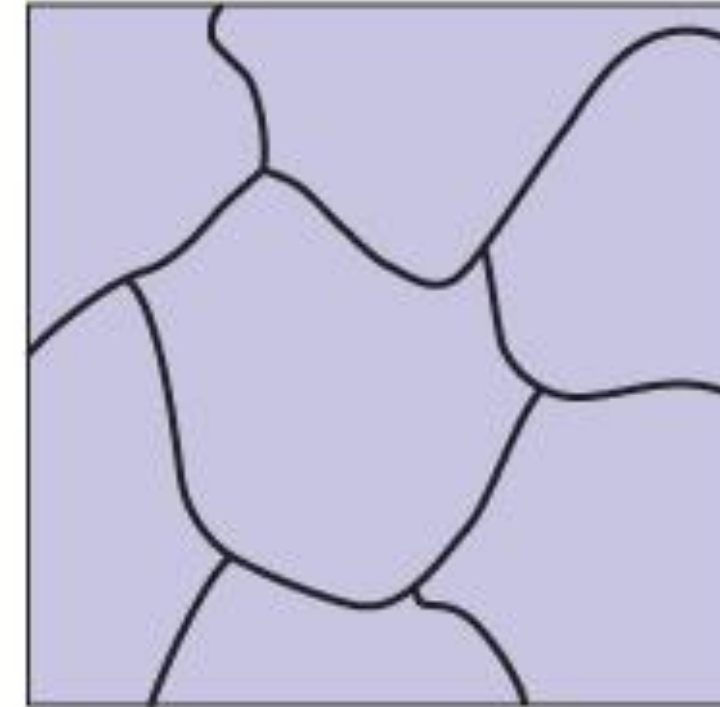
- Dislocations move & form sub-grain structures;
- residual stress released

(2) Recrystallization



- New, small grains emerge;
- Strength drop but ductility increase

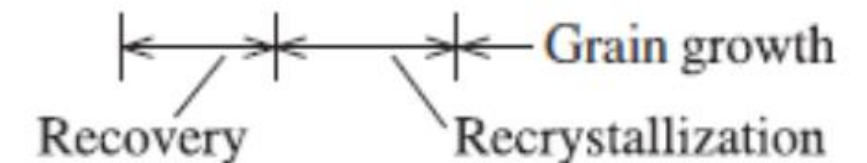
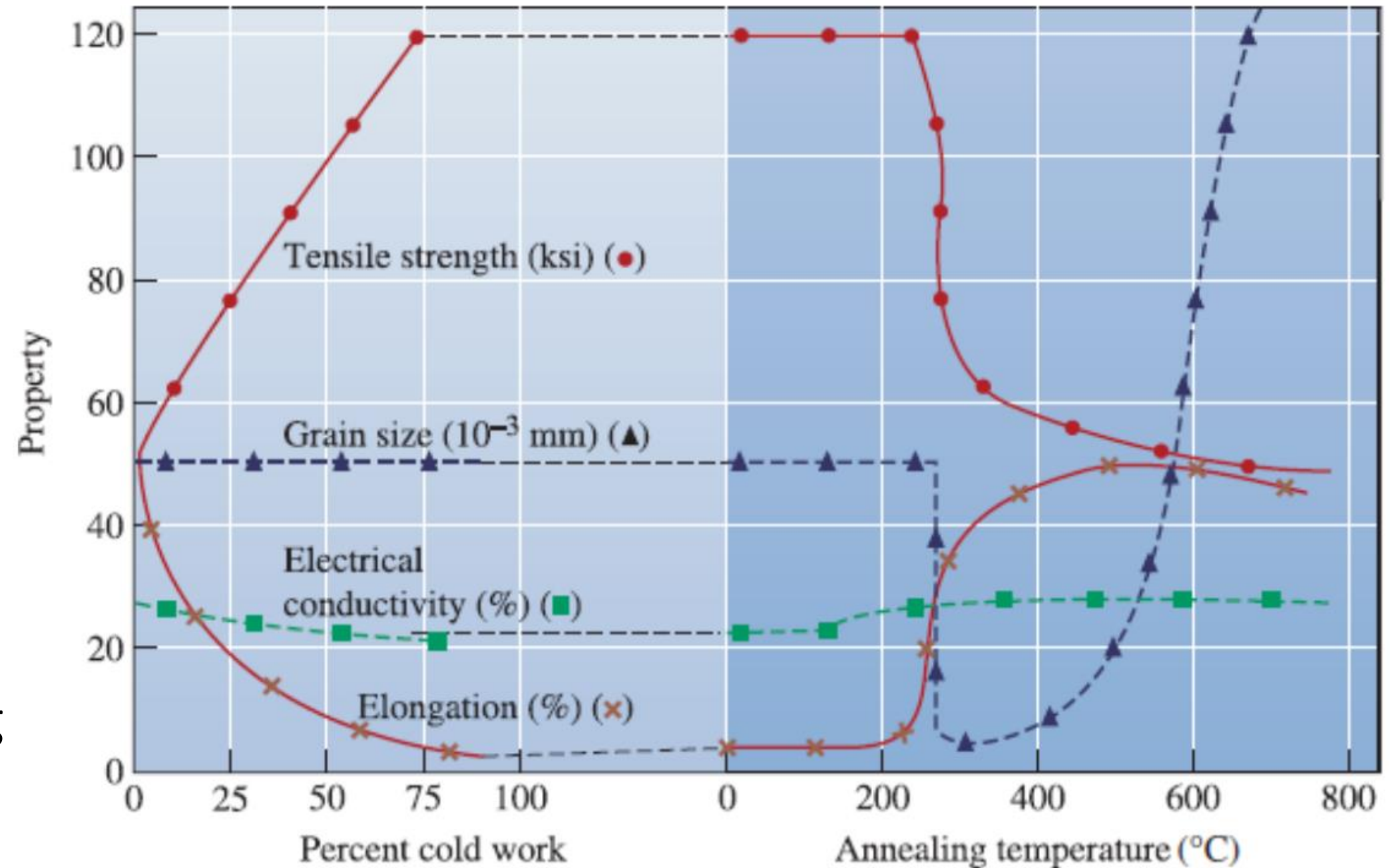
(3) Grain Growth



- Small grains grow/coalesce into large grains
- Continued drop in strength

# Metal Properties Changes in Cold Working & Annealing

- Cold working
  - Tensile strength & yield strength increase
  - Ductility drops
  - Conductivity drops
- Annealing
  - Tensile strength & yield strength drop (back)
  - Ductility increase back/recover
  - Conductivity increase back/recover
- Cold-working/annealing cycle may be repeated to achieve large plastic deformation (e.g., from 1 in to 0.001in thick)



# Hot Working

- Process metal piece above recrystallization temperature so that no hardening occur, i.e., continuous recover/recrystallization, enables large plastic deformation without fear of rupture
- Surface finish/dimension not as desirable and will need subsequent processing



END

# Homework 8.0

Carefully review chapter 8 lecture slides and, if time allows, read textbook sections (Askeland 8.1-8.9) and give an honor statement confirming the reading

# Homework 8.1

Two previously undeformed samples of the same metal are going through cold rolling. Sample A has a circular cross-section and its diameter reduces from 0.6 inch to 0.4 inch, while sample B has rectangular cross-section and its dimension changes from  $4 \times 5 \text{ inch}^2$  to  $2 \times 6 \text{ inch}^2$ . Which sample is expected to have higher yield strength and tensile strength? Which sample is expected to have higher ductility? Why?