

Manufacturing Technology II

Forming Processes

FUNDAMENTALS OF METAL FORMING

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

1. Overview of Metal Forming

Definition of Forming

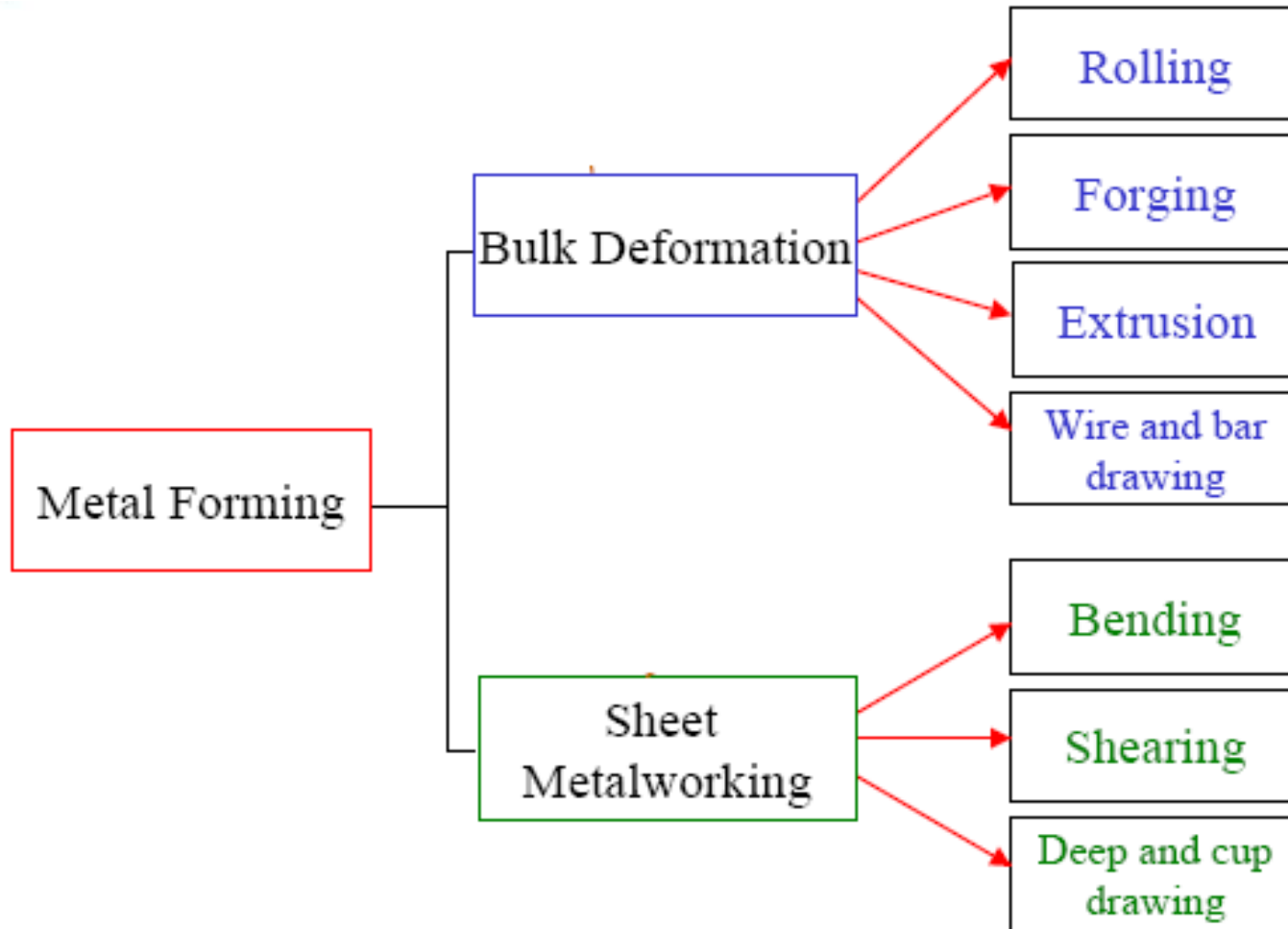
Forming is a fabrication process for solid substances by controlled plastic deformation in order to obtain alterations of:

- the form,
- the material properties and/or
- the surface properties,

Terms for Classifying Forming Processes

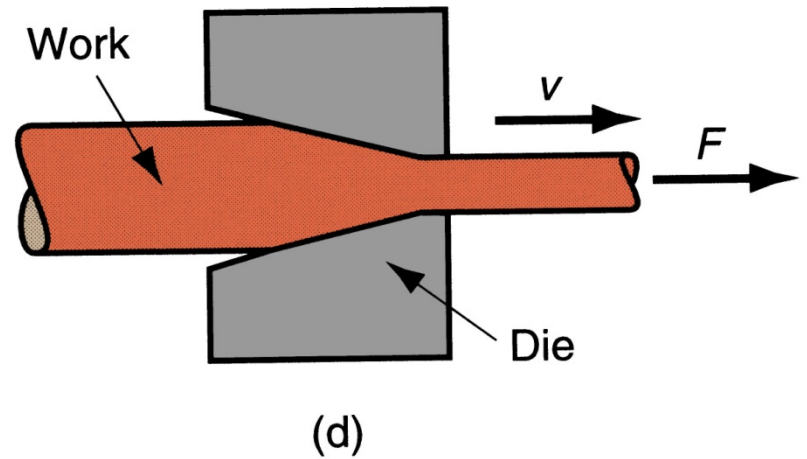
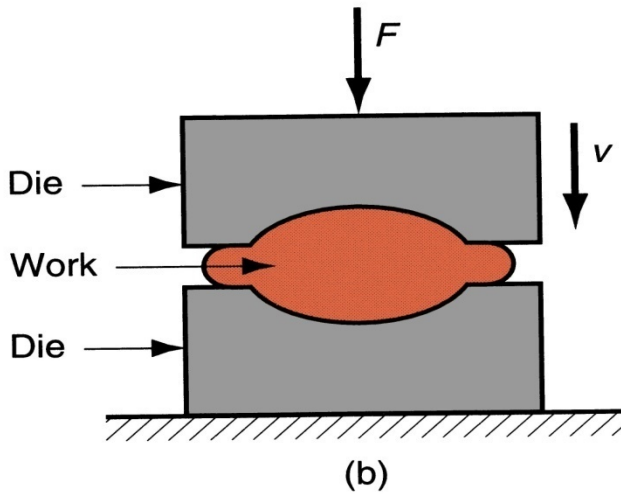
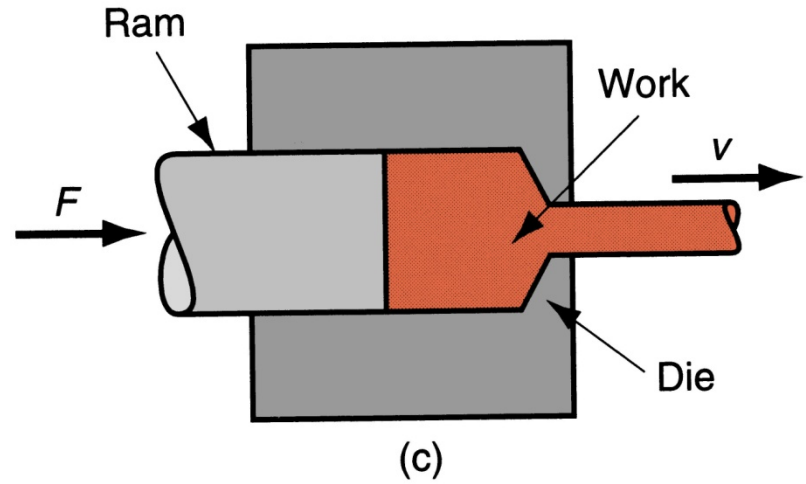
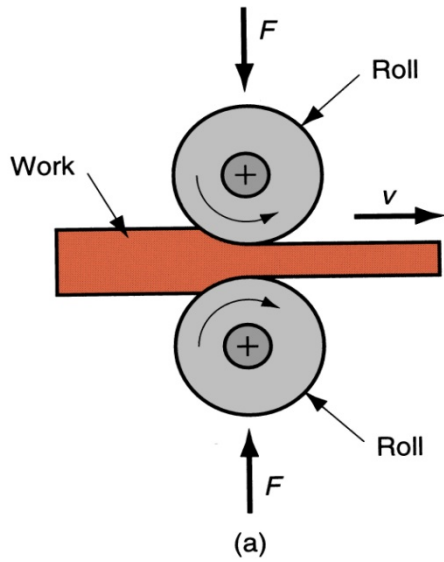
- Classification by Type of Raw Material
- Classification by State of Stress
- Classification by Forming Temperature
- Classification by Methods of Induction of Forces into the Work-Piece

Forming 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 include cylindrical billets and rectangular bars



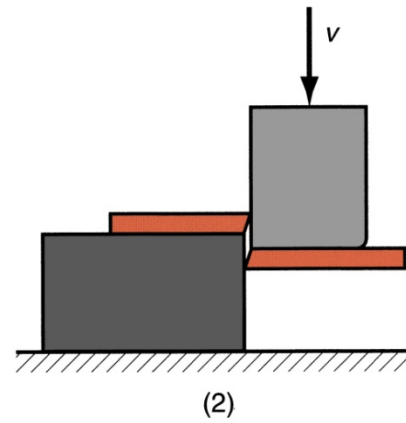
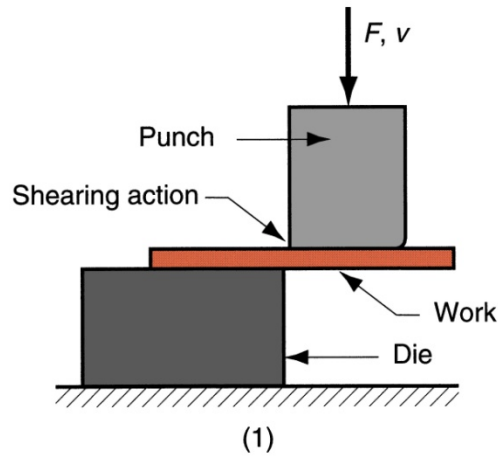
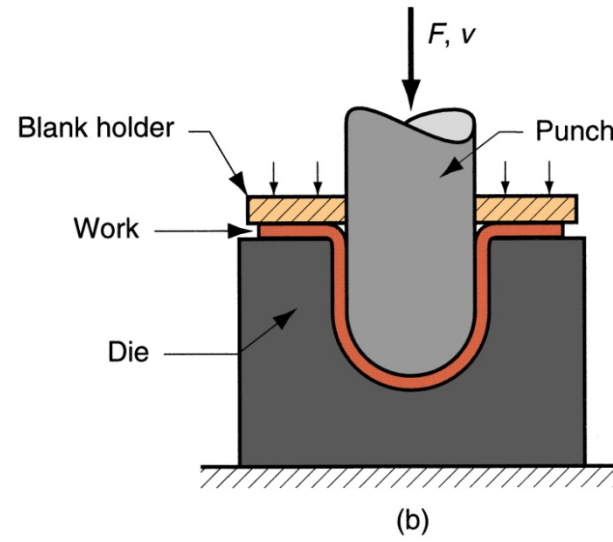
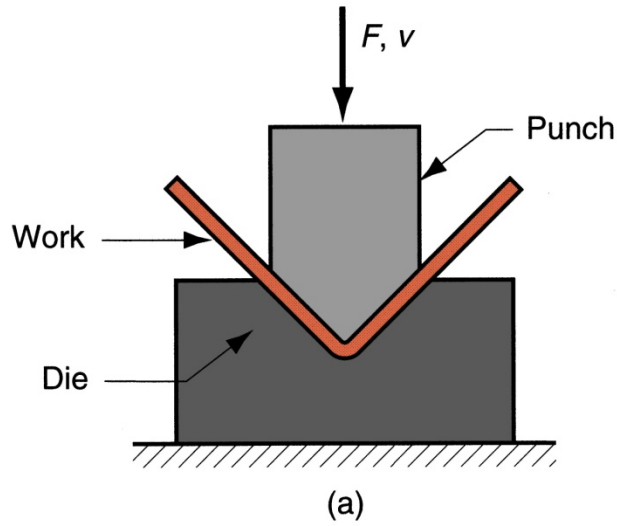
Basic bulk deformation processes: (a) rolling (b) forging (c) extrusion (d) drawing

Sheet Metalworking

- Forming and related operations performed on **metal sheets** and **strips**
- **High surface area-to-volume ratio** of starting metal, which distinguishes these from bulk deformation
- Often called ***pressworking*** because presses perform these operations

Parts are called *stampings*

Usual tooling: ***punch and die***



(c)

Basic sheet metalworking operations: (a) bending (b) Deep drawing
(c) shearing

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 yield strength** of metal
- The metal **takes a shape** determined by the **geometry of the die**

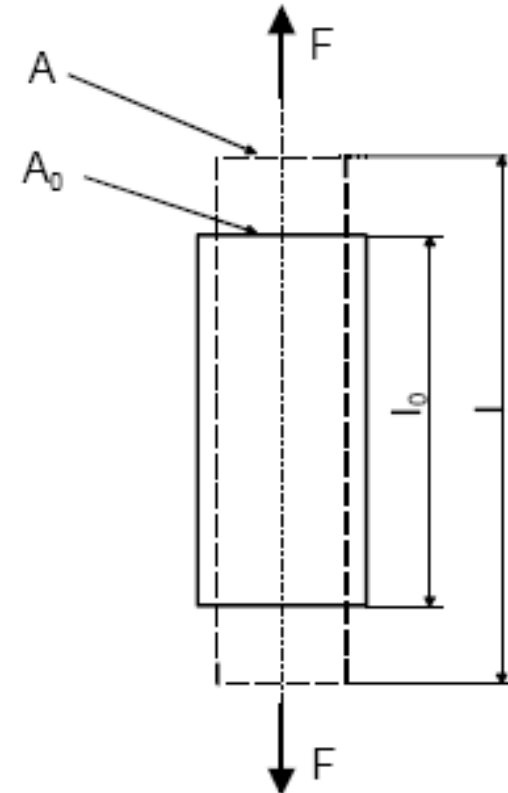
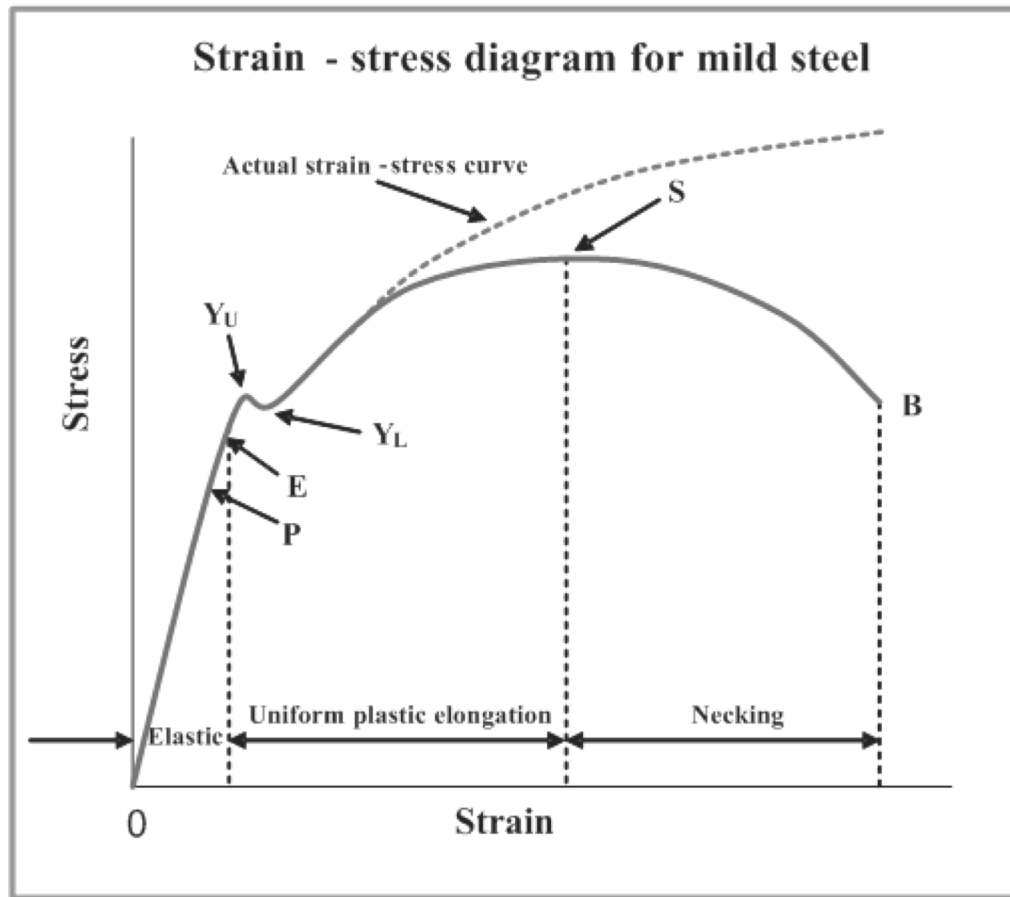
Stresses in Metal Forming

- 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 and *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*

Material Behavior in Metal Forming



Tensile Testing Machine



- 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:

$$Y_f = K \varepsilon^n$$

where Y_f = flow stress, K = strength coefficient; and n = strain hardening exponent

strain

$$\varepsilon = \int_{l_0}^l \frac{dl}{l} = \ln \frac{l}{l_0}$$

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

Average Flow Stress

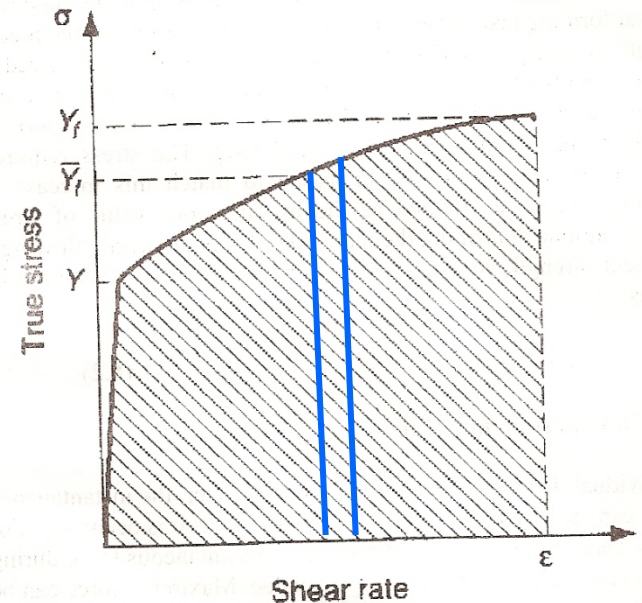
Determined by integrating the flow curve equation between zero and the final strain value defining the range of interest

$$\bar{Y}_f = \frac{\int_0^\varepsilon Y_f d\varepsilon}{\varepsilon} = \frac{\int_0^\varepsilon K\varepsilon^n d\varepsilon}{\varepsilon}$$

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

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

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



Example (1)

A metal has a flow curve with parameters: $K = 850 \text{ MPa}$ and strain hardening exponent $n = 0.30$. A tensile specimen of the metal with gage length = 100 mm is stretched to a length = 157 mm. Determine the flow stress at the new length and the average flow stress that the metal has been subjected to during the deformation.

Solution

$$\varepsilon = \ln (157/100) = \ln 1.57 = 0.451$$

$$\text{Flow stress } Y_f = 850(0.451)^{0.30} = \mathbf{669.4 \text{ MPa.}}$$

$$\text{Average flow stress } \bar{Y}_f = 850(0.451)^{0.30}/1.30 = \mathbf{514.9 \text{ MPa.}}$$

Example (2)

For a certain metal. $K = 700$ MPa and $n = 0.27$. Determine the average flow stress that the metal experiences if it's subjected to a stress that is equal to its strength coefficient K .

Solution

$$Y_f = K = 700 = K\varepsilon^n = 700\varepsilon^{.27}$$

$$\varepsilon = 1$$

$$\bar{Y}_f = 700(1.0)^{.27}/1.27 = 700/1.27 = \mathbf{551.2 \text{ MPa}}$$

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

Temperature in Metal Forming

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

- **At elevated temperature**

$$n = 0$$

$$\bar{Y}_f = Y_f = K$$

- Three temperature ranges in metal forming:

Cold working

Warm working

Hot working

Cold Working

- Performed at room temperature
- 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

Advantages of Cold Forming vs. Hot Working

- Better accuracy, closer tolerances
- Better surface finish
- Strain hardening increases strength and hardness
- No heating of work required
- Grain flow during deformation can cause desirable directional properties in product

Disadvantages of Cold Forming

- Higher forces and power required
- Surfaces of starting workpiece must be free of scale and dirt
- In some operations, metal must be annealed to allow further deformation
- In other cases, metal is simply not ductile enough to be cold worked

Warm Working

- Performed at temperatures above room temperature but below recrystallization temperature
- Warm working: T/T_m from 0.3 to 0.5, where T_m = melting point (absolute temperature) for metal

Advantages of Warm Working

- Lower forces and power than in cold working
- More intricate work geometries possible
- Need for annealing may be reduced or eliminated

Hot Working

- Deformation at temperatures *above recrystallization temperature*
- 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

Advantages of Hot Working vs. Cold Working

- Workpart **shape** can be significantly altered
- Lower **forces** and **power** required
- Metals that usually **fracture** in cold working can be hot formed
- Strength properties of product are generally **isotropic**
- No **strengthening** of part occurs from work hardening

Disadvantages of Hot Working

- Lower dimensional **accuracy**
- Higher **total energy** required (due to the thermal energy to heat the workpiece)
- Work **surface oxidation** (scale), **poorer surface finish**
- Shorter **tool life**

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:

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

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

Strain Rate Sensitivity Equation

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

where

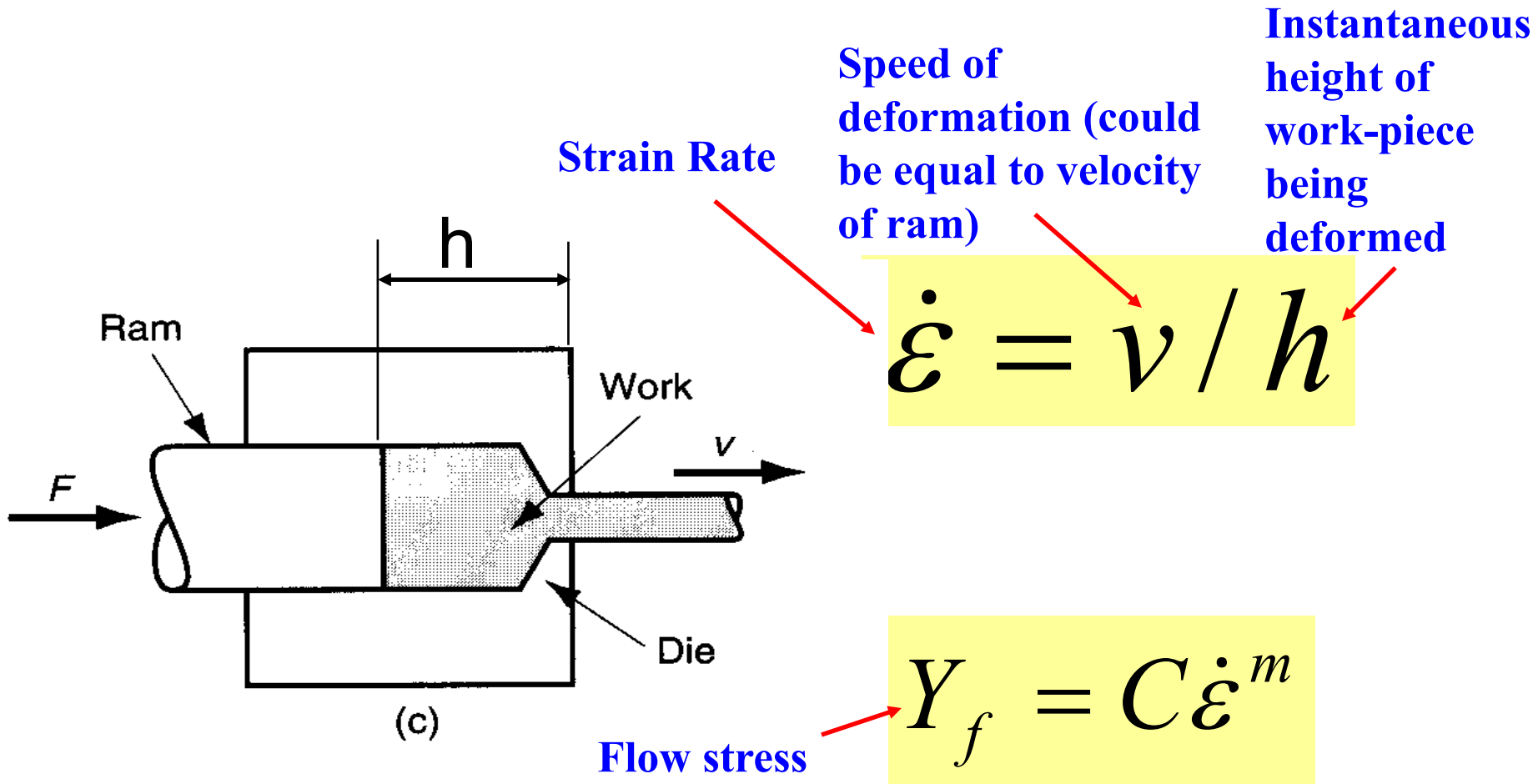
C = strength constant (similar but not equal to strength coefficient in flow curve equation),
and

m = strain-rate sensitivity exponent

• Strain rate (related to elevated temperatures)

Rate at which metal is strained in a forming process

- In the hot forming or warm forming, the strain rate can affect the flow stress



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

Strength coefficient but not the same as K

where

C → strength constant

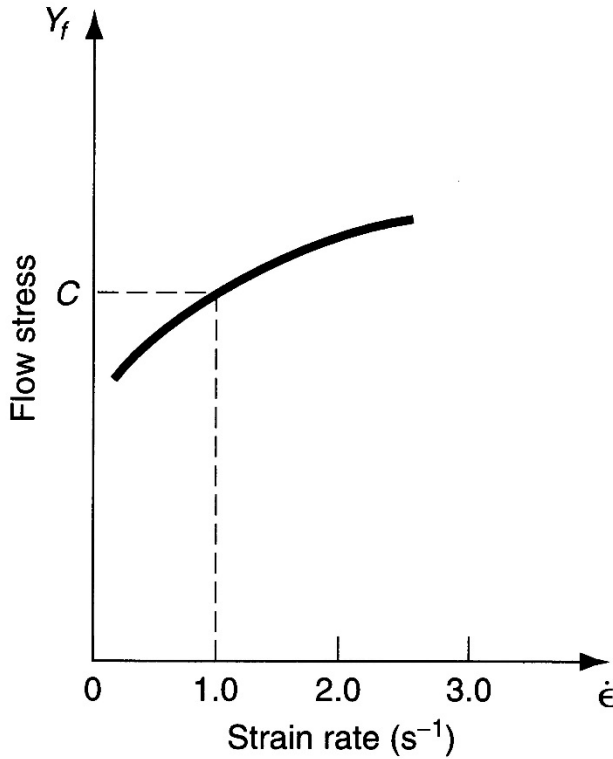
m → strain-rate sensitivity exponent

$$Y_f = K \epsilon^n$$

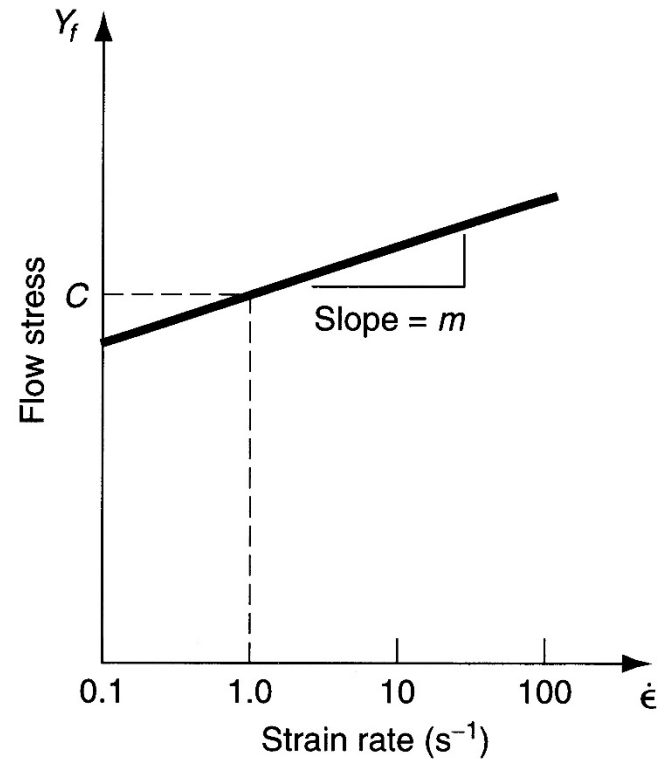
and n are determined by the following figure which is generated from the experiment

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 effect is known as *strain-rate sensitivity*



(a)



(b)

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

Example (3) The gage length of a tensile test specimen = 150 mm. It is subjected to a tensile test in which the grips holding the end of the test specimen are moved with a relative velocity = 0.1 m/s. Construct a plot of the strain rate as a function of length as the specimen is pulled to a length = 200 mm.

Solution

The following values are calculated for the plot:

$$\text{At } L = 150 \text{ mm, } \dot{\epsilon} = 0.1/0.15 = 0.667 \text{ s}^{-1}$$

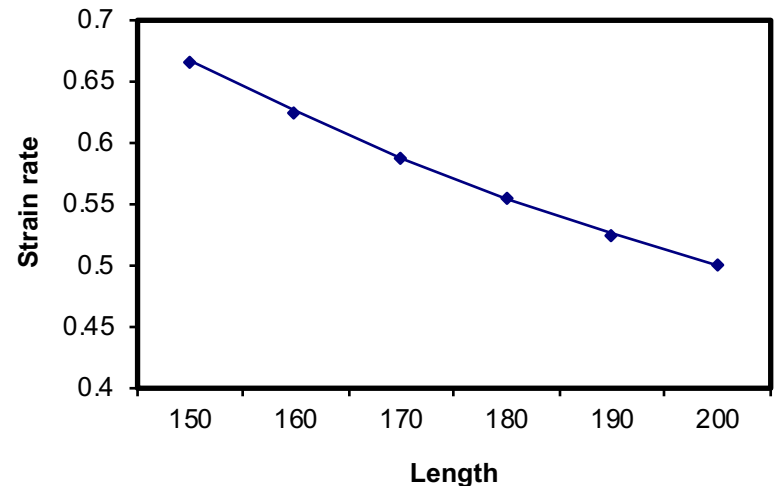
$$\text{At } L = 160 \text{ mm, } \dot{\epsilon} = 0.1/0.16 = 0.625 \text{ s}^{-1}$$

$$\text{At } L = 170 \text{ mm, } \dot{\epsilon} = 0.1/0.17 = 0.588 \text{ s}^{-1}$$

$$\text{At } L = 180 \text{ mm, } \dot{\epsilon} = 0.1/0.18 = 0.555 \text{ s}^{-1}$$

$$\text{At } L = 190 \text{ mm, } \dot{\epsilon} = 0.1/0.19 = 0.526 \text{ s}^{-1}$$

$$\text{At } L = 200 \text{ mm, } \dot{\epsilon} = 0.1/0.20 = 0.500 \text{ s}^{-1}$$



Friction in Metal Forming

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

Lubrication in Metal Forming

- Metal working lubricants are applied to tool-work interface in many forming operations to reduce harmful effects of friction
- Benefits:
 - Reduced sticking, forces, power, tool wear
 - Better surface finish
 - Removes heat from the tooling

Considerations in Choosing a Lubricant

- Type of forming process (rolling, forging, sheet metal drawing, etc.)
- Hot working or cold working
- Work material
- Chemical reactivity with tool and work metals
- Ease of application
- Cost

Metal Forming Laws

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

$$\varepsilon = \int_{l_0}^l \frac{dl}{l} = \ln \frac{l}{l_0}$$

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

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