Metal Forming

FUNDAMENTALS OF METAL FORMING

- Overview of Metal Forming
- Material Behavior in Metal Forming
- Temperature in Metal Forming
- Strain Rate Sensitivity
- Friction and Lubrication in Metal Forming

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**

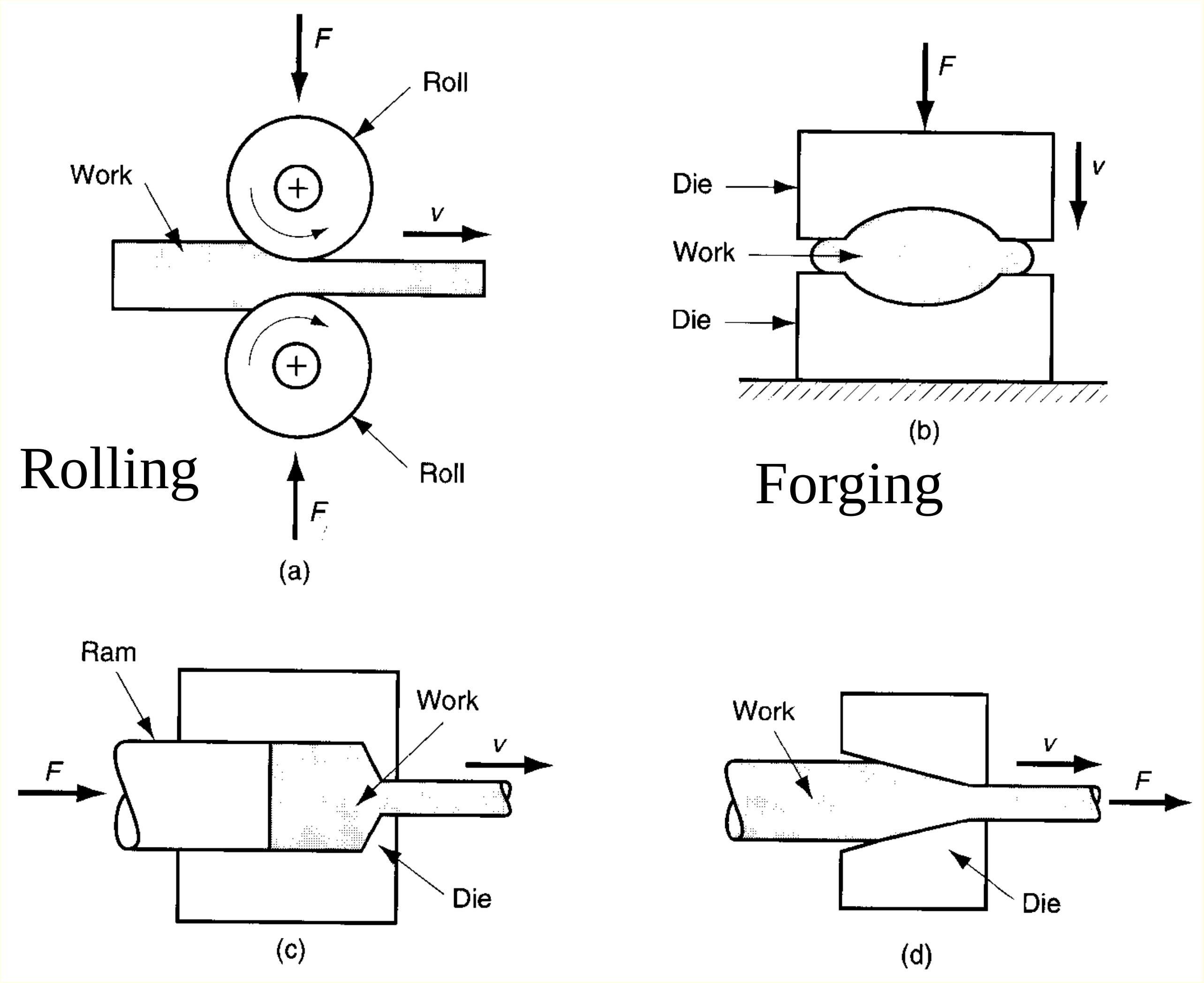
Overview

- Process Classification
  - Bulk Deformation Process
  - Sheet Metalworking
- Material Behaviour in Metal Forming
  - Flow Stress
  - Average Flow Stress
- Temperature in Metal Forming
- Effect of Strain Rate
- Friction & Lubrication

Bulk Metal Forming

- Rolling - compression process to reduce the thickness of a slab by a pair of rolls.
- Forging - compression process performing between a set of opposing dies.
- Extrusion - compression process sqeezing metal flow a die opening.
- Drawing - pulling a wire or bar through a die opening.

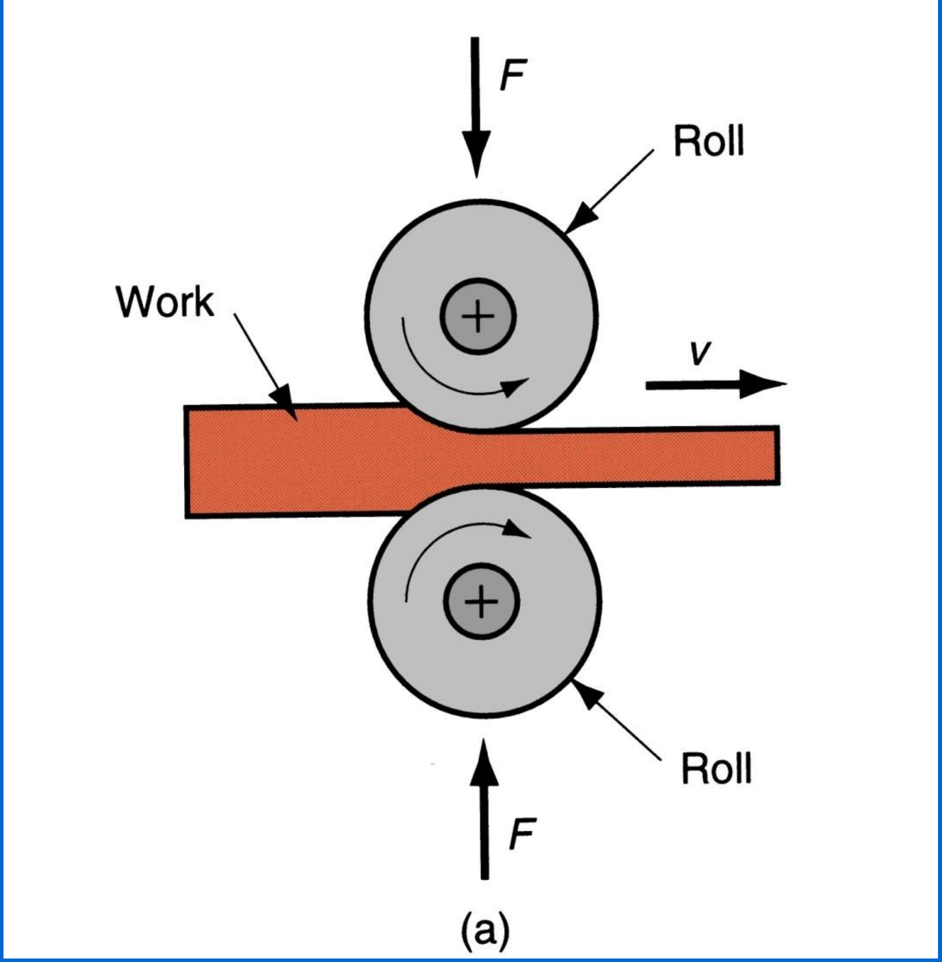
Bulk Metal Forming



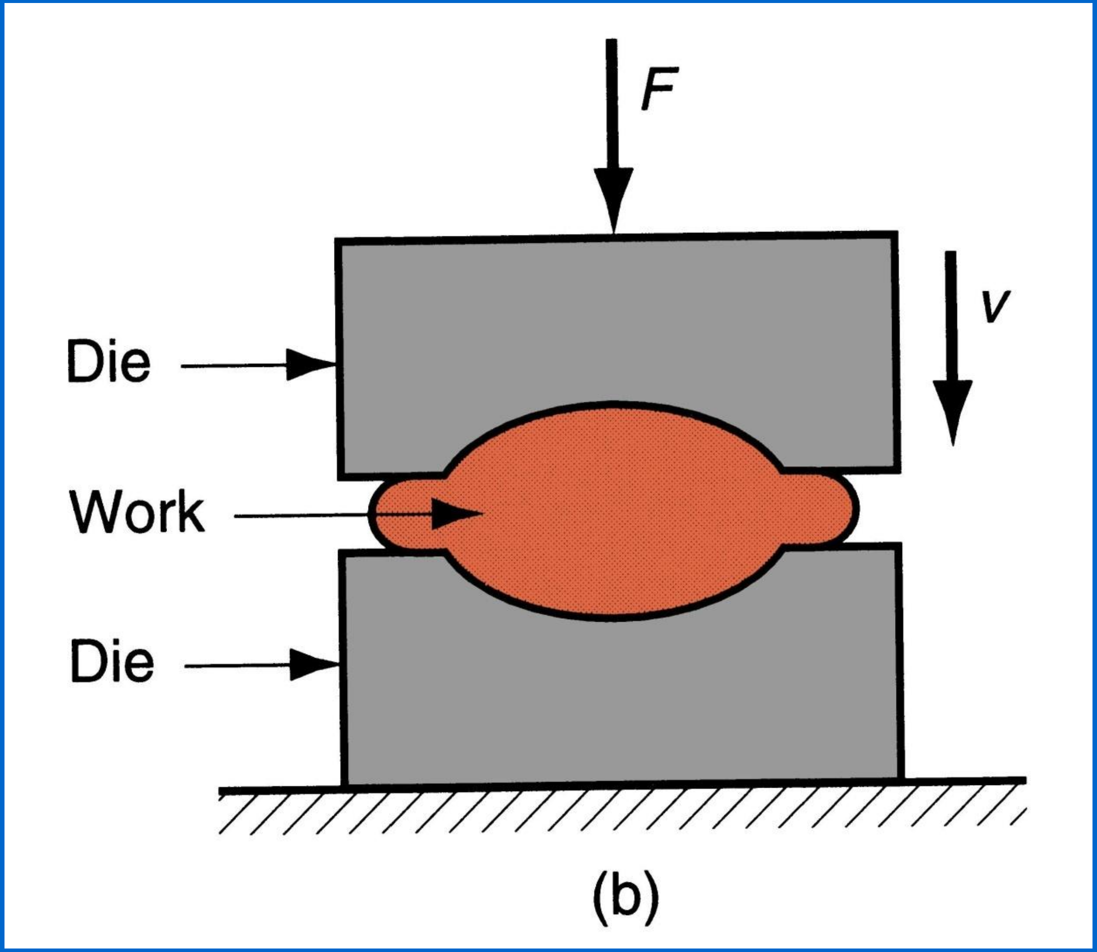
Extrusion Drawing

Bulk Deformation Processes

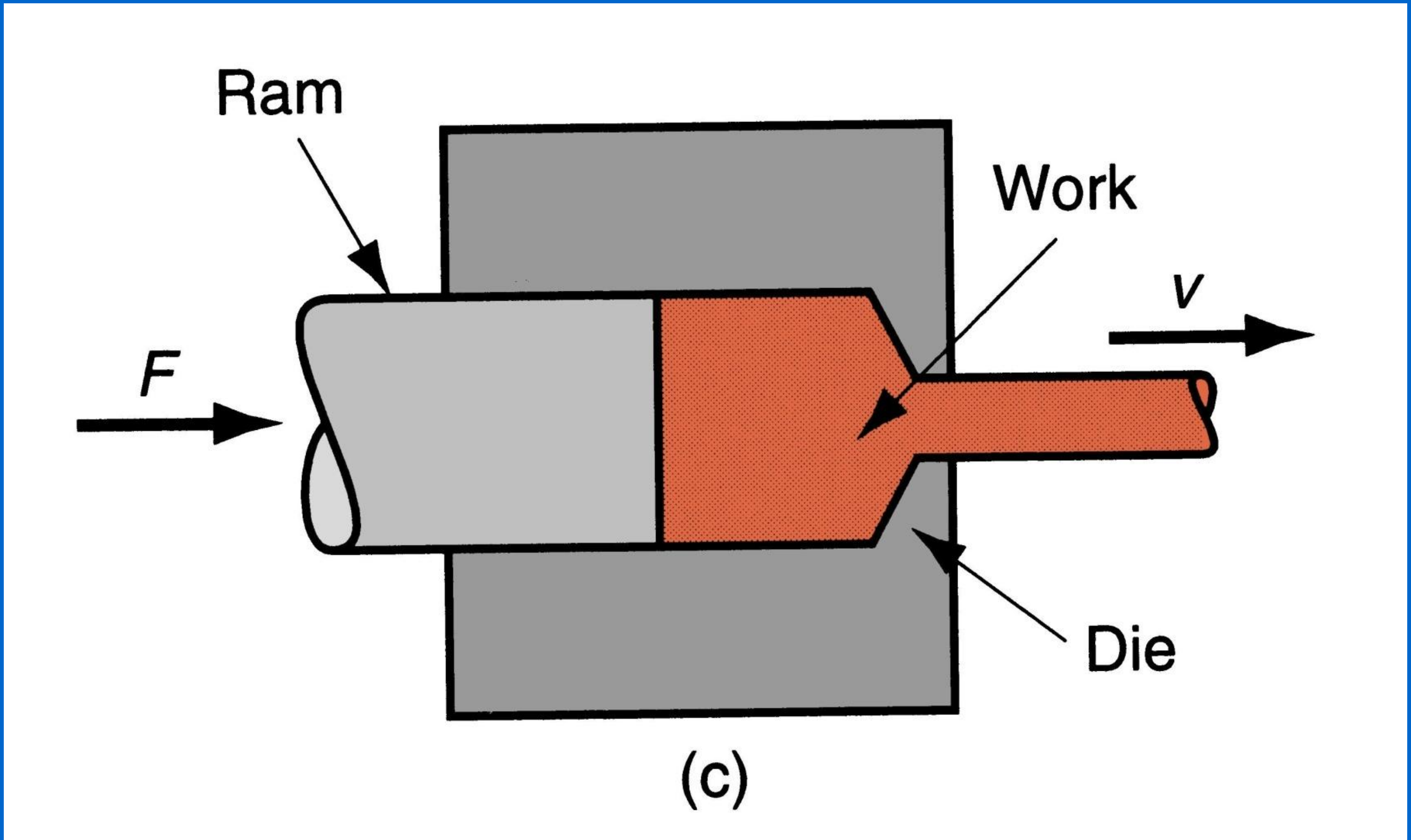
- **Characterized by significant deformations and massive shape changes**
- **"Bulk" refers to workparts with relatively low surface area-to-volume ratios**
- **Starting work shapes include cylindrical billets and rectangular bars**



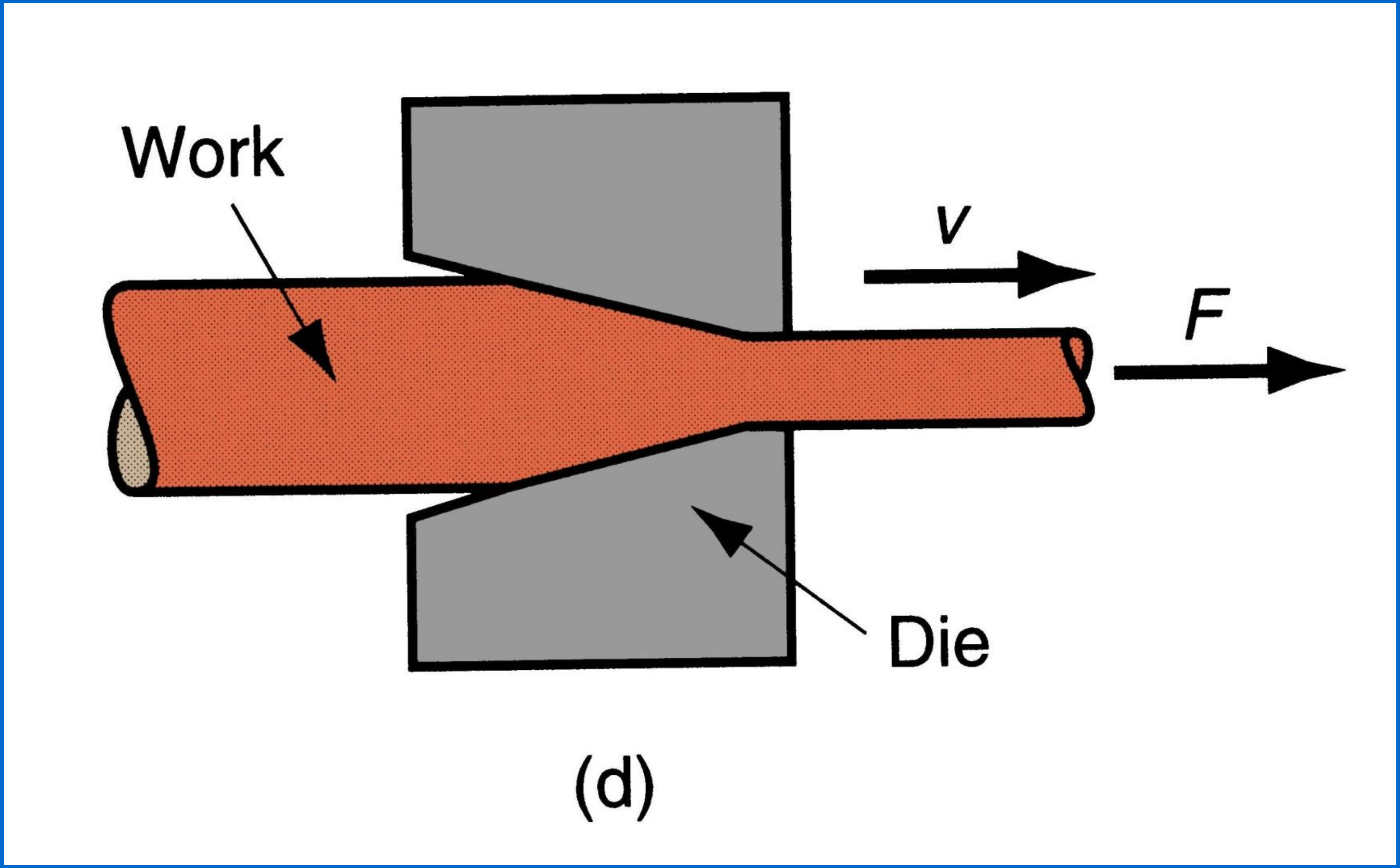
Basic bulk deformation processes: (a) rolling



Basic bulk deformation processes: (b) forging



Basic bulk deformation processes: (c) extrusion



Basic bulk deformation processes: (d) drawing

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**

Sheet Metalworking

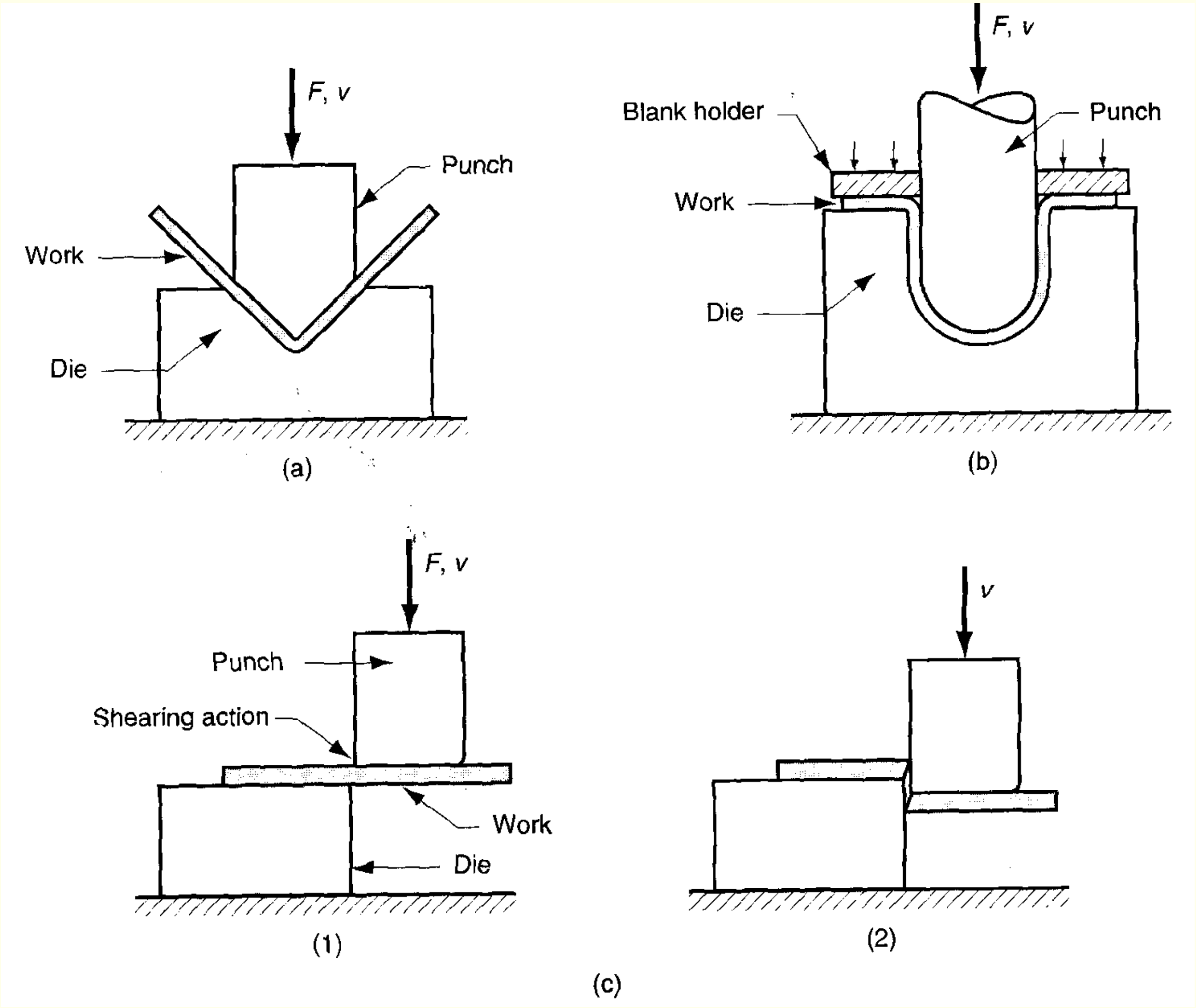
Forming on metal sheets, strips, and coils. The process is normally a cold working process using a set of *punch* and *die*.

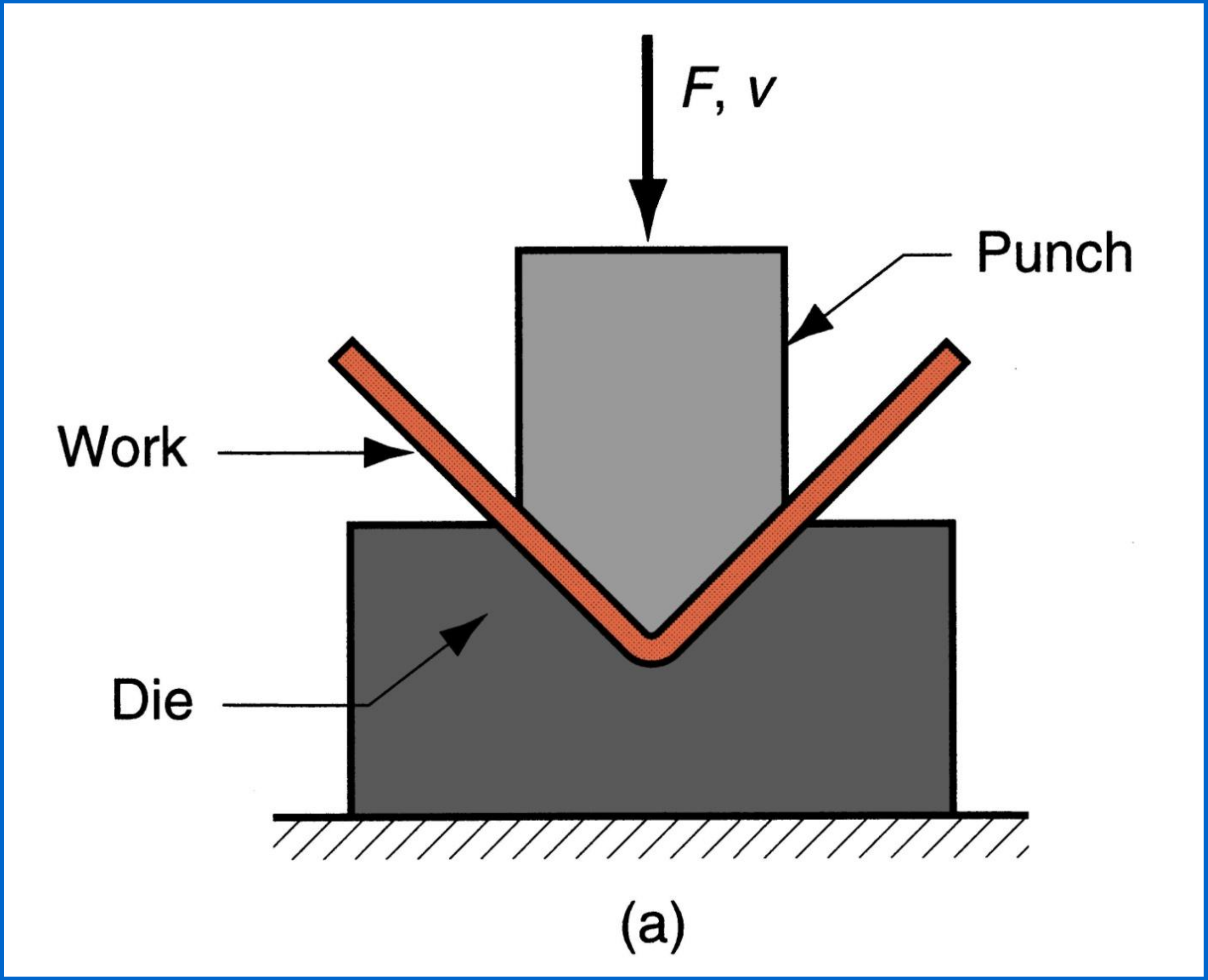
- Bending - straining of a metal sheet to form an angle bend.
- Drawing - forming a sheet into a hollow or concave shape.
- Shearing - not a forming process but a cutting process.

Sheet Metal working

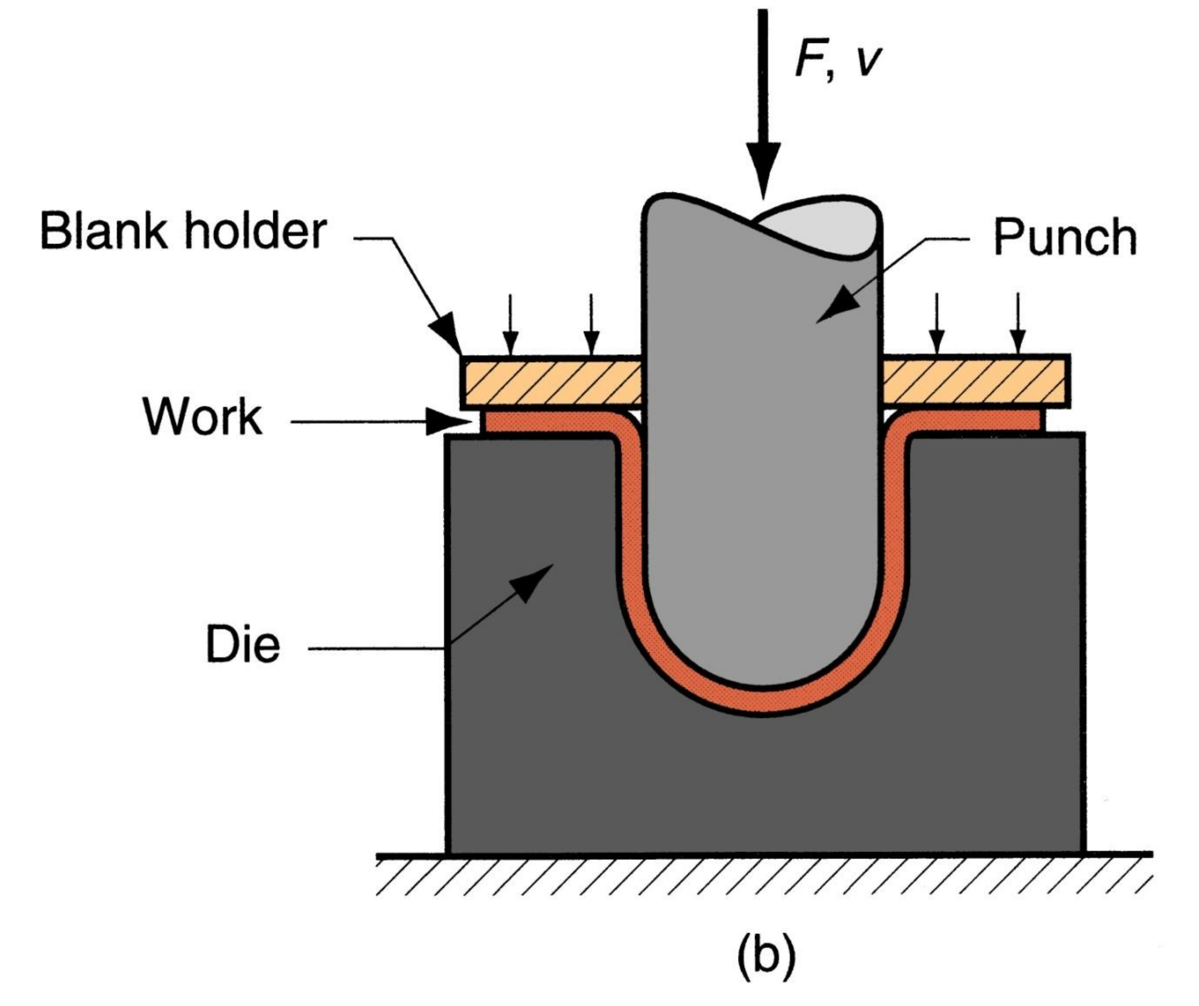
- **Forming and related operations performed on metal sheets, strips, and coils**
- **High surface area-to-volume ratio of starting metal, which distinguishes these from bulk deformation**
- **Often called *pressworking* because presses perform these operations**
  - **Parts are called *stampings***
  - **Usual tooling: *punch* and *die***

Sheet Metalworking

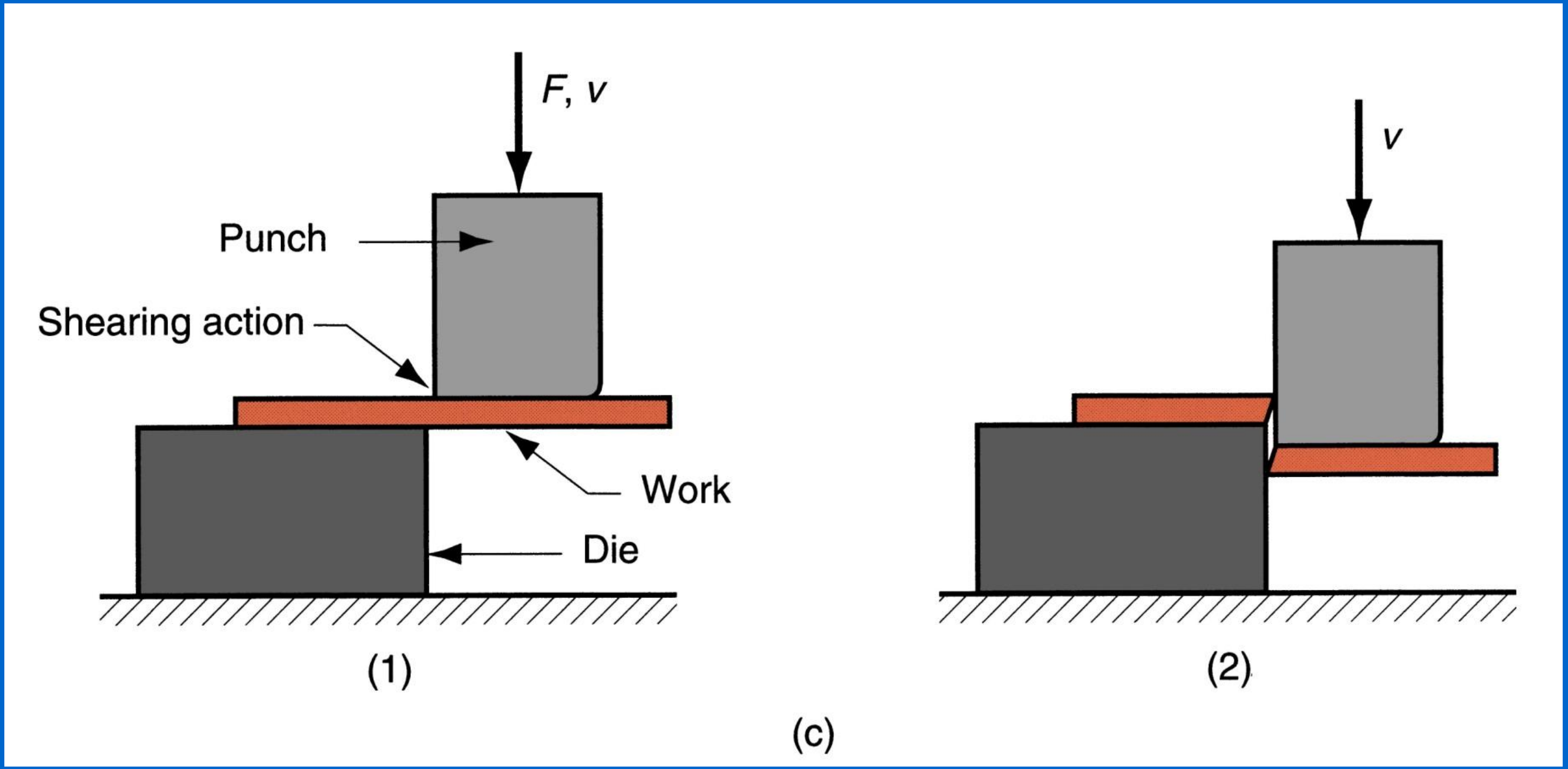




Basic sheet metal working operations: (a) bending



Basic sheet metal working operations: (b) drawing



Basic sheet metal working operations: (c) shearing

Material Behavior in Metal Forming

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

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

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

- **Stress and strain in flow curve are true stress and true strain**

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

Material Behavior in Metal Forming

$$Y_f = K\varepsilon^n$$

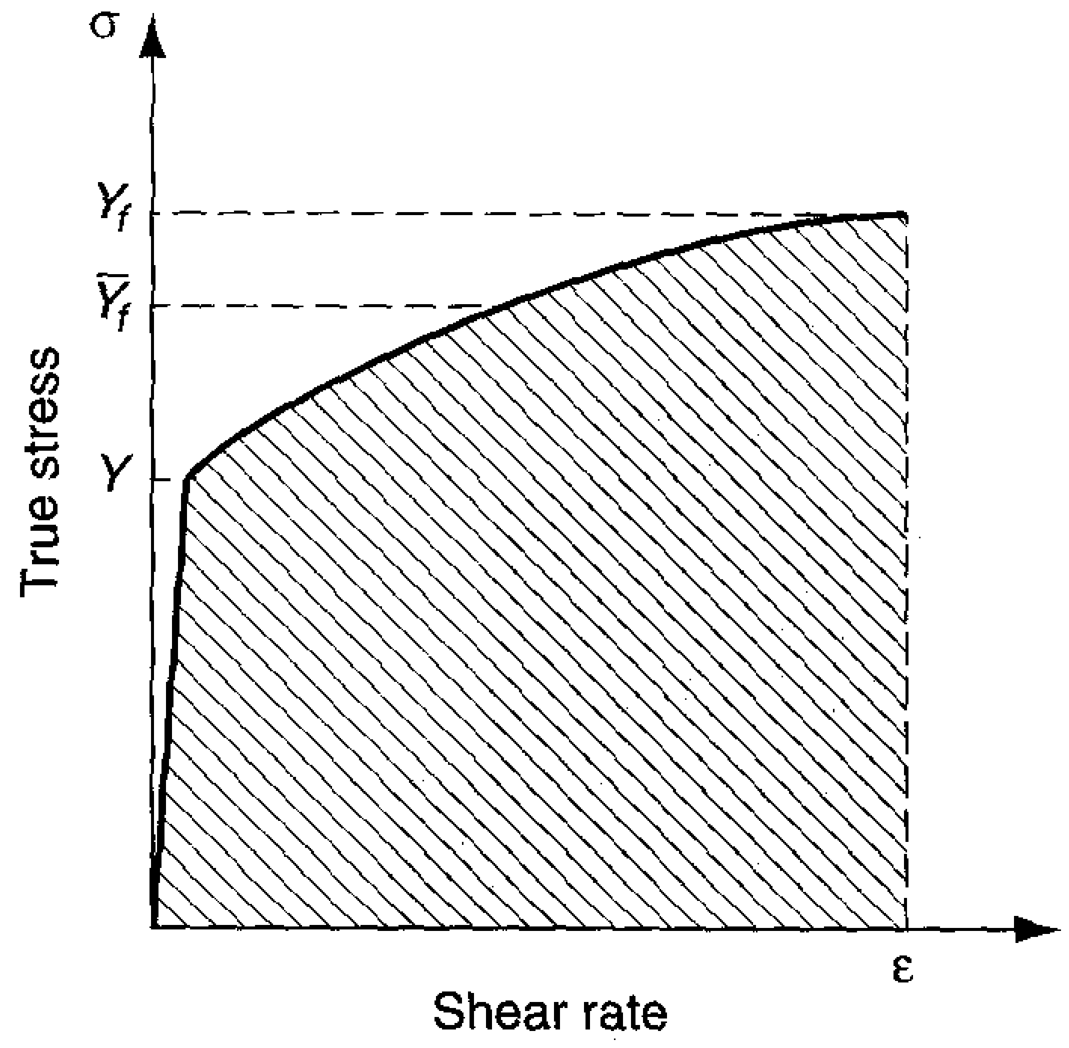
$$\bar{Y}_f = \frac{K\varepsilon^n}{1+n}$$

Y_f Flow Stress

ε Maximum strain for forming process

K Strength coefficient

$\bar{Y}_f$ Average flow stress



Temperature in Metalworking

- Cold working
  - Pros
    - better accuracy
    - better surface finish
    - strain hardening increases strength and hardness
    - grain flow during deformation provides directional properties
    - no heating is needed
  - Cons
    - higher forces and power are required
    - surface should be cleansed
    - ductility and strain-hardening limits the extent of forming

Temperature in Metalworking

- Warm working - temperature between room temperature and recrystallization temperature, roughly about 0.3 T_m
  - Pros against cold working
    - Lower forces and power
    - more intricate work geometries possible
    - need for annealing may be reduced/eliminated.

Temperature in Metalworking

- Hot working - Deformation at temperature above recrystallization temperature typically between $0.5T_m$ to $0.75T_m$
  - Pros
    - larger deformation possible
    - lower forces and power
    - forming of room temperature low ductility material is possible
    - isotropic properties resulted from process
    - no work hardening

Temperature in Metalworking

- Isothermal Forming - preheating the tools to the same temperature as the work metal. This eliminates the surface cooling and the resulting thermal gradient in the workpart.
- Normally applies to highly alloyed steels, titanium alloys and high-temperature nickel alloys.

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**
- **Three temperature ranges in metal forming:**
  - **Cold working**
  - **Warm working**
  - **Hot working**

Cold Working

- **Performed at room temperature or slightly above**
- **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 v/s. Hot Working

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

Disadvantages of Cold Forming

- **Higher forces and power required**
- **Surfaces of starting workpiece must be free of scale and dirt**
- **Ductility and strain hardening limit the amount of forming that can be done**
  - **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**

- **Dividing line between cold working and warm working often expressed in terms of melting point:**

  - **$0.3T_m$, 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***

- **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**

Why Hot Working?

Capability for substantial plastic deformation of the metal - far more than possible with cold working or warm working

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

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**
  - **Advantageous in cases when part is to be subsequently processed by cold forming**

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**

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

Evaluation of Strain Rate

- **In most practical operations, valuation of strain rate is complicated by**
  - **Workpart geometry**
  - **Variations in strain rate in different regions of the part**

- **Strain rate can reach 1000 s^{-1} or more for some metal forming operations**

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***

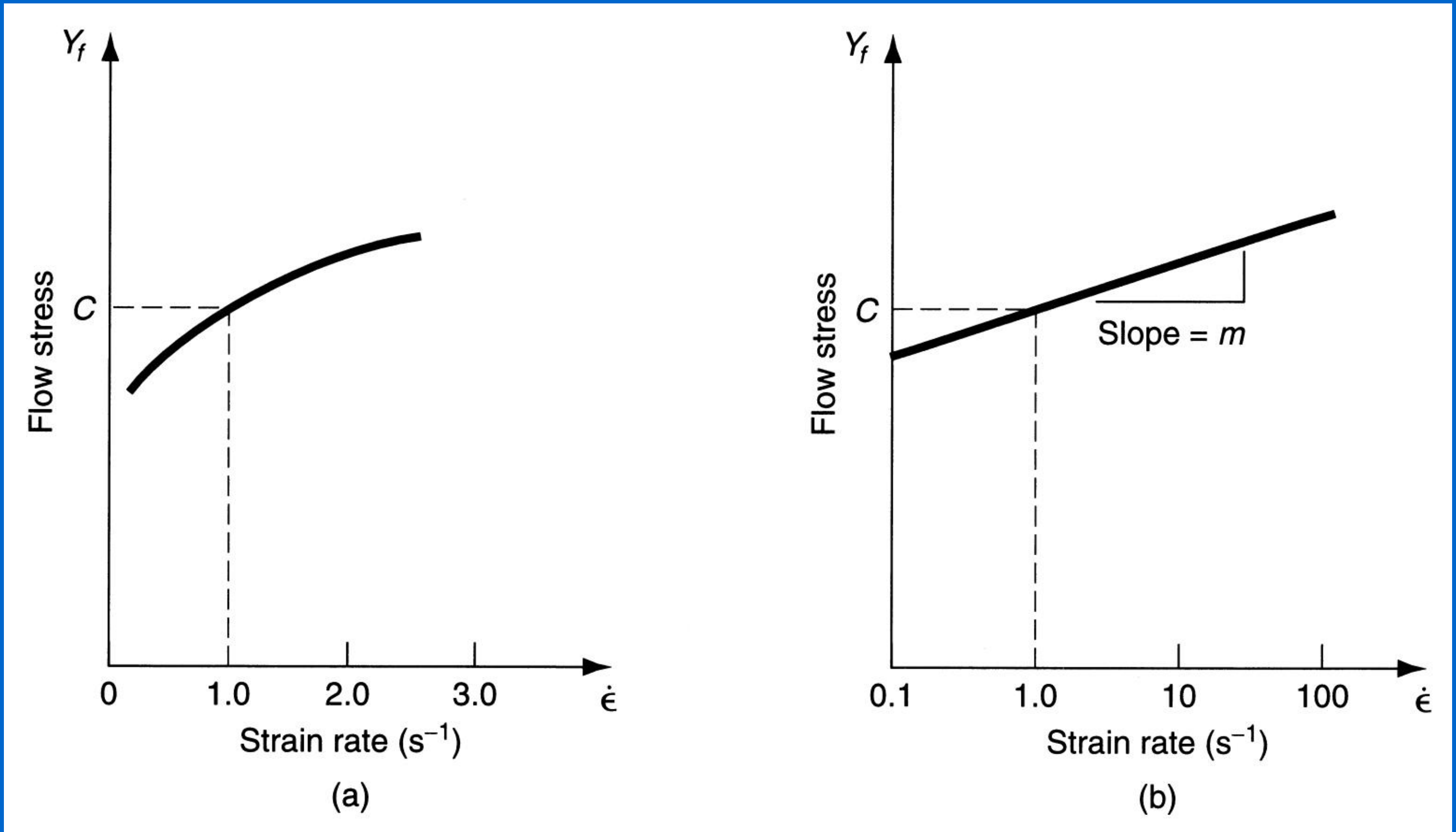


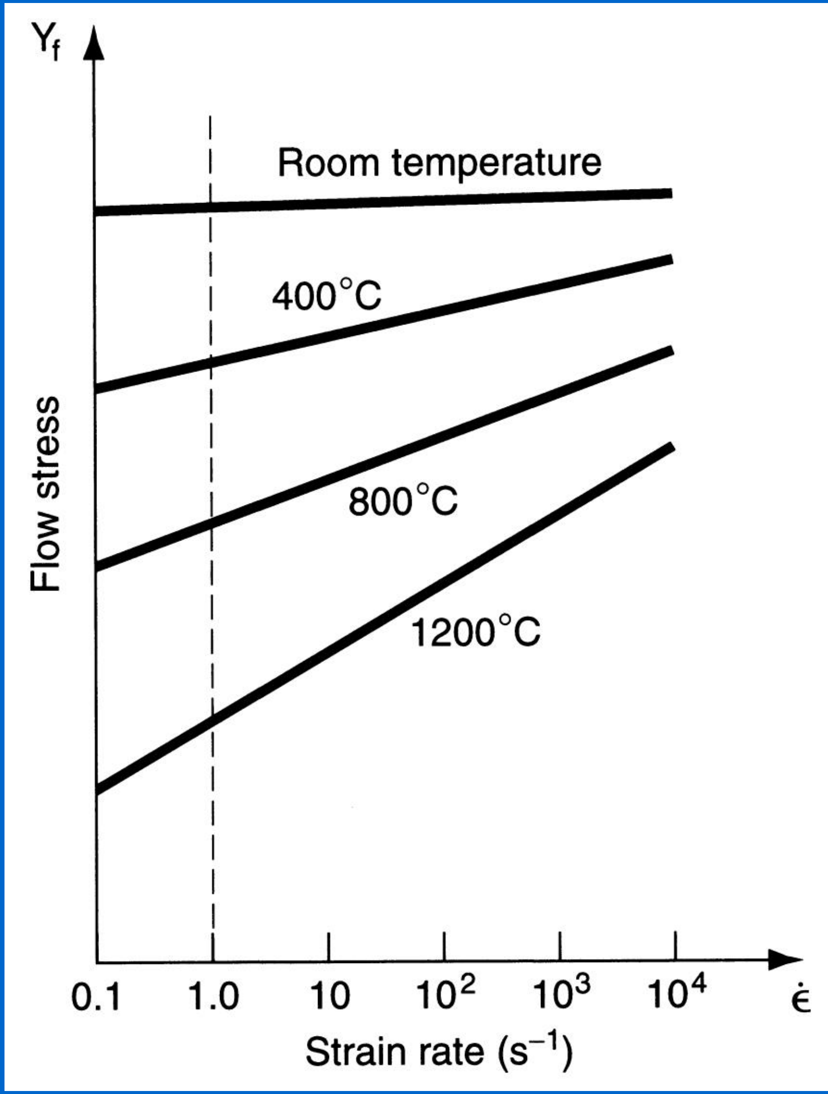
Figure (a) Effect of strain rate on flow stress at an elevated work temperature.

(b) Same relationship plotted on log-log coordinates

Strain Rate Sensitivity Equation

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

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* 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

Effect of Strain Rate

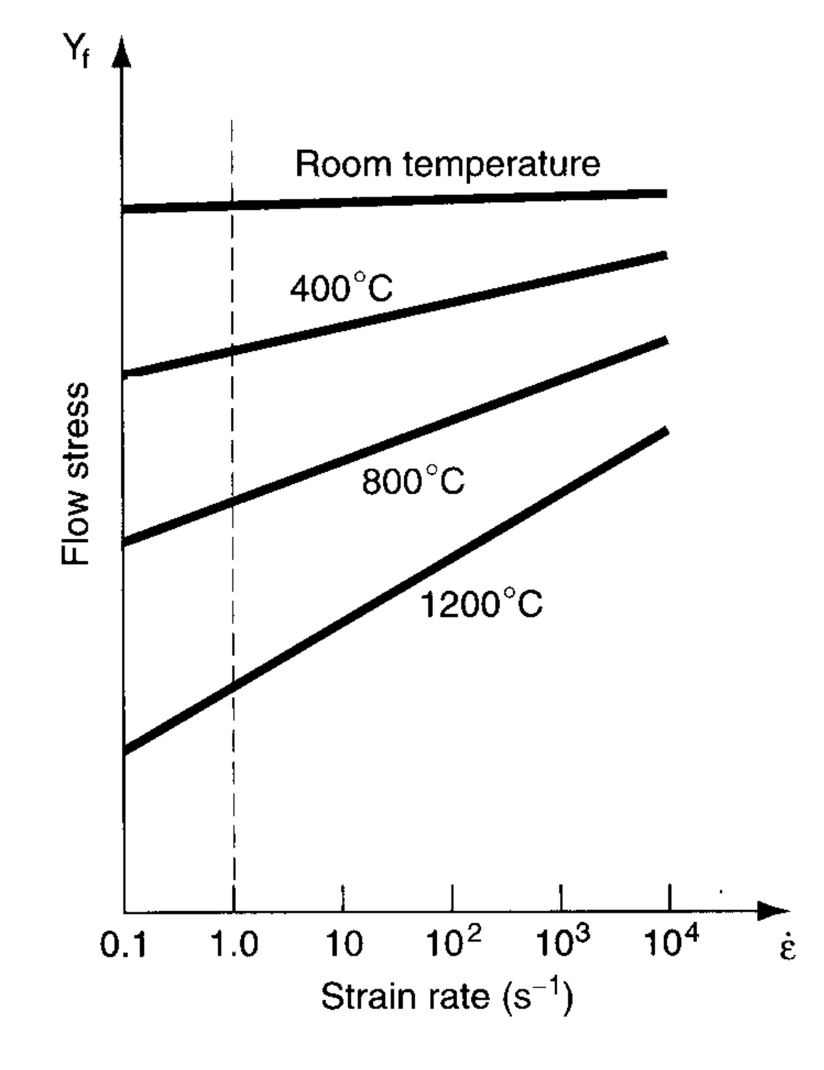
$$\bar{Y}_f = C\dot{\varepsilon}^m$$

$\dot{\varepsilon}$ strain rate

The strain rate is strongly affected by the temperature.

$$Y_f = A\varepsilon^n \dot{\varepsilon}^m$$

A = a strength coefficient



Observations about Strain Rate Sensitivity

- **Increasing temperature decreases *C*, increases *m***
  - **At room temperature, effect of strain rate is almost negligible**
    - **Flow curve 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 retarded**
  - **Forces and power are increased**
  - **Wears tooling faster**
- **Friction and tool wear are more severe in hot working**

Lubrication in Metal Forming

- **Metalworking 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**

Friction and Lubrication

- 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 workpiece-tool interface

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

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**