TA201A
Manufacturing Processes

Week-9

18 Oct, 2022

2022-2023 Semester-I

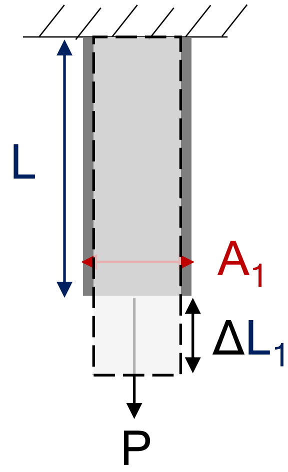
Lecture 9

Metal Forming

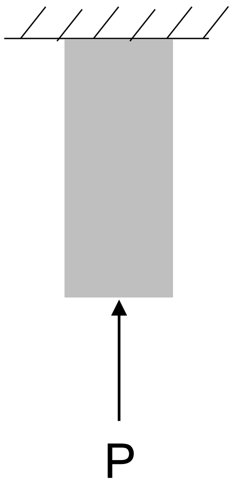
Grover: Chapters-18,19,20

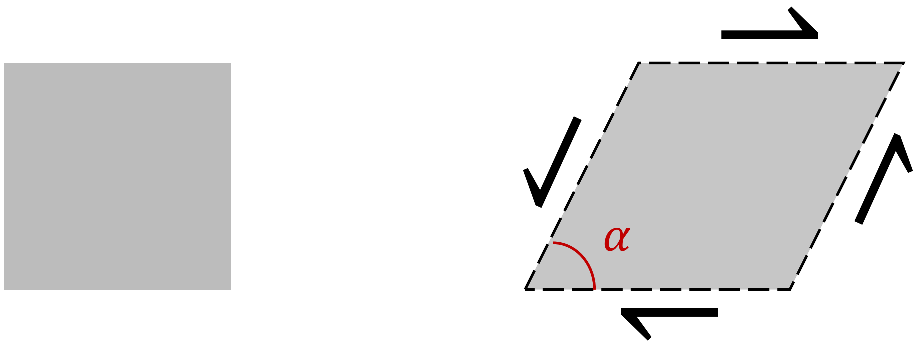
Nature of Stresses

Tensile



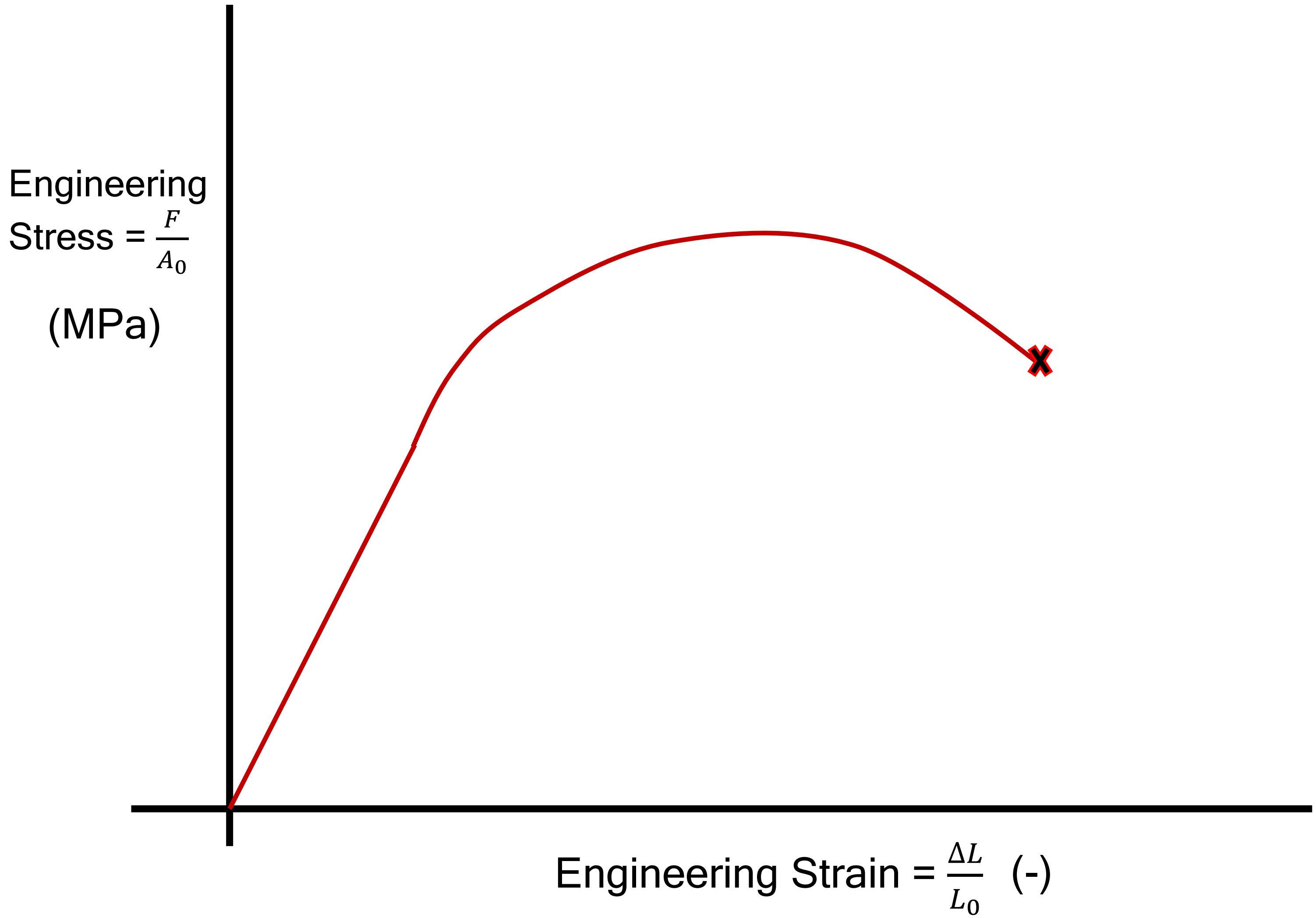
Compressive





Shear stress

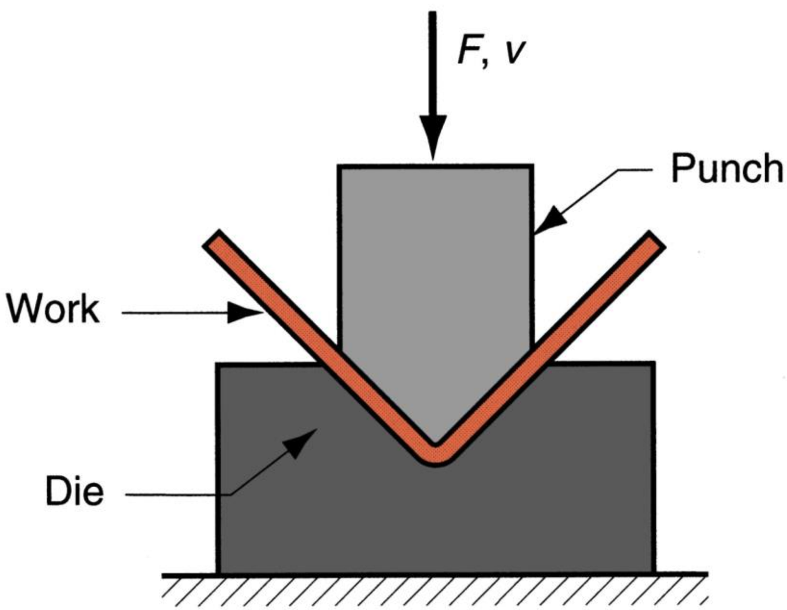
Nature of deformation

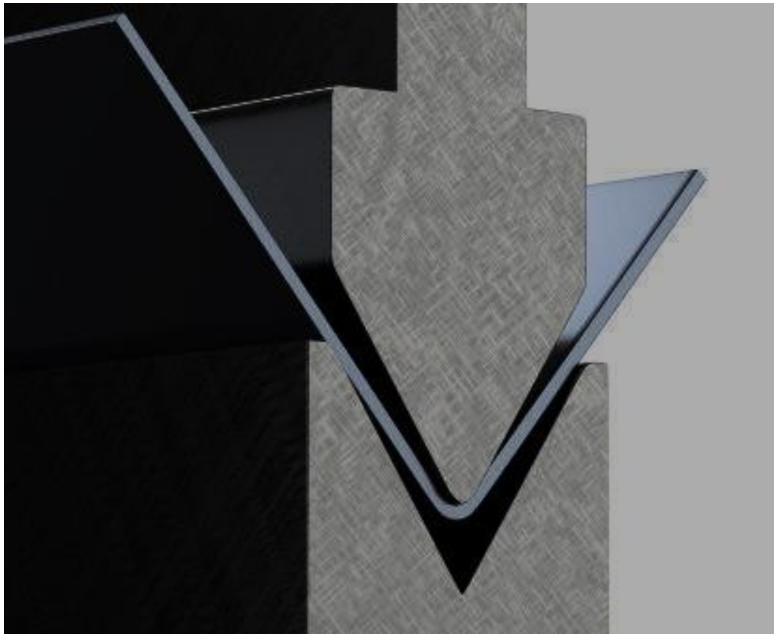


Metal Forming

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

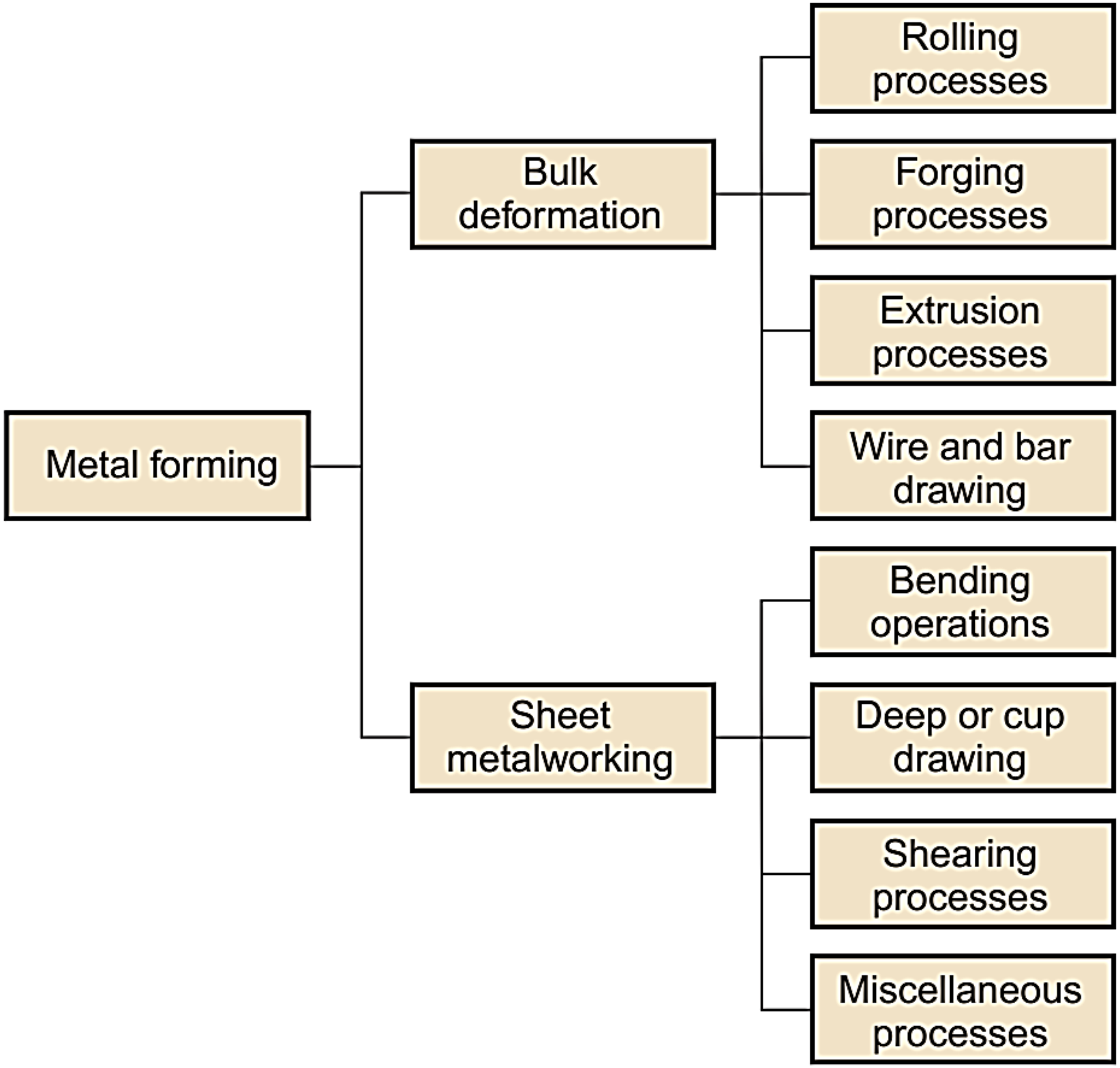
The tool, usually called a *punch*, applies stresses that exceed yield strength of metal. The metal takes a shape determined by the geometry of the *die*



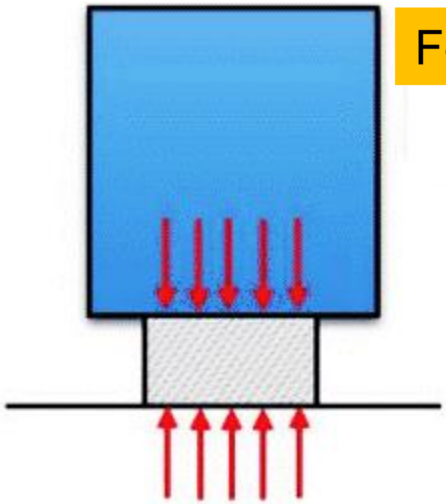


Courtesy: Google Images

Metal Forming: Classifications



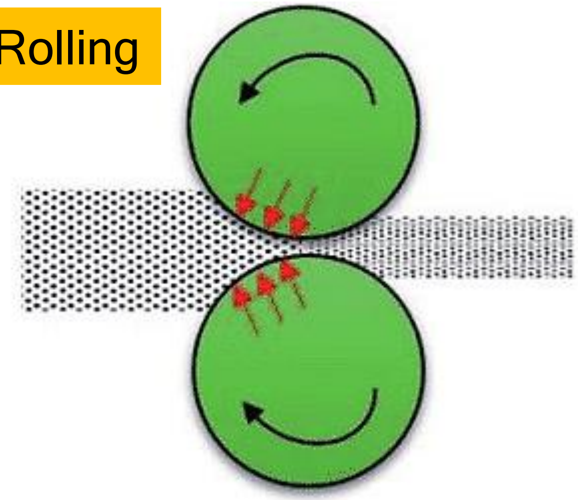
Bulk deformation



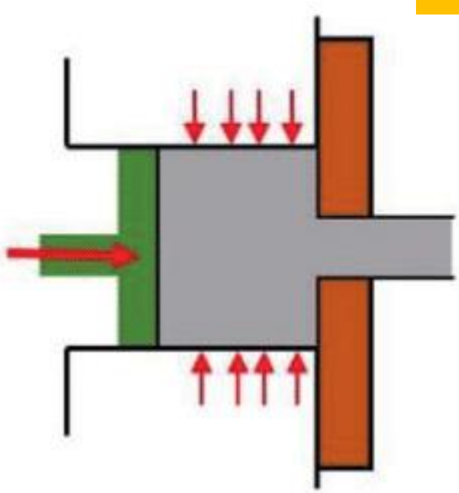
Forging

Direct Compression

Rolling

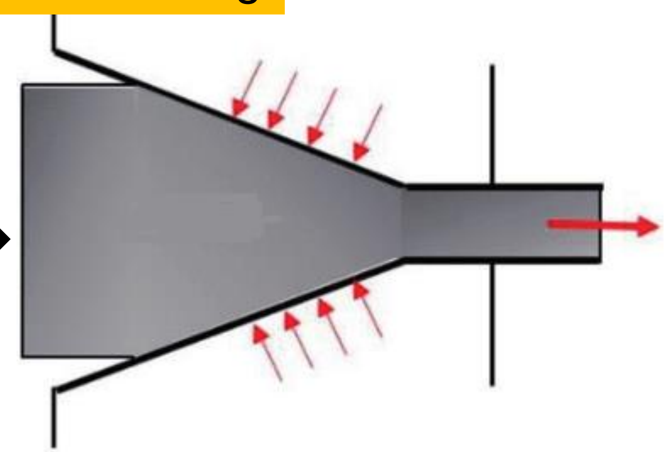


Extrusion



Indirect Compression

Wire Drawing



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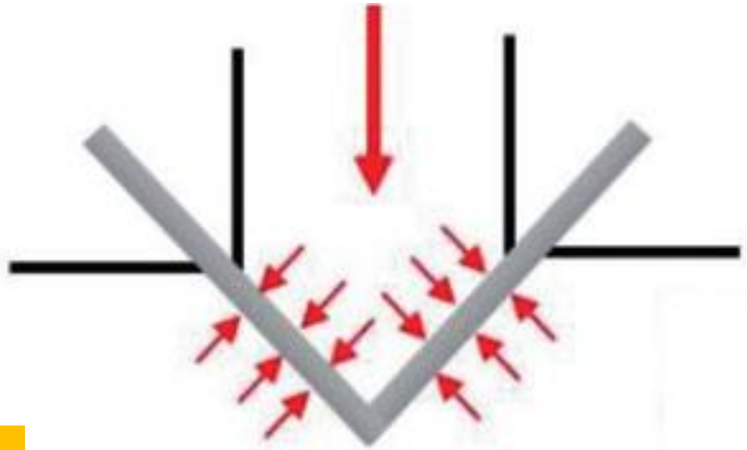
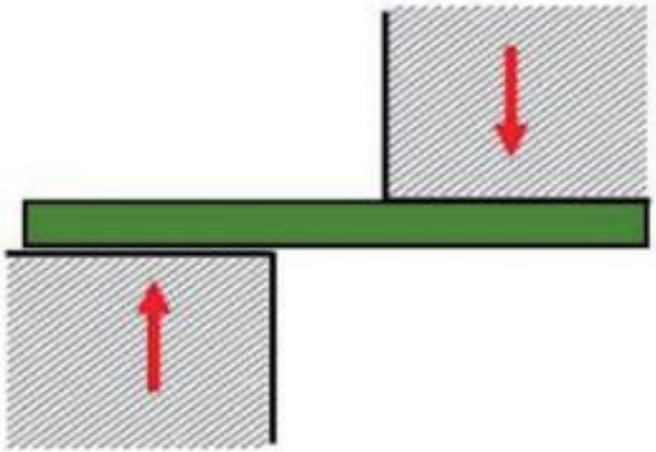
Sheet Metalworking

Tension

Bending



Shearing



Courtesy: Google Images

Bulk Deformation Processes

Characterized by significant deformations and massive shape changes

- "Bulk" refers to work parts

  with relatively low surface area to volume ratios

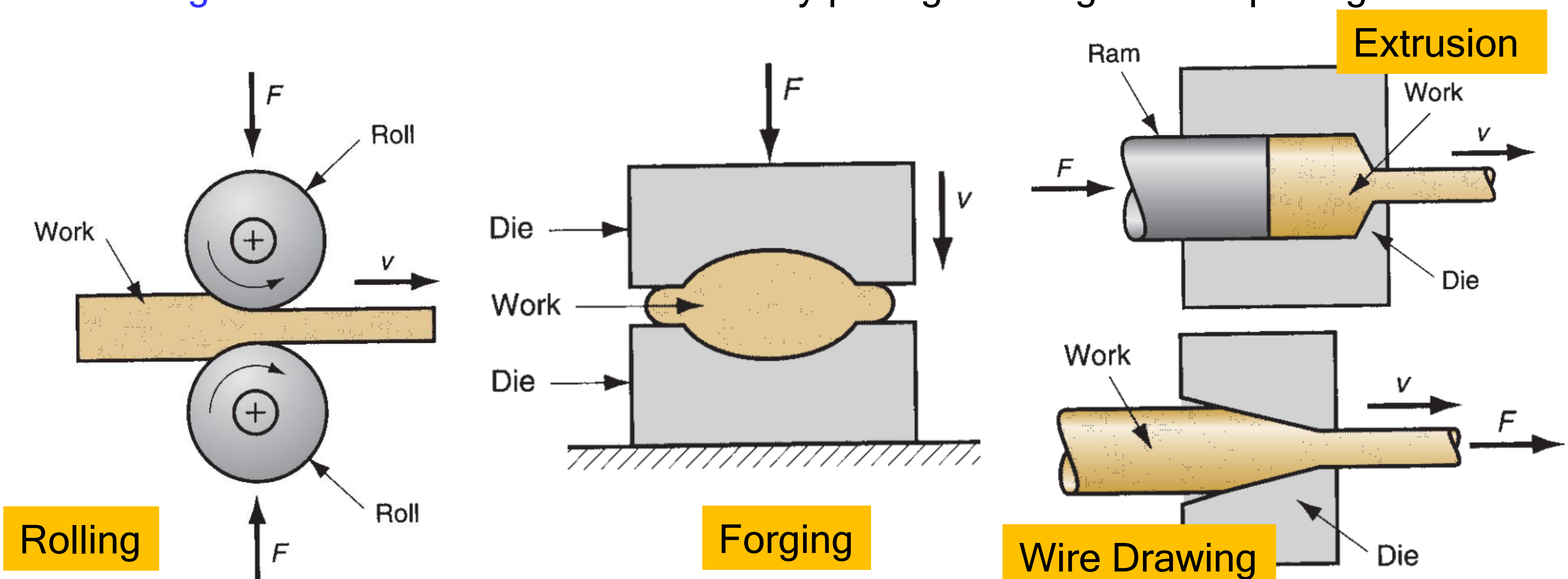
- Starting work shapes include cylindrical billets and rectangular bars

- Stresses to plastically deform the metal are usually *Compressive*

  - - Examples: Rolling, Forging, Extrusion

Bulk Deformation Processes

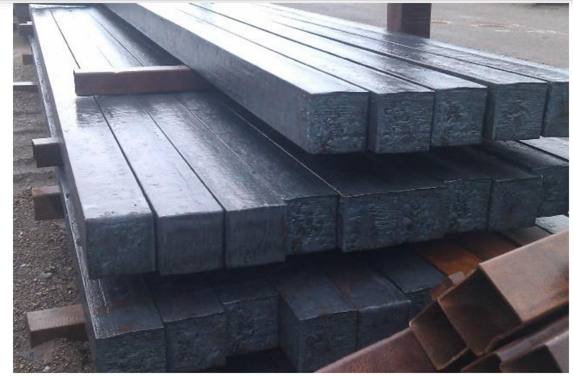
- Rolling: Compressive deformation process
  - ✓ Thickness of plate or slab is reduced by two opposing cylindrical tools called rolls
- Forging: Workpiece is compressed between two opposing dies
- Extrusion: Work metal compressed to flow through die opening thereby taking the shape of the opening as its own cross section
- Drawing: Diameter of the bar is reduced by pulling it through a die opening



Rolling

https://www.youtube.com/watch?v=cmN8BOF0eUs

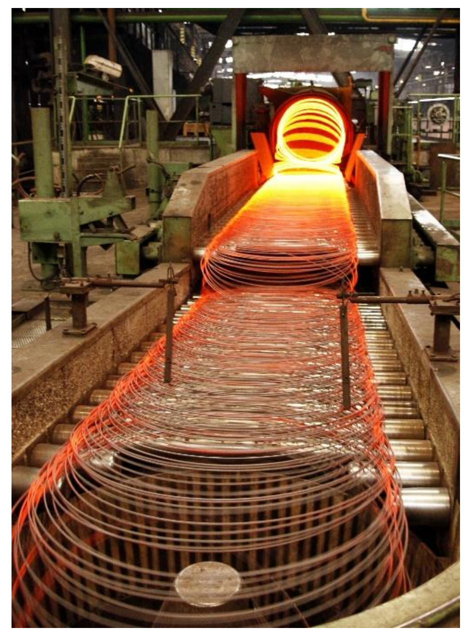
Use of Rolling



Billets

Roof

Pipes



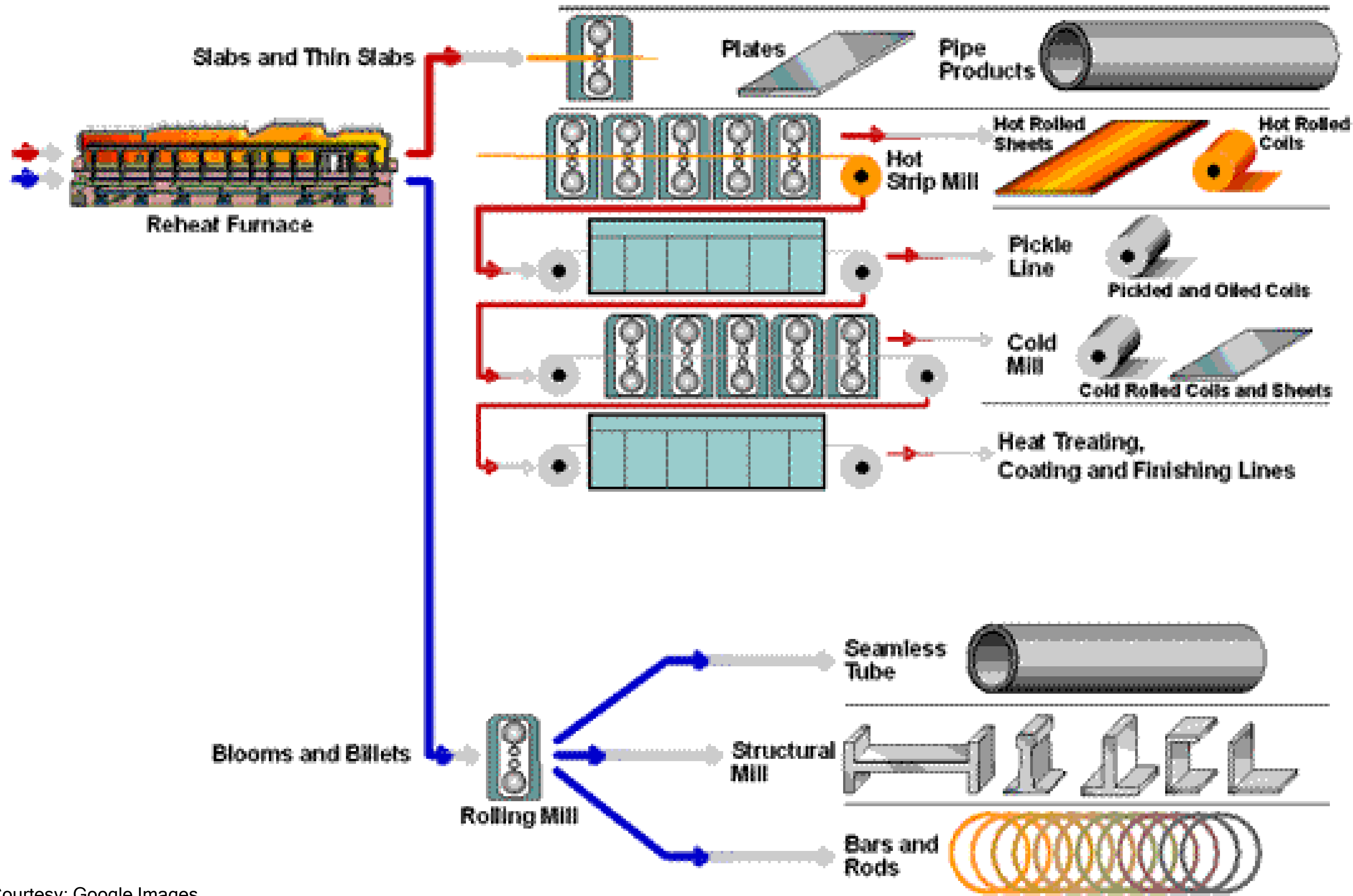
Wires

Rebars (Saria)

Speed up to 120 m/s

Courtesy: Google Images

Overview of Rolling and products



Courtesy: Google Images

Sheet Metalworking

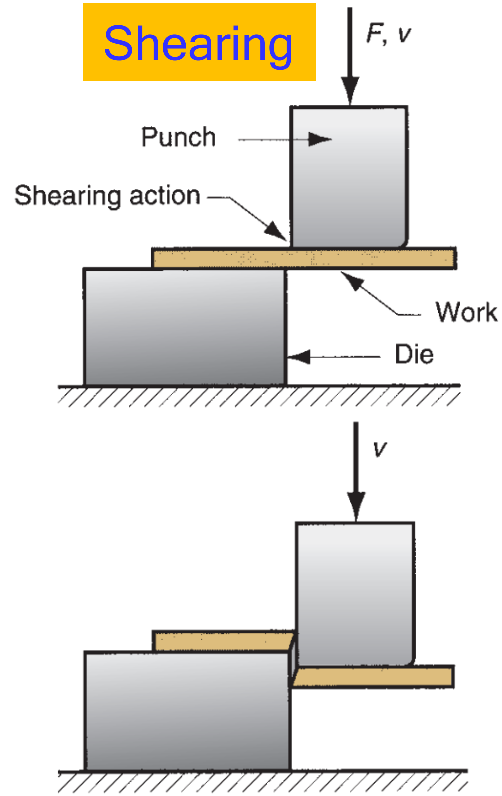
Characterized by localized deformation and configuration changes

- Includes processes like cutting, bending and drawing
- Stresses required are combination of tensile, compressive and shear
  - ➢ Stretch the metal (*Tensile* stresses)
  - ➢ Bend the metal (*Tensile* and *Compressive*)
  - ➢ Still others apply *shear* stresses

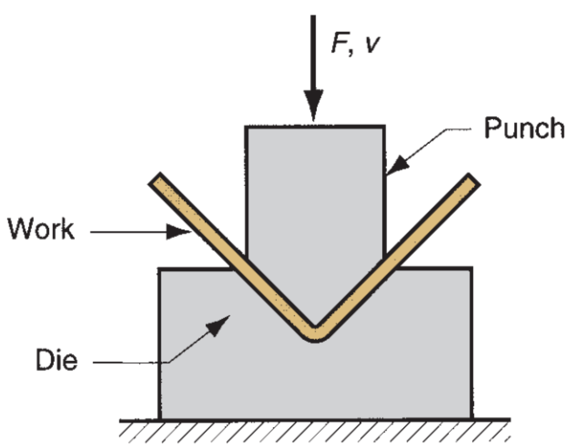
Sheet Metalworking

- Bending: Straining a metal sheet (or plate) to take and angle along straight axis
- (Deep) Drawing: Forming a flat metal sheet into a hollow or concave shape (cup) by stretching the metal
  - ✓ Blank holder is used to hold down the blank while the punch pushes into the sheet metal
- Shearing: Cuts the work using a punch and a die

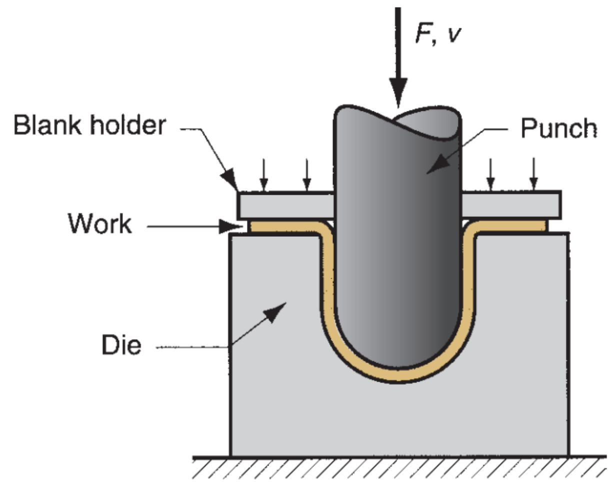
Shearing



Bending

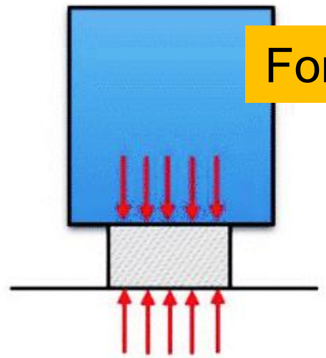


Deep Drawing

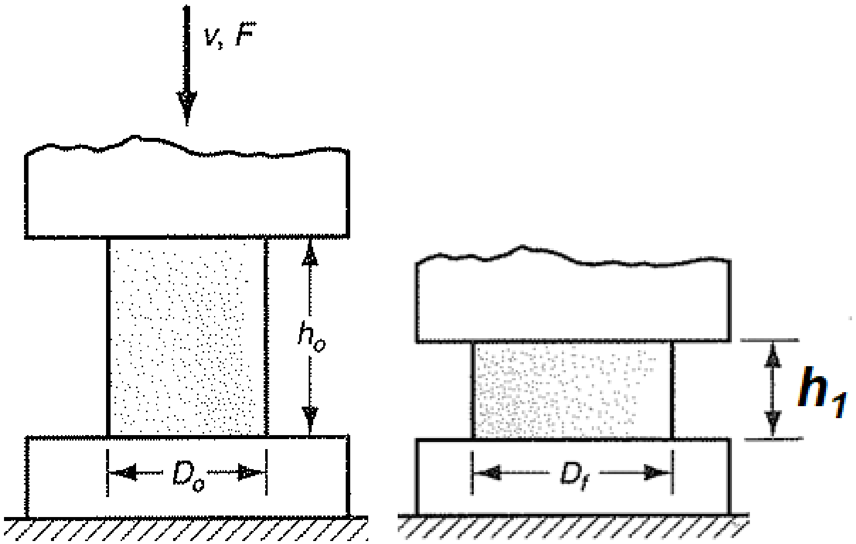


Strain calculation (Forging)

In metalworking, compressive stress and strain are predominant.



If a block of initial height h_o is compressed to h_1, the axial compressive strain will be:



Engineering strain

$$e = \frac{h_1 - h_o}{h_o} = \frac{h_1}{h_o} - 1$$

True strain

$$\varepsilon = \int_{h_o}^{h_1} \frac{dh}{h} = \ln\frac{h_1}{h_o} = -\ln\frac{h_o}{h_1}, \quad h_o > h_1$$

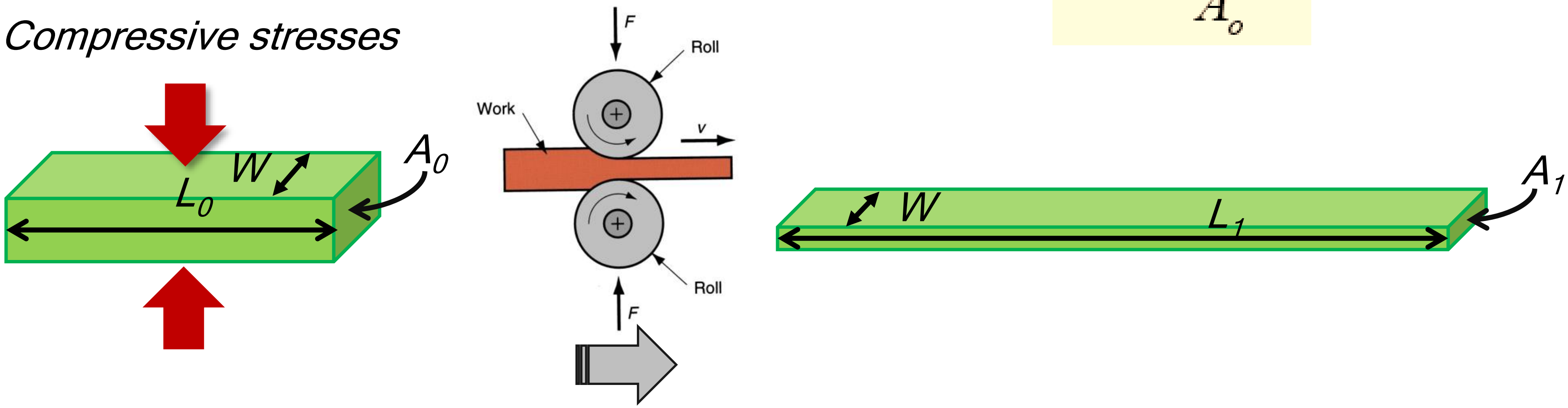
Note: The calculated strain is negative for compressive strains.
However, the convention is reversed in metalworking problems so that compressive stresses and strains are defined as positive.

$$\varepsilon_c = \ln\frac{h_o}{h_1}, \quad e_c = \frac{h_o - h_1}{h_o} = 1 - \frac{h_1}{h_o}$$

Fractional reduction (reduction of area) in metal working deformation is given by

$$r = \frac{A_o - A_1}{A_o}$$

Compressive stresses



Again from constancy in volume before and after deformation

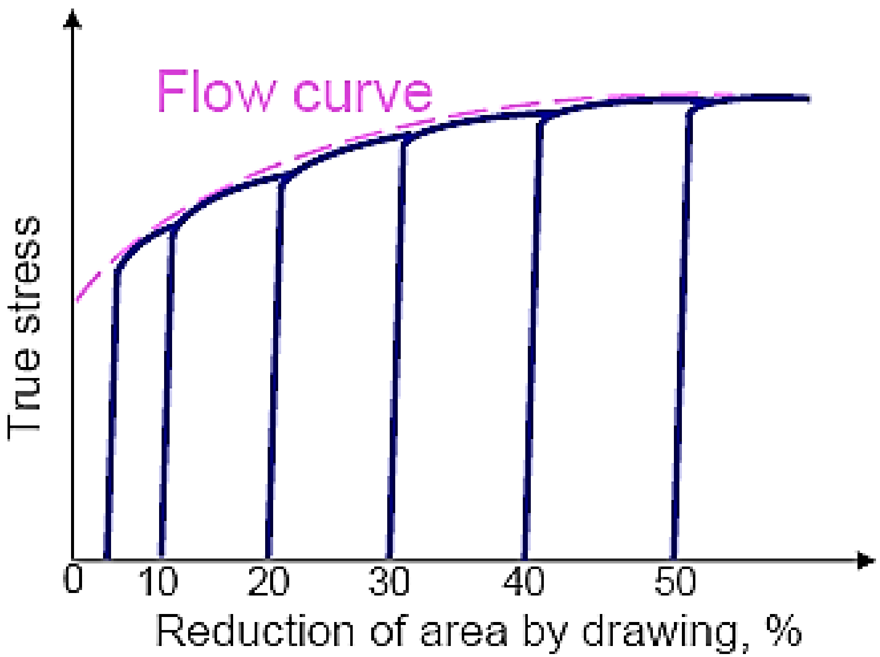
$$A_1 L_1 = A_o L_o$$

$$r = 1 - \frac{A_1}{A_o} \quad or \quad \frac{A_1}{A_o} = 1 - r$$

$$\varepsilon = \ln\frac{L_1}{L_o} = \ln\frac{A_o}{A_1} = \ln\frac{1}{1-r}$$

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



Flow curve constructed from stress-strain curves after different amounts of reduction.

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

$$Y_f = K\varepsilon^n$$

K is the strength coefficient, MPa (lb/in^2); and n is the strain hardening exponent

What if n = 0?

Average Flow Stress

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

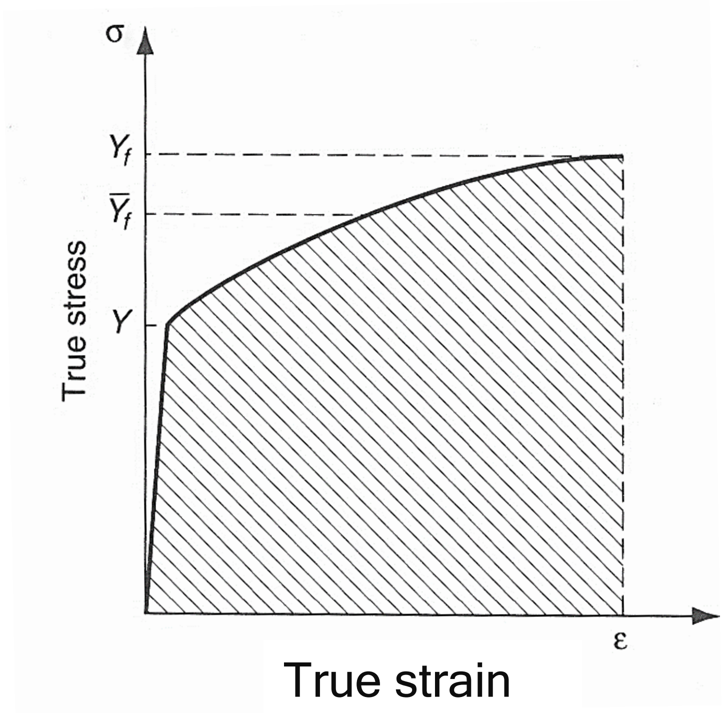
Where ε = maximum strain during deformation process

$$\bar{Y}_f\,(mean) = \frac{1}{\varepsilon}\int_0^{\varepsilon} Y_f\, d\varepsilon$$

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

Given that $\varepsilon_2 = \varepsilon$ and ε_1 (initial) = 0

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



Example

- During cold rolling, a metal sheet is reduced in thickness by 20%.

  If the material behavior is given by Y = 250$\varepsilon^{0.2}$ (in MPa),

  Find the average stress required for this deformation?

$$Total\ strain = ln\left(\frac{1}{1-r}\right) = \ln\left(\frac{1}{1-0.2}\right) = 0.22$$

Since, $\bar{Y}_f = \dfrac{K\varepsilon^n}{1+n}$

$$Average\ Flow\ stress = \frac{250(0.22)^{0.2}}{1.2} = 153.9\ MPa$$

Temperature in Metal Forming

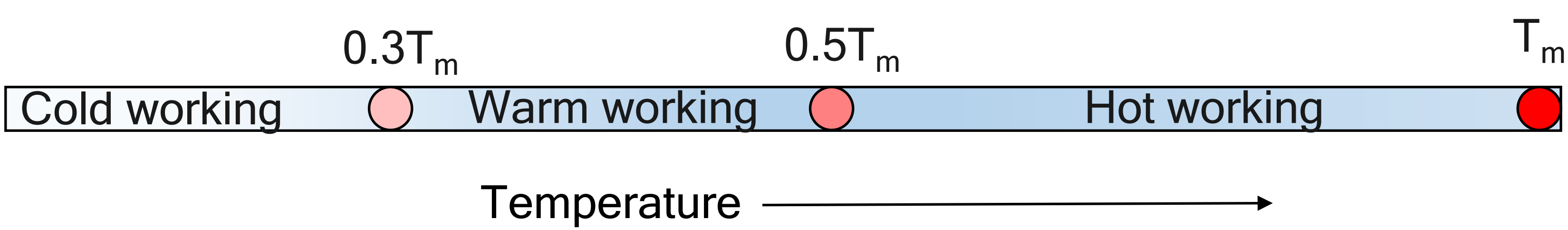
- For any metal, *K* and *n* in the flow curve depend on temperature

  Both strength and strain hardening are reduced at higher temperatures

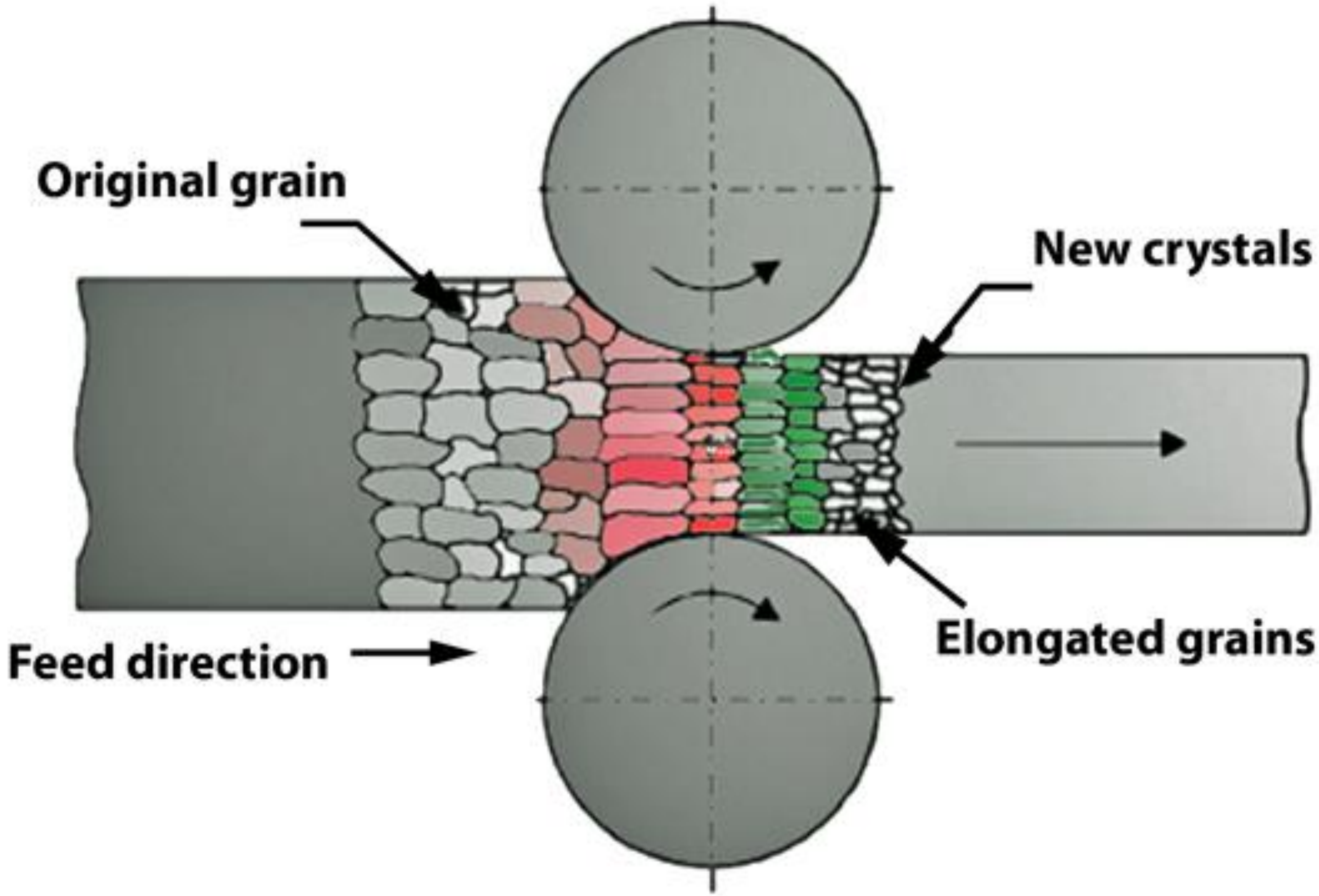
  In addition, ductility is increased at higher temperatures

- Any deformation operation can be accomplished with lower forces and power at elevated temperature

- Cold working ($<0.3T_m$)
- Warm working ($0.3T_m$ to $0.5T_m$)
- Hot working ($>0.5T_m$)

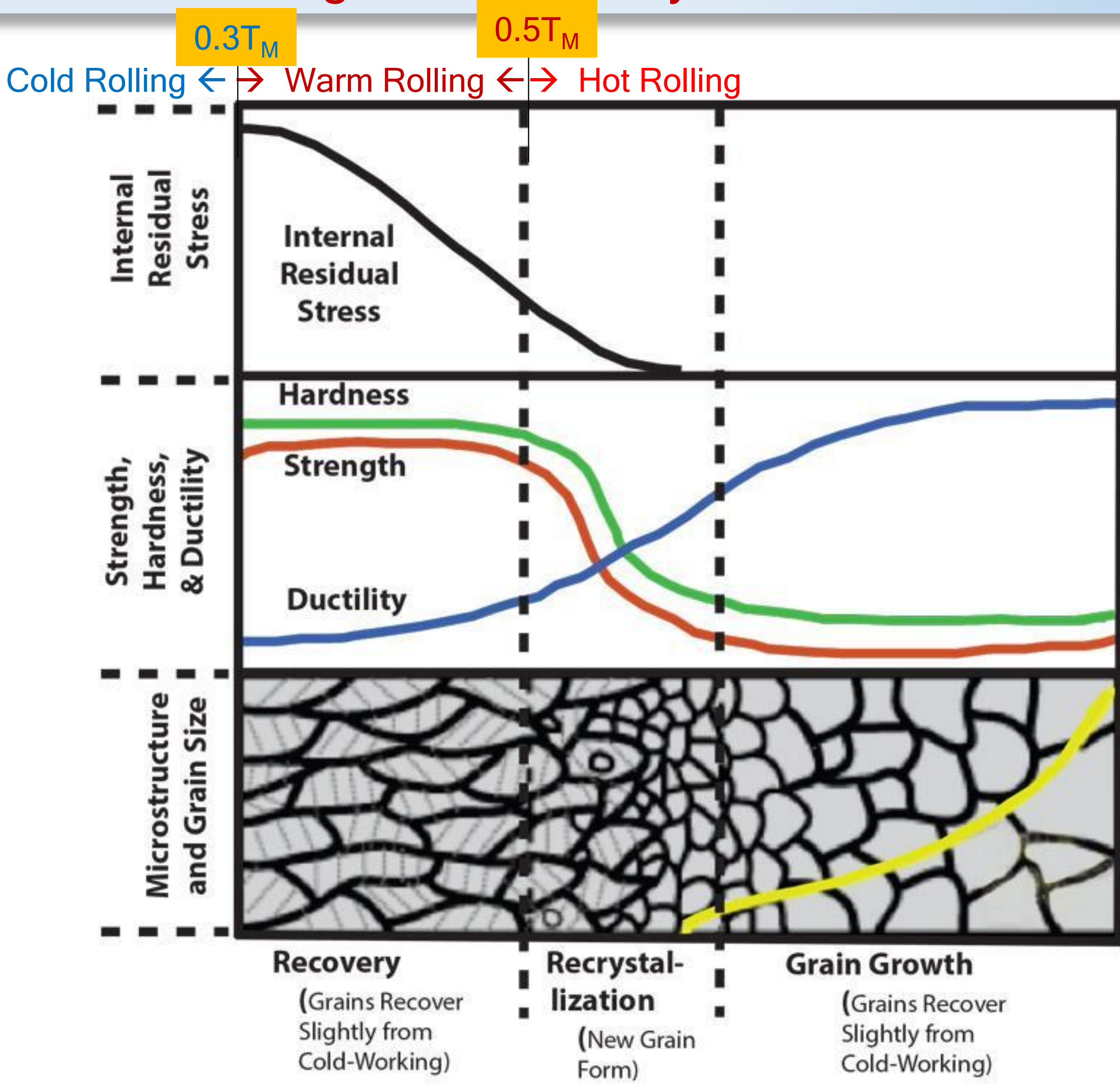


Hot Rolling: Microstructure



Courtesy: Google Images

Influence of Annealing Temperature on the Tensile Strength and Ductility



< 0.3Tm: No microstructural changes

Recovery: Defect rearrangement

Recrystallization: New strain-free grain formation

Grain Growth: Increase in size of strain-free grains

https://www.thefabricator.com/tubepipejournal/article/tubepipeproduction/grain-size-control-for-successfully-fabricating-stainless-and-inconel-alloy-tubing

Cold Working

- Performed at a temperature $\leq 0.3T_m$

- Many cold forming processes are important mass production operations

- Minimum or no machining usually required

  \- These operations are *near net shape* or *net shape* processes

Hot Working

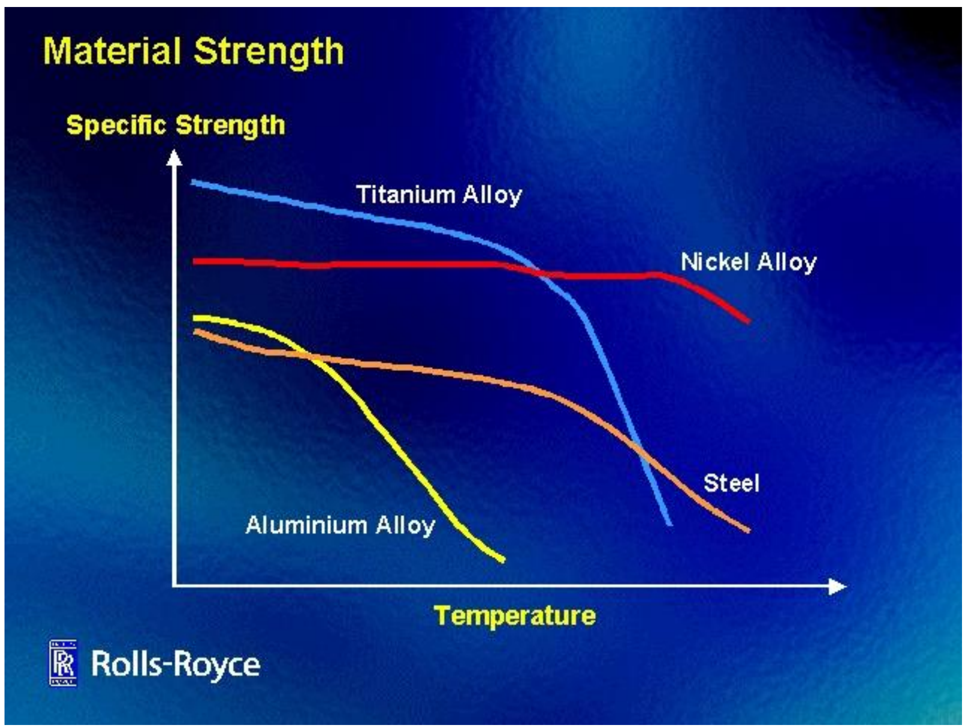
- Deformation at temperatures above *recrystallization temperature*

- Recrystallization temperature = about one-half of melting point on absolute scale

  - In practice, hot working usually performed somewhat above 0.5 T_m
  - Metal continues to soften as temperature increases above 0.5 T_m, enhancing advantage of hot working above this level

Why Hot Working?

- Capability for substantial plastic deformation of the metal - far more than possible with cold working or warm working
- Any deformation operation can be accomplished with lower forces and power
- Why?
  - Strength coefficient is substantially less than at room temperature
  - Ductility is significantly increased



Temperature ↑

Yield Strength

Hardness

Strength Coefficient ↓

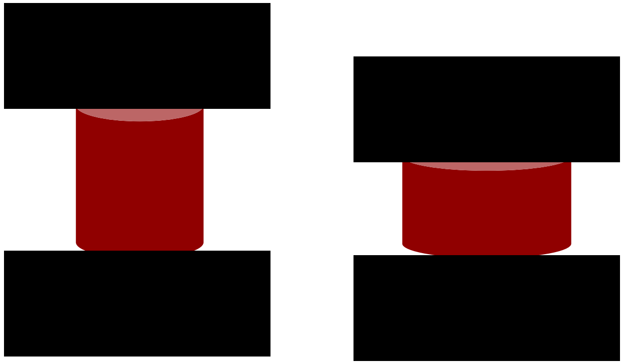
Ductility ↑

Strain Rate

- Rate of straining 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: $$\dot{\varepsilon} = \frac{\vartheta}{h}$$

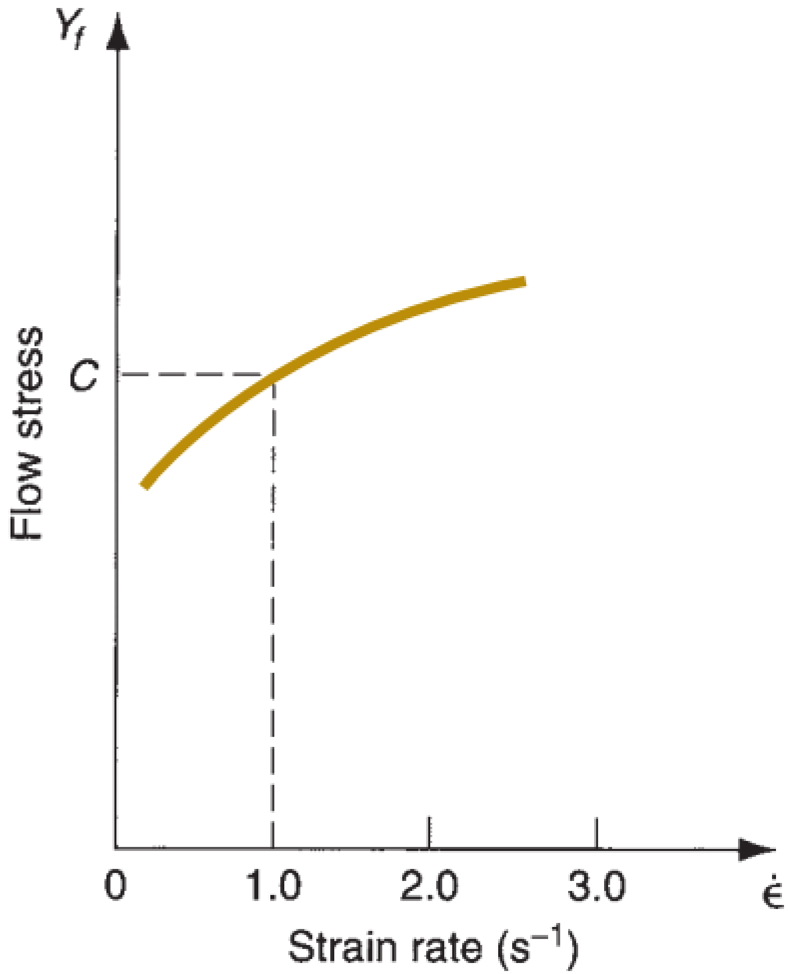


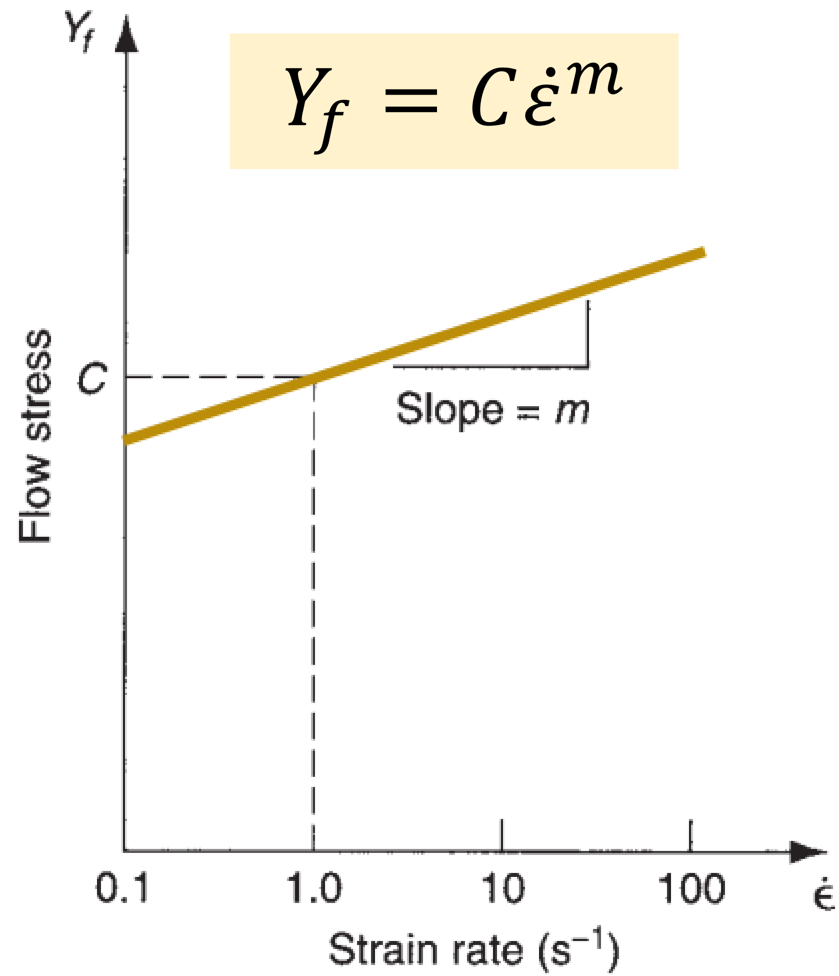
Where, $\dot{\varepsilon}$ = true strain rate;
and h = instantaneous height of workpiece being deformed

- Strain-rate is complicated by geometry of work-part
- Values can range from 10^{-3} to 100 s^{-1}

What if *v* is constant?

Flow-stress Vs Strain-rate





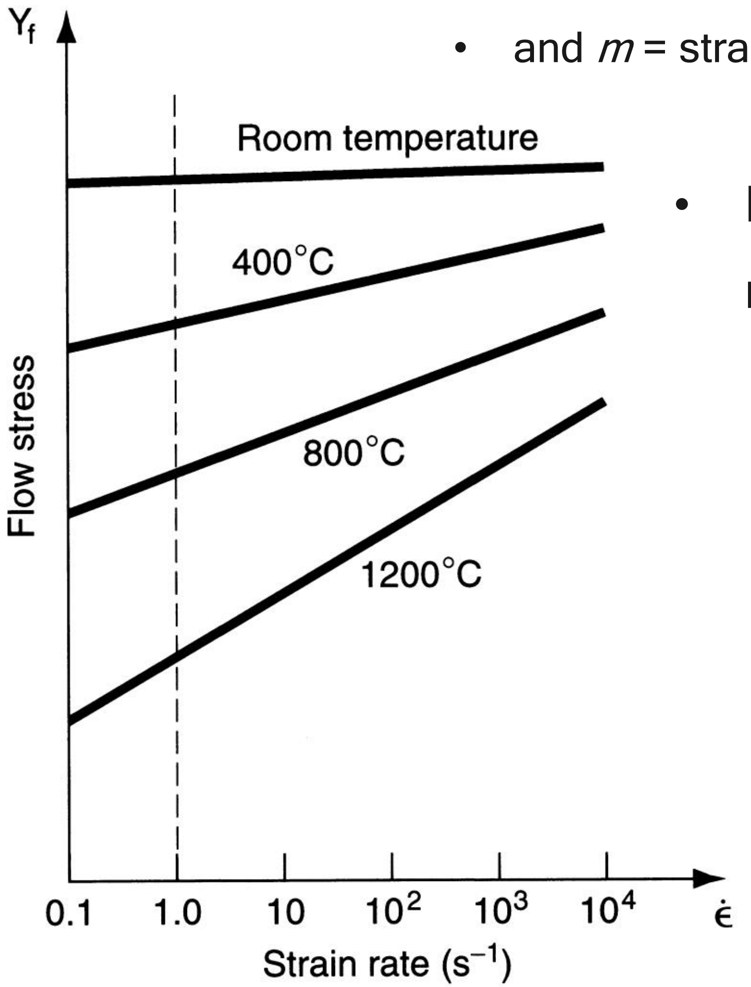
$$Y_f = C\dot{\varepsilon}^m$$

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

Strain rate sensitivity and Temperature

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

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



- **Effect of temperature on flow stress for a typical metal:**
  - The constant C in the above equation (indicated by the intersection of each plot with the vertical dashed line at strain rate = 1.0) decreases,
  - m (slope of each plot) increases with increasing temperature

Fun fact… Beverage cans

- Beverage cans are made of Al alloys
- Cold rolled to get a crystallographic texture
- Easily crumbled from outside
- But need more energy/force to deform it from inside

Courtesy: Google Images