FUNDAMENTALS OF METAL FORMING

1. Overview of Metal Forming
2. Material Behavior in Metal Forming
3. Temperature in Metal Forming
4. Strain Rate Sensitivity

Metal Forming

Large group of manufacturing processes in which plastic deformation is used to change the shape of metal workpieces

- The tool, usually called a *die*, applies stresses that exceed the yield strength of the metal
  - The metal takes a shape determined by the geometry of the die

Stresses in Metal Forming

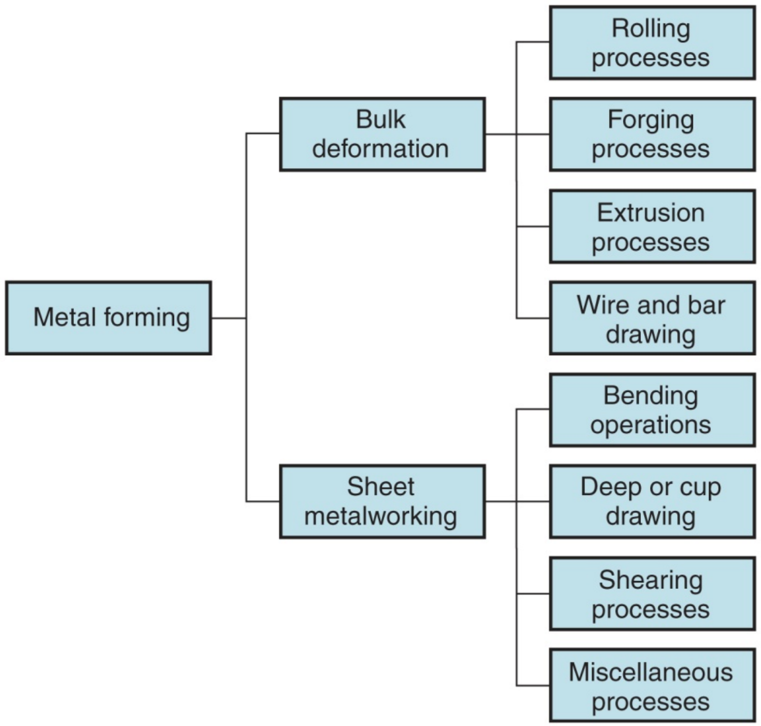
- Stresses to plastically deform the metal are usually compressive
  - Examples: rolling, forging, extrusion
- However, some forming processes
  - Stretch the metal (tensile stresses)
  - Others bend the metal (tensile and compressive)
  - Still others apply shear stresses

Material Properties in Metal Forming

- Desirable material properties:
  - Low yield strength
  - High ductility
- These properties are affected by temperature:
  - Ductility increases and yield strength decreases when work temperature is raised
- Other factors:
  - Strain rate and friction

Basic Types of Metal Forming Processes

1. Bulk deformation
   - Rolling processes
   - Forging processes
   - Extrusion processes
   - Wire and bar drawing
2. Sheet metalworking
   - Bending operations
   - Deep or cup drawing
   - Shearing processes

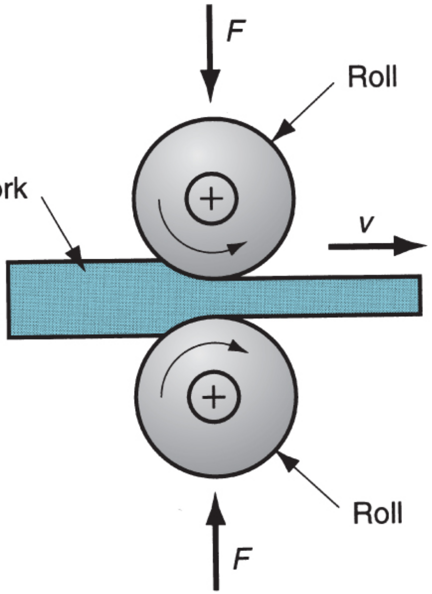


Bulk Deformation Processes

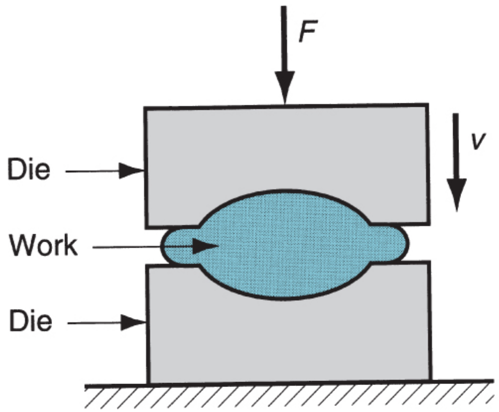
- Characterized by significant deformations and massive shape changes
- "Bulk" refers to workparts with relatively low surface area-to-volume ratios
- Starting work shapes are usually simple geometries
  - Examples:
    - Cylindrical billets
    - Rectangular bars

Bulk Deformation Processes

- (a) Rolling and (b) forging



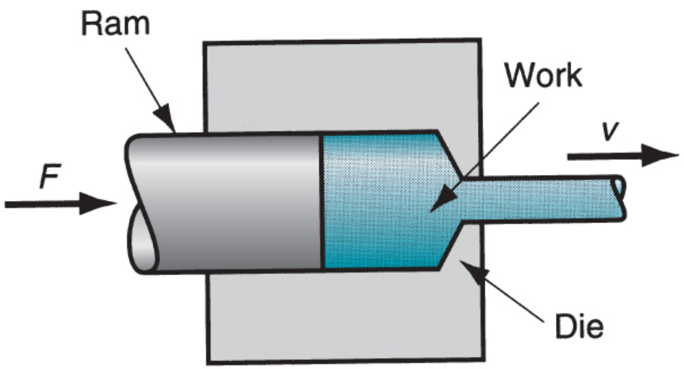
(a)



(b)

Bulk Deformation Processes

- (c) Extrusion and (d) wire and bar drawing



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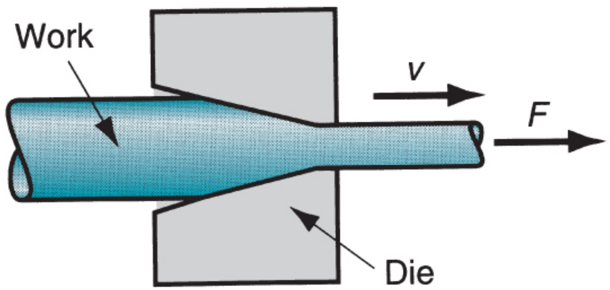


(d)

Material Behavior in Metal Forming

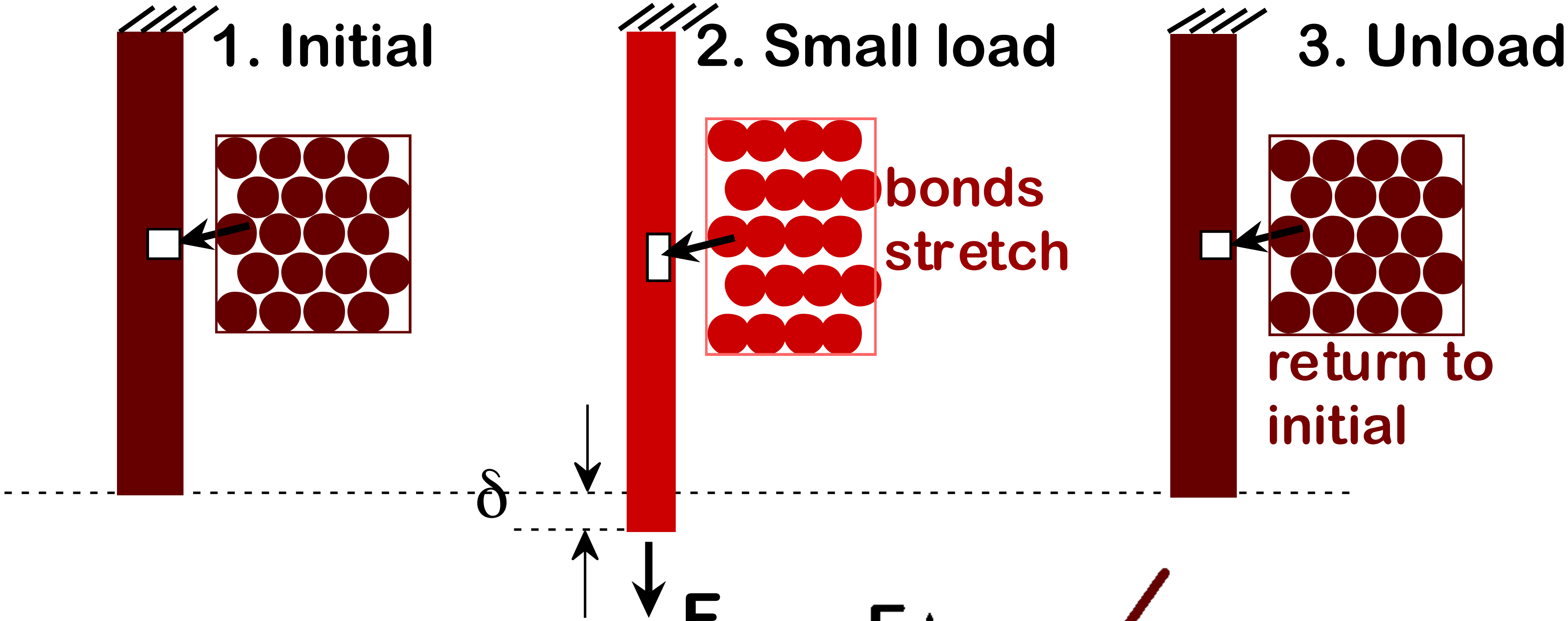
- Plastic region of stress-strain curve is primary interest because material is plastically deformed
- In plastic region, metal's behavior is expressed by the flow curve:

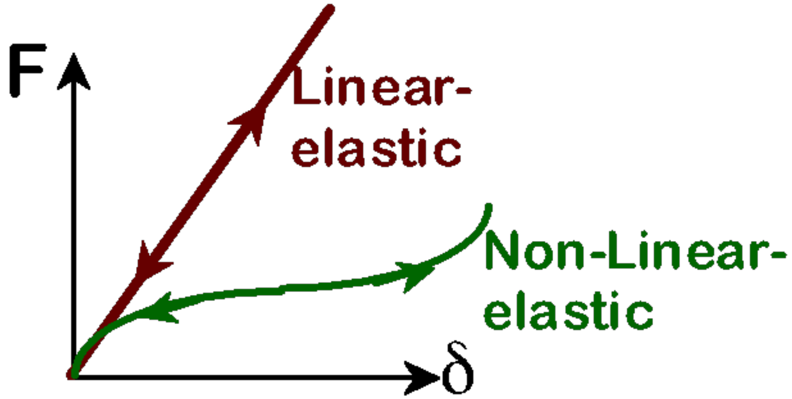
$$\sigma = K\varepsilon^n$$

where K = strength coefficient; and n = strain hardening exponent

- Flow curve based on true stress and true strain

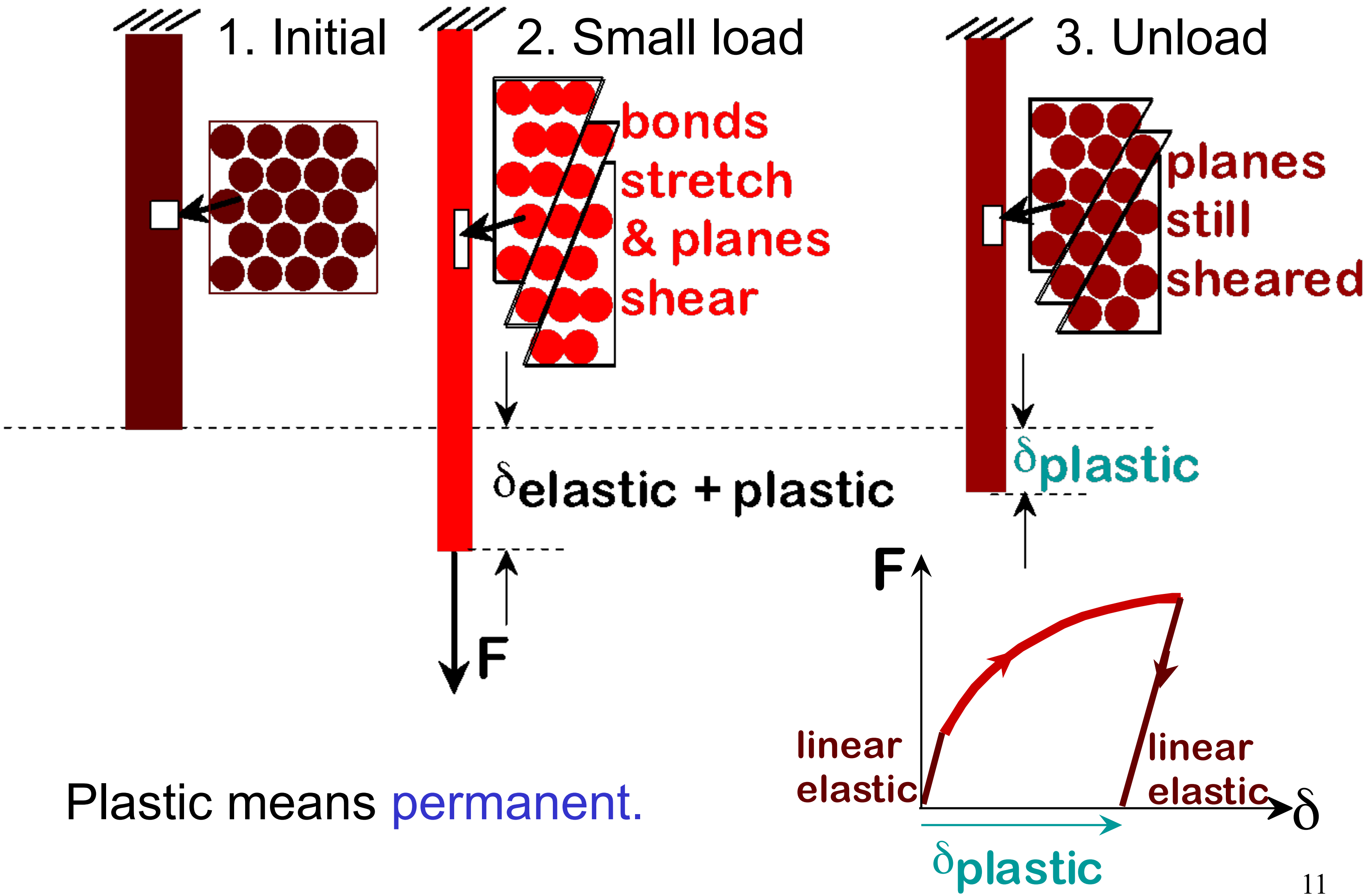
Elastic Deformation





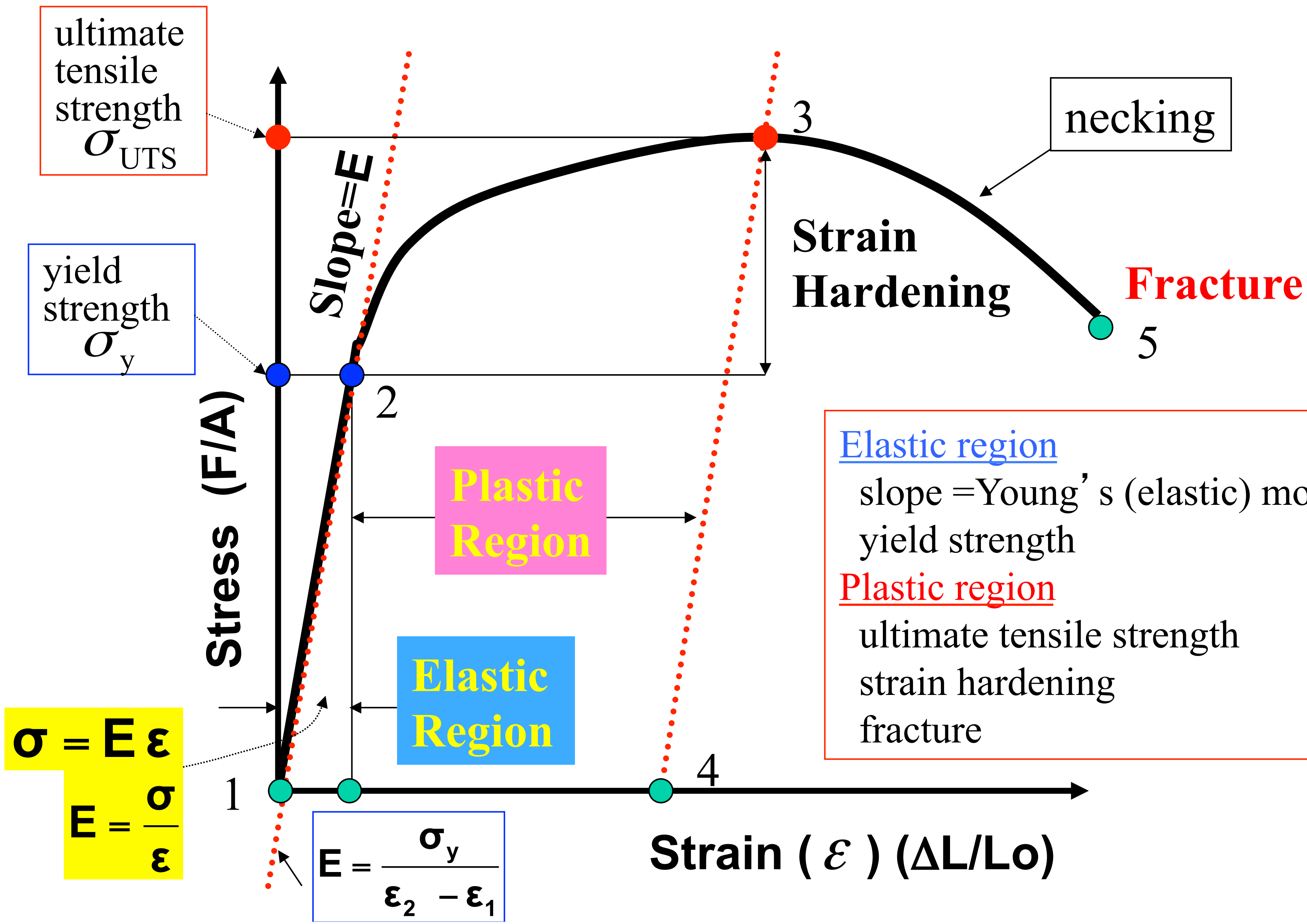
Elastic means reversible.

Plastic Deformation (Metals)



Plastic means permanent.

Stress-Strain Diagram

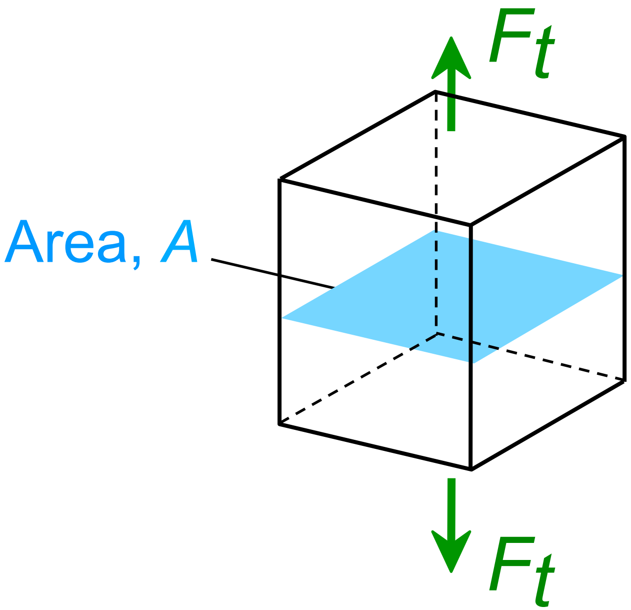


Elastic region
- slope =Young's (elastic) modulus
- yield strength

Plastic region
- ultimate tensile strength
- strain hardening
- fracture

Engineering Stress

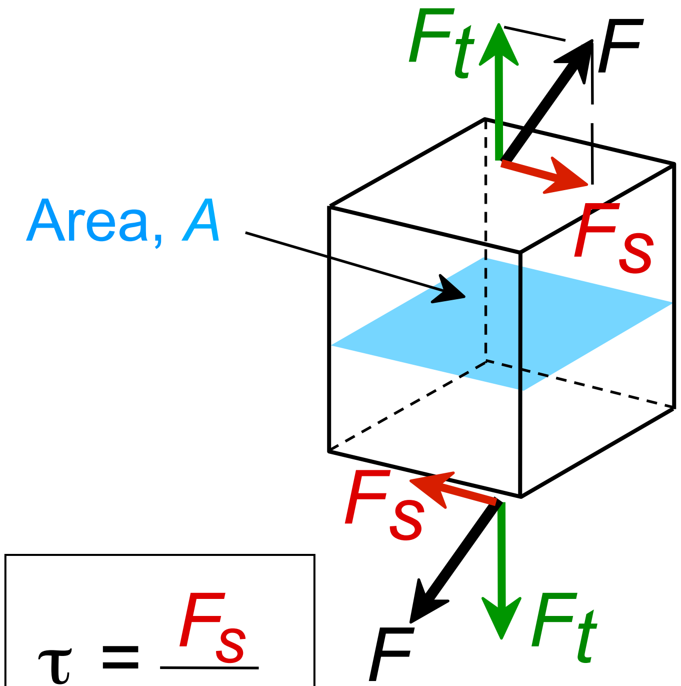
- Tensile stress, σ:



$$\sigma = \frac{F_t}{A_o} = \frac{\text{lb}_f}{\text{in}^2} \text{ or } \frac{\text{N}}{\text{m}^2}$$

original area
before loading

- Shear stress, τ:



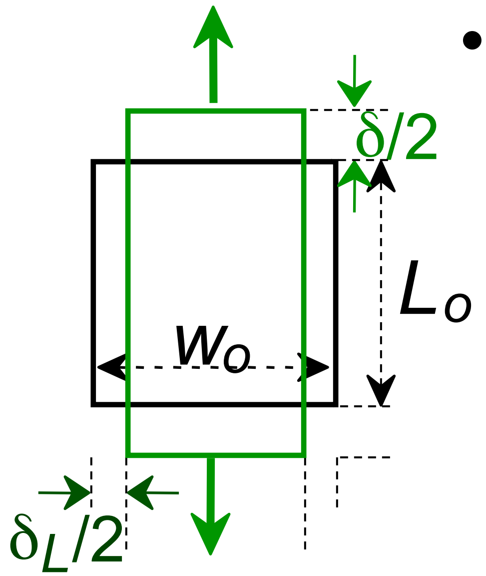
$$\tau = \frac{F_s}{A_o}$$

$\therefore$ Stress has units:
N/m^2 or lb_f/in^2

Engineering Strain

- **Tensile strain:**

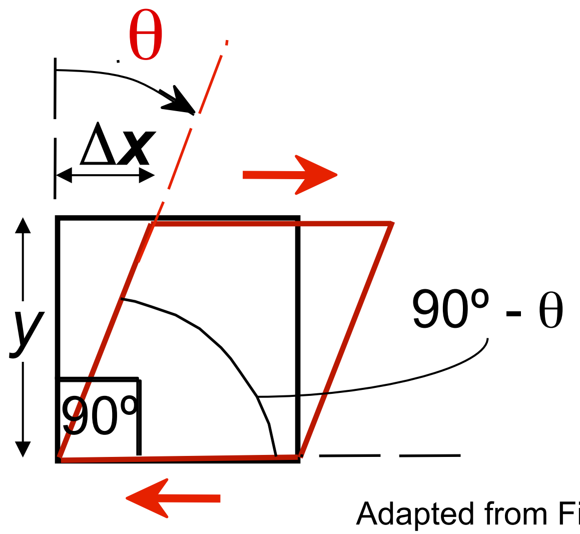
$$\varepsilon = \frac{\delta}{L_o}$$



- **Lateral strain:**

$$\varepsilon_L = \frac{-\delta_L}{w_o}$$

- **Shear strain:**



$$\gamma = \Delta x / y = \tan\theta$$

Strain is always dimensionless.

Adapted from Fig. 6.1 (a) and (c), *Callister 7e.*

Example 1

Tensile Testing of Aluminum Alloy

Convert the change in length data in the table to engineering stress and strain and plot a stress-strain curve.

The results of a tensile test of a 0.505-in. diameter aluminum alloy test bar, initial length (l_0) = 2 in.

Measured Change in Length (Δl)		Calculated	
Load (lb)	**(in.)**	**Stress (psi)**	**Strain (in./in.)**
0	0.000	0	0
1000	0.001	5,000	0.0005
3000	0.003	15,000	0.0015
5000	0.005	25,000	0.0025
7000	0.007	35,000	0.0035
7500	0.030	37,500	0.0150
7900	0.080	39,500	0.0400
8000 (maximum load)	0.120	40,000	0.0600
7950	0.160	39,700	0.0800
7600 (fracture)	0.205	38,000	0.1025

Example 1 SOLUTION

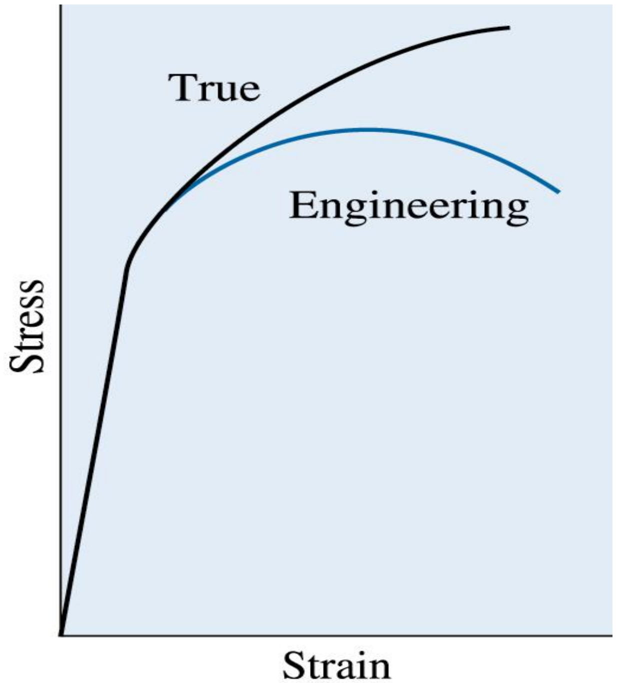
For the 1000-lb load:

$$\sigma = \frac{F}{A_0} = \frac{1000 \text{ lb}}{(\pi/4)(0.505 \text{ in.})^2} = \frac{1000 \text{ lb}}{0.2 \text{ in.}^2} = 5000 \text{ psi}$$

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{0.001 \text{ in.}}{2.000 \text{ in.}} = 0.0005 \text{ in./in.}$$

True Stress and True Strain

- **True stress** The load divided by the actual cross-sectional area of the specimen at that load.
- **True strain** The strain calculated using actual and not original dimensions, given by $\varepsilon_t \ln(l/l_0)$.



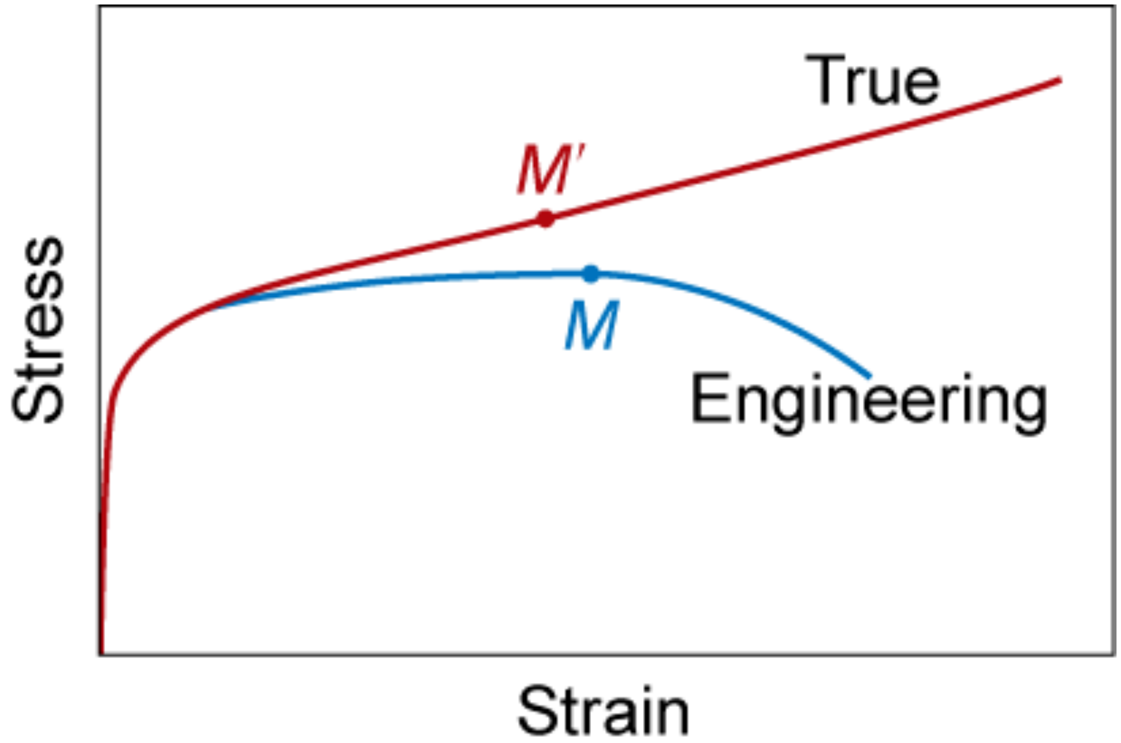
•The relation between the true stress-true strain diagram and engineering stress-engineering strain diagram.
•The curves are identical to the yield point.

True Stress & Strain

Note: S.A. changes when sample stretched

- True stress $\sigma_T = F/A_i$
- True Strain $\varepsilon_T = \ln(\ell_i/\ell_o)$

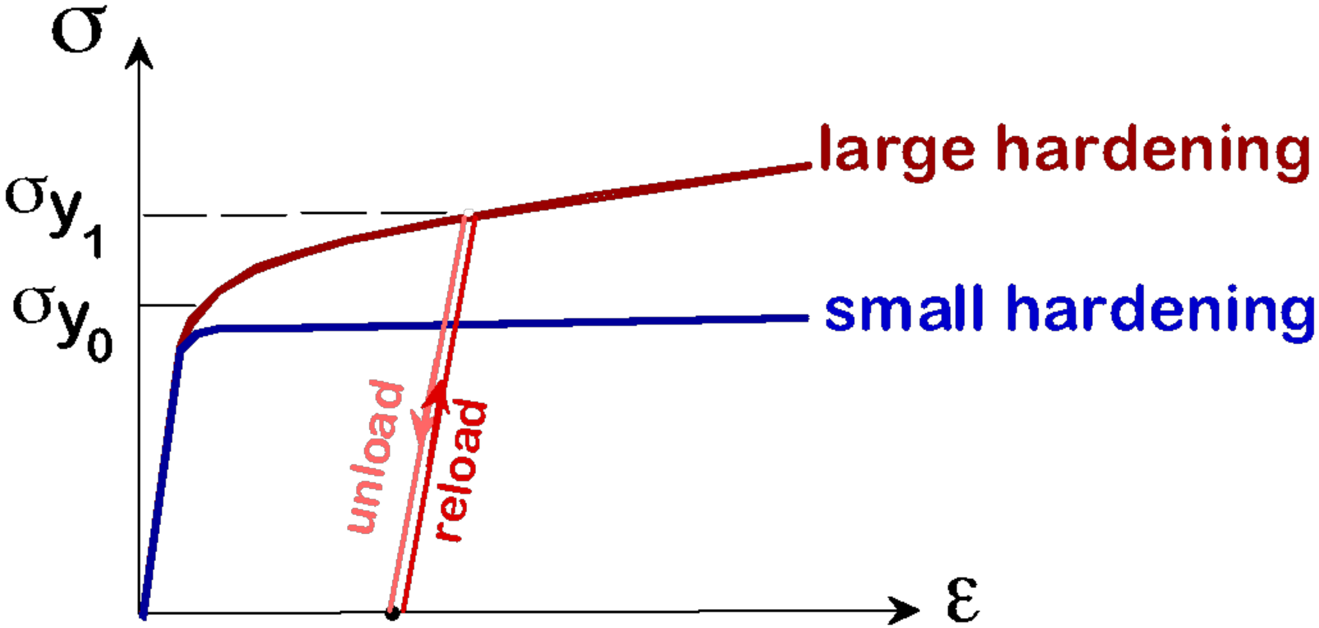
$$\boxed{\begin{aligned}\sigma_T &= \sigma(1+\varepsilon)\\ \varepsilon_T &= \ln(1+\varepsilon)\end{aligned}}$$



Adapted from Fig. 6.16, *Callister 7e.*

Hardening

HARDENING: **An increase in σ_y due to plastic deformation.**



- **Curve fit to the stress-strain response:**

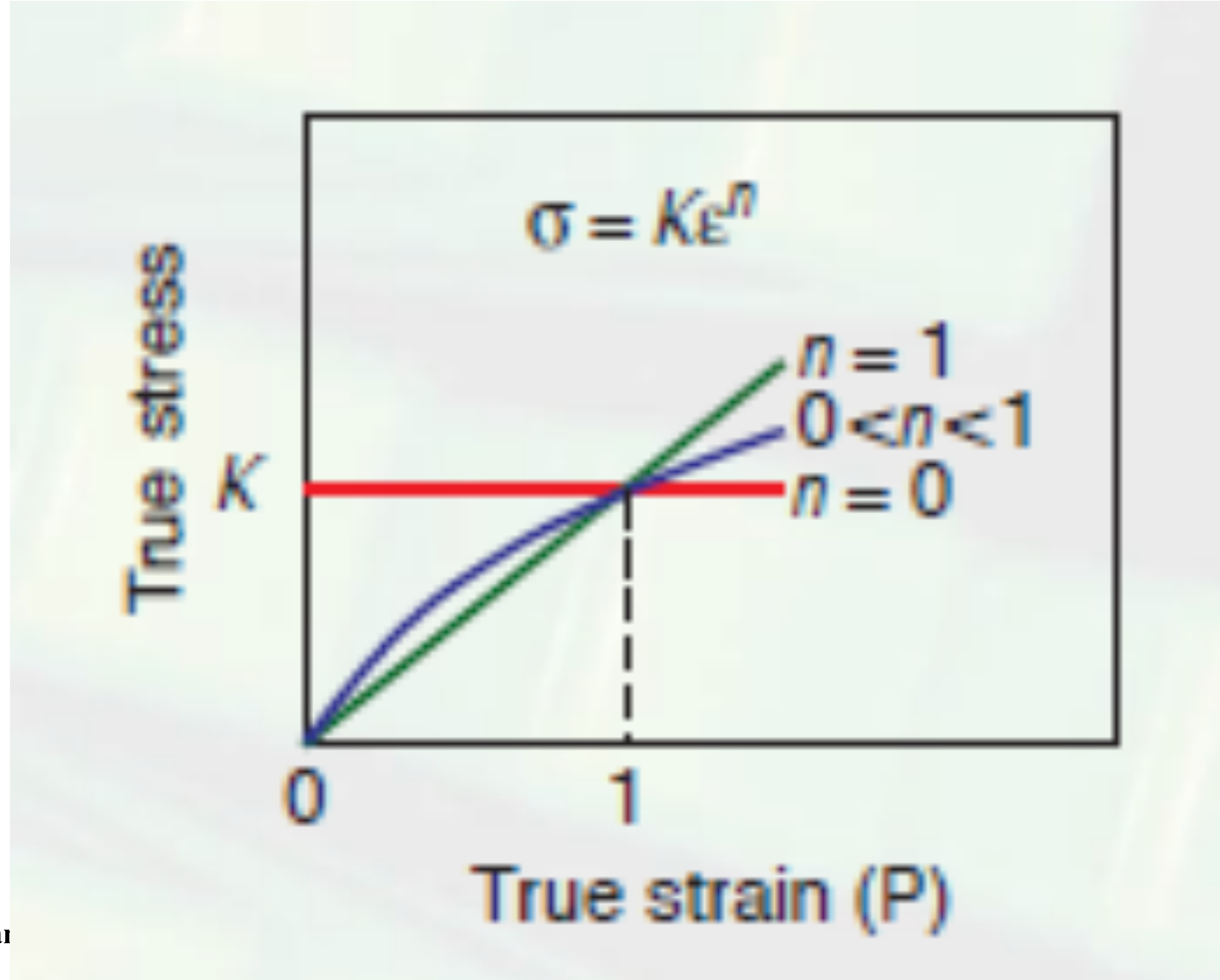
$$\sigma_T = K\varepsilon_T^n$$

n = hardening exponent
n = 0.15 (some steels)
n = 0.5 (some copper)

Table 7.4 Tabulation of *n* and *K* Values (Equation 7.19) for Several Alloys

		K	
Material	*n*	*MPa*	*psi*
Low-carbon steel (annealed)	0.21	600	87,000
4340 steel alloy (tempered @ 315°C)	0.12	2650	385,000
304 stainless steel (annealed)	0.44	1400	205,000
Copper (annealed)	0.44	530	76,500
Naval brass (annealed)	0.21	585	85,000
2024 aluminum alloy (heat treated—T3)	0.17	780	113,000
AZ-31B magnesium alloy (annealed)	0.16	450	66,000

Idealized stress strain curves



Flow Stress

- For most metals at room temperature, strength increases when deformed due to strain hardening
- *Flow stress* = instantaneous value of stress required to continue deforming the material

$$Y_f = K\varepsilon^n$$

where Y_f = flow stress, that is, the yield strength as a function of strain

Average Flow Stress

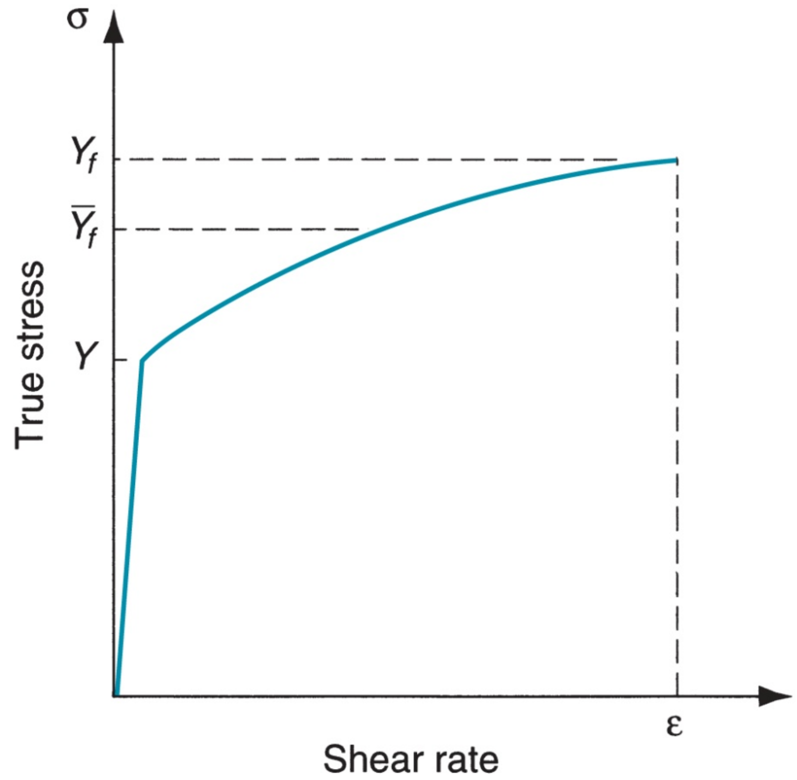
- Determined by integrating the flow curve equation between zero and the final strain value defining the range of interest

$$\bar{Y}_f = \frac{K\varepsilon^n}{1+n}$$

where $\bar{Y}_f$ = average flow stress; and ε = maximum strain during deformation process

Stress-Strain Relationship

- Average flow stress $\overline{Y}_f$ in relation to
  - Flow stress Y_f
  - Yield strength Y



Example 1

Question: The strength coefficient = 550 MPa and strain-hardening exponent = 0.22 for a certain metal. During a forming operation, the final true strain that the metal experiences = 0.85. Determine the flow stress at this strain and the average flow stress that the metal experienced during the operation.

Solution: Flow stress $Y_f = 550(0.85)_{0.22} =$ ***531 MPa.***
Average flow stress $\bar{Y}_f = 550(0.85)_{0.22}/1.22 =$ ***435 MPa***

Example 2

Question: Determine the value of the strain-hardening exponent for a metal that will cause the average flow stress to be 3/4 of the final flow stress after deformation

Solution: n = 0.333

Example 3

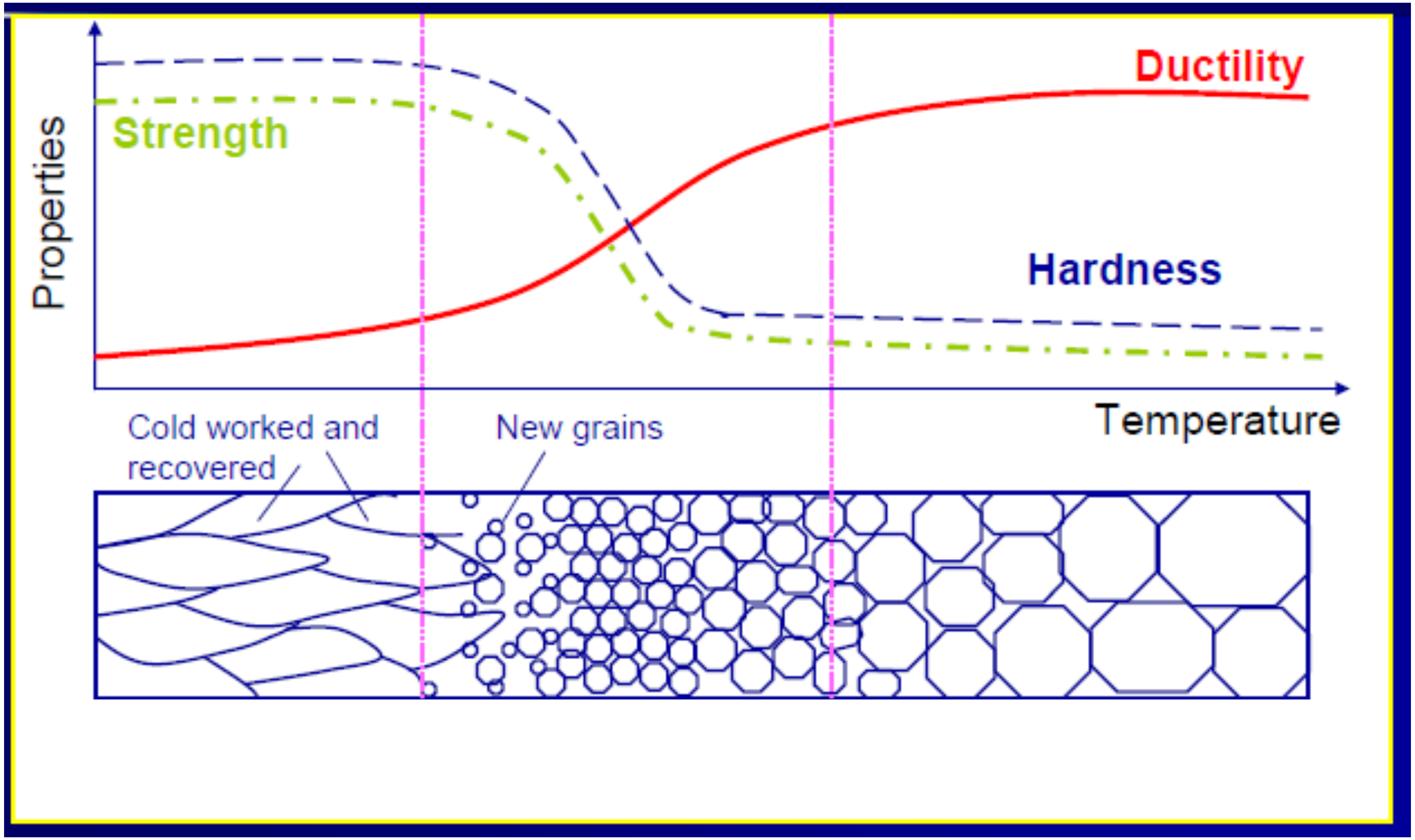
Question: In a tensile test, two pairs of values of stress and strain were measured for the specimen metal after it had yielded: (1) True stress = 217 MPa and true strain = 0.35, and (2) true stress = 259 MPa and true strain = 0.68. Based on these data points, determine the strength coefficient and strain-hardening exponent.

Solution: n = 0.2664 and K = 287 MPa

Temperature in Metal Forming

- For any metal, *K* and *n* in the flow curve depend on temperature
  - Both strength (*K*) and strain hardening (*n*) are reduced at higher temperatures
  - In addition, ductility is increased at higher temperatures

Temperature in Metal Forming



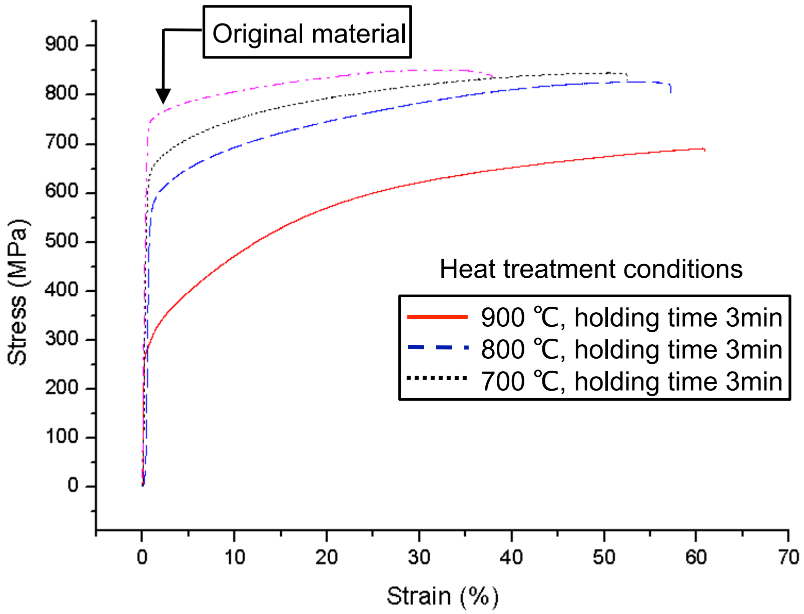
Temperature in Metal Forming

- Any deformation operation can be accomplished with lower forces and power at elevated temperature
- Three temperature ranges in metal forming:
  - Cold working
  - Warm working
  - Hot working

Hot Working

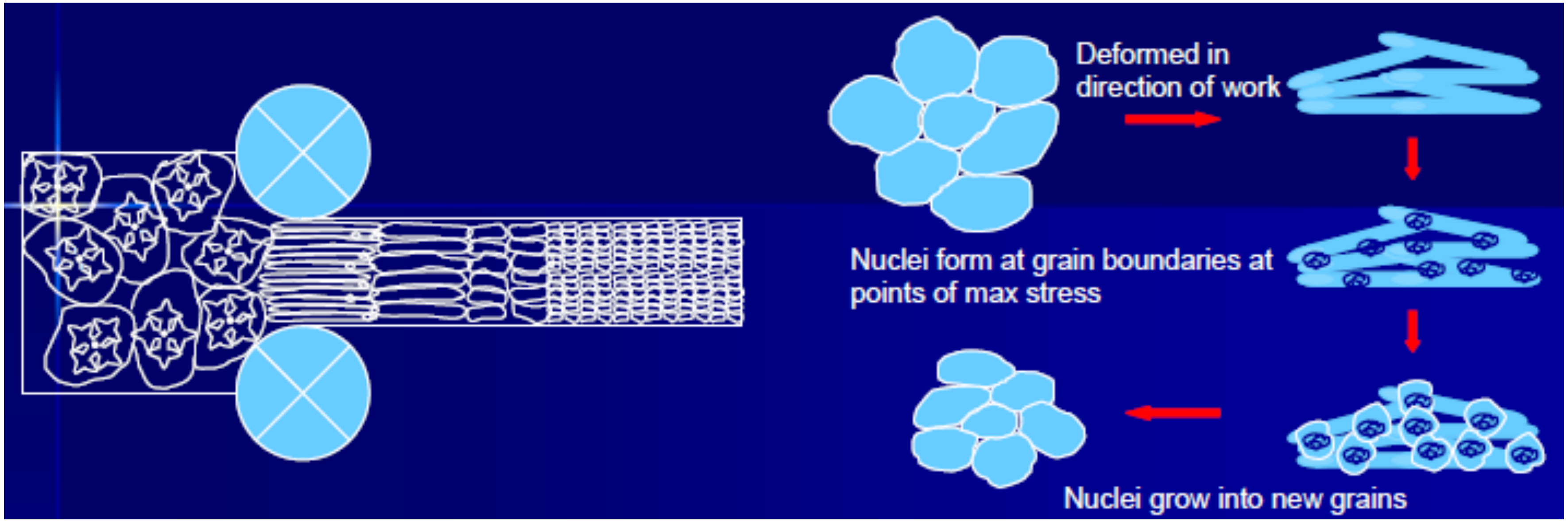
- Deformation at temperatures above the *recrystallization temperature*
  - Recrystallization temperature = about one-half of melting point on absolute scale
    - In practice, hot working usually performed somewhat above $0.5T_m$
    - Metal continues to soften as temperature increases above $0.5T_m$, enhancing advantage of hot working above this level

- Effect of annealing
  (In case of sheet metal)



Material♪		Y.S (MPa)♪	T.S (MPa)♪	El (%)♪	Hardness (Hv)♪
STS 304-1/2H	Original material♪	651.4♪	851.8♪	38.4♪	270.07♪
	700℃♪	618.5♪	845.7♪	52.5♪	258.76♪
	800℃♪	552.5♪	827.3♪	57.2♪	237.32♪
	900℃♪	272.1♪	691.3♪	60.9♪	155.08♪

Hot Working (Recrystallization)



Why Hot Working?

Capability for substantial plastic deformation - far more than is possible with cold working or warm working

- Why?
  - Strength coefficient (*K*) is substantially less than at room temperature
  - Strain hardening exponent (*n*) is zero (theoretically)
  - Ductility is significantly increased

Strain Rate Sensitivity

- Theoretically, a metal in hot working behaves like a perfectly plastic material, with strain hardening exponent $n = 0$
  - The metal should continue to flow at the same flow stress, once that stress is reached
  - However, an additional phenomenon occurs during deformation, especially at elevated temperatures:
    - Strain rate sensitivity

What is Strain Rate?

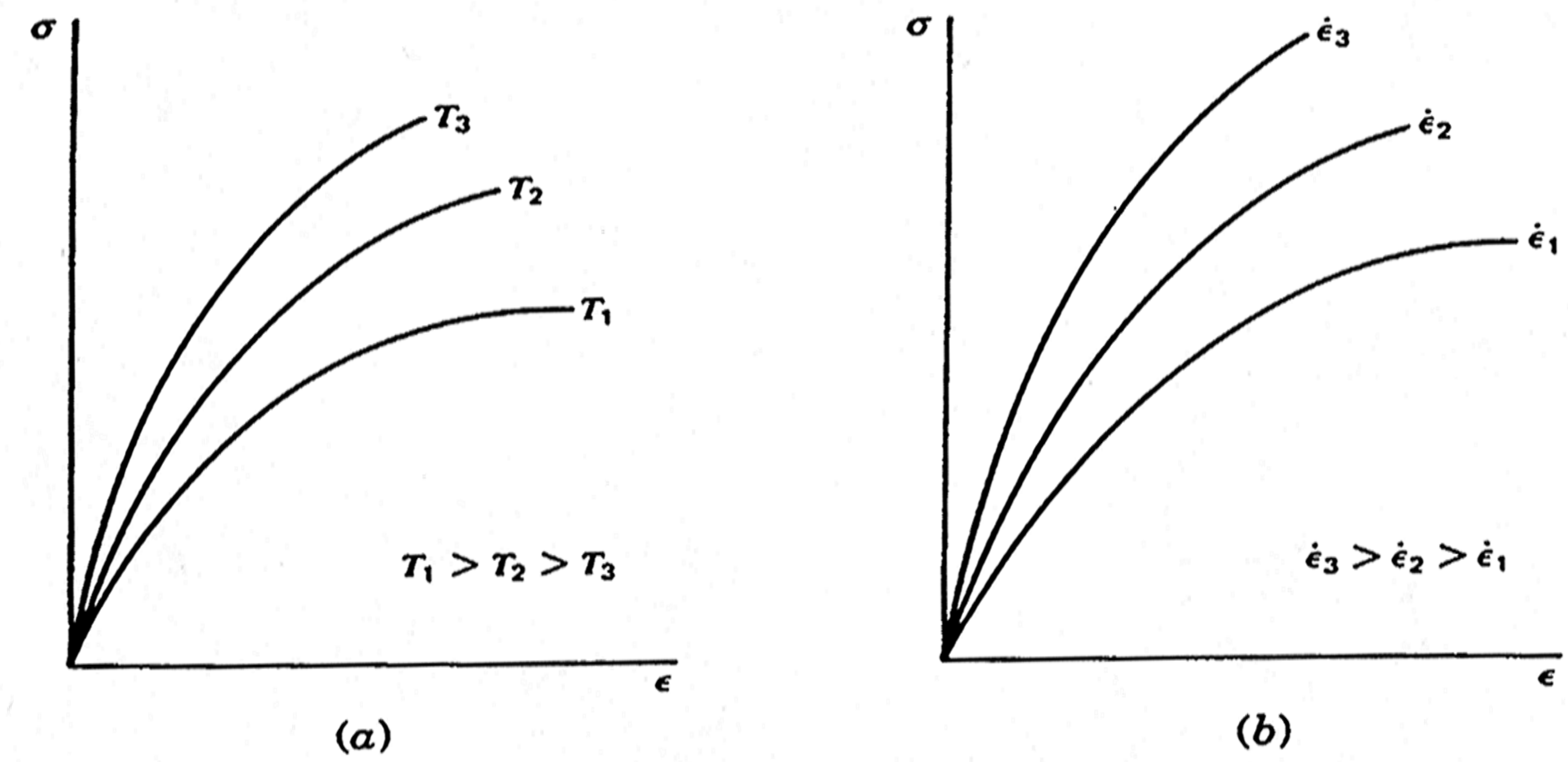
- Strain rate in forming is directly related to speed of deformation *v*
- Deformation speed *v* = velocity of the ram or other movement of the equipment
- *Strain rate* is defined:

$$\dot{\varepsilon} = \frac{v}{h}$$

where $\dot{\varepsilon}$ = true strain rate; and *h* = instantaneous height of workpiece being deformed

Effect of Strain Rate on Flow Stress

- Flow stress is a function of temperature
- At hot working temperatures, flow stress also depends on strain rate
  - As strain rate increases, resistance to deformation increases
  - This is the effect known as strain-rate sensitivity



Yield strength changes as a function of (a) temperature and (b) strain rate

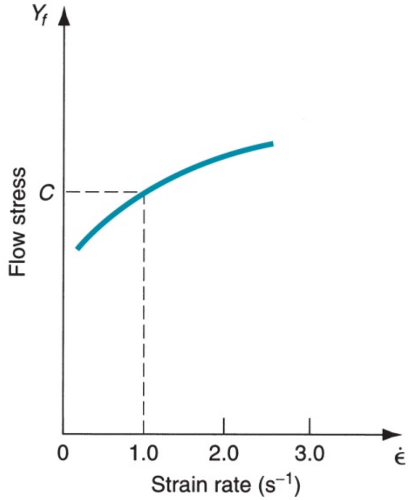
Strain Rate Sensitivity Equation

$$Y_f = C\dot{\varepsilon}^m$$

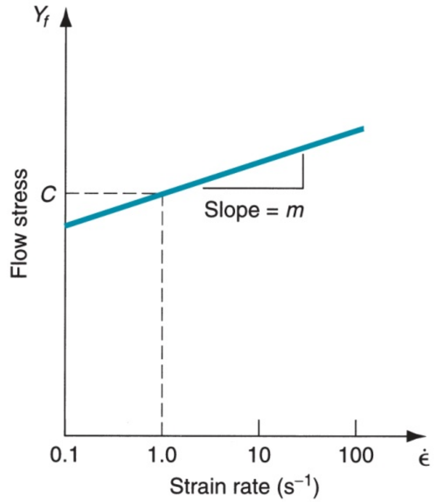
where C = strength constant (analogous but not equal to strength coefficient in flow curve equation), and m = strain-rate sensitivity exponent

Strain Rate Sensitivity

- (a) Effect of strain rate on flow stress at an elevated work temperature
- (b) Same relationship plotted on log-log coordinates



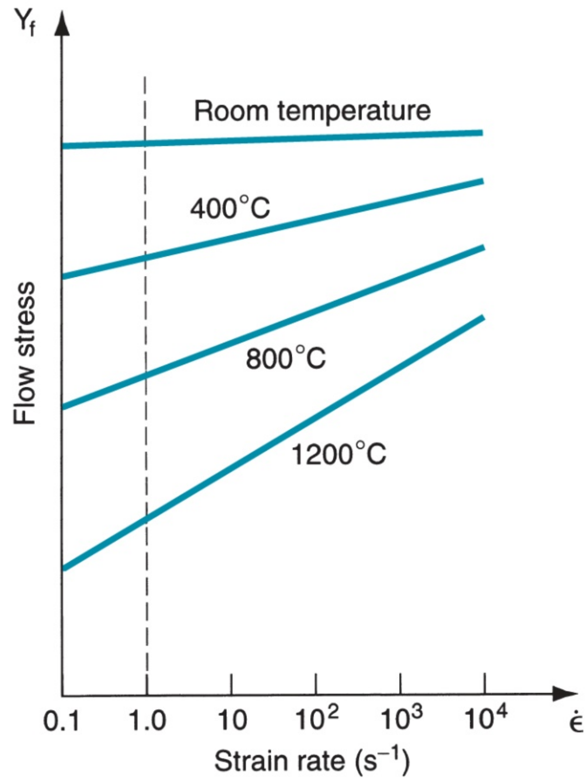
(a)



(b)

Effect of Temperature on Flow Stress

- The constant *C*, indicated by the intersection of each plot with the vertical dashed line at strain rate = 1.0, decreases
- And *m* (slope of each plot) increases with increasing temperature



Observations about Strain Rate Sensitivity

- Increasing temperature decreases *C* and increases *m*
  - At room temperature, effect of strain rate is almost negligible
    - Flow curve alone is a good representation of material behavior
  - As temperature increases
    - Strain rate becomes increasingly important in determining flow stress

Friction in Metal Forming

- In most metal forming processes, friction is undesirable:
  - Metal flow is reduced
  - Forces and power are increased
  - Tools wear faster
- Friction and tool wear are more severe in hot working

Friction in Metal Forming

- Friction is undesirable:
  - retard metal flow causing residual stress
  - increase forces and power
  - rapid wear of tooling
- Lubrication is used to reduce friction at the

Category	Temperature range	Strain-rate sensitivity exponent	Coefficient of friction
Cold working	$\leq 0.3T_m$	$0 \leq m \leq 0.05$	0.1
Warm working	$0.3T_m$–$0.5T_m$	$0.05 \leq m \leq 0.1$	0.2
Hot working	$0.5T_m$–$0.75T_m$	$0.05 \leq m \leq 0.4$	0.4–0.5