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

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

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

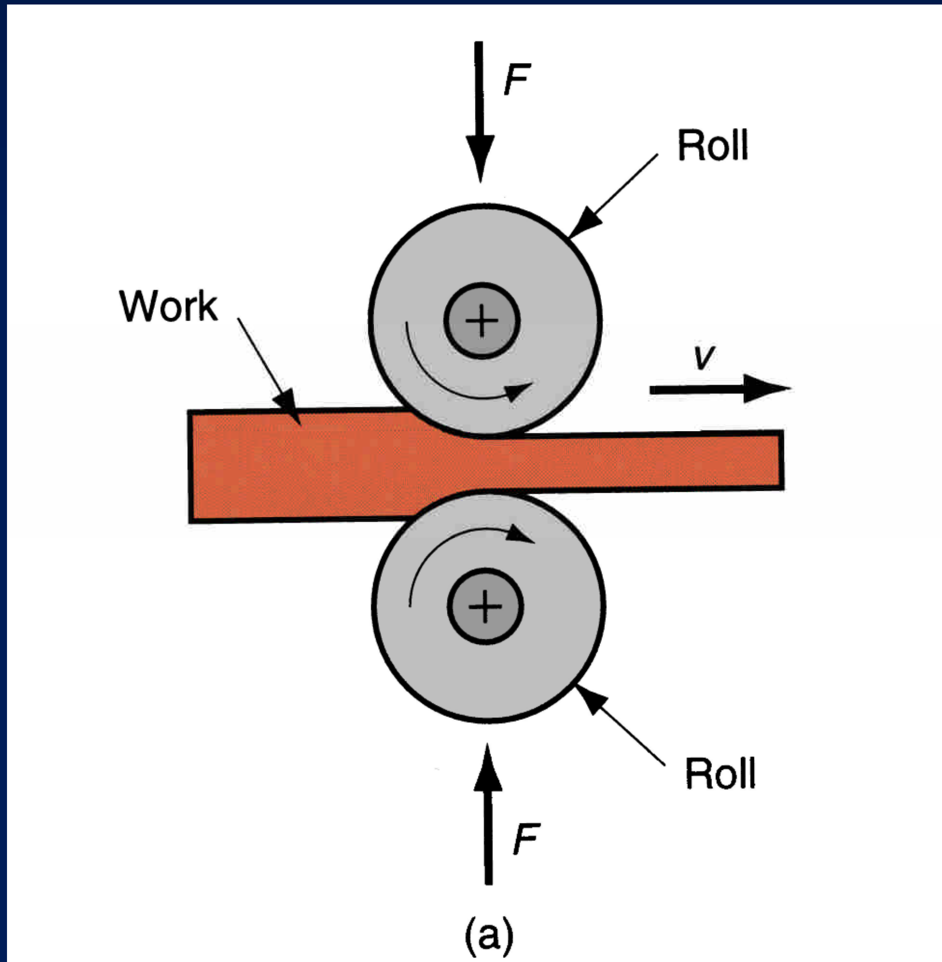

Figure 18.2 – Basic bulk deformation processes: (a) rolling

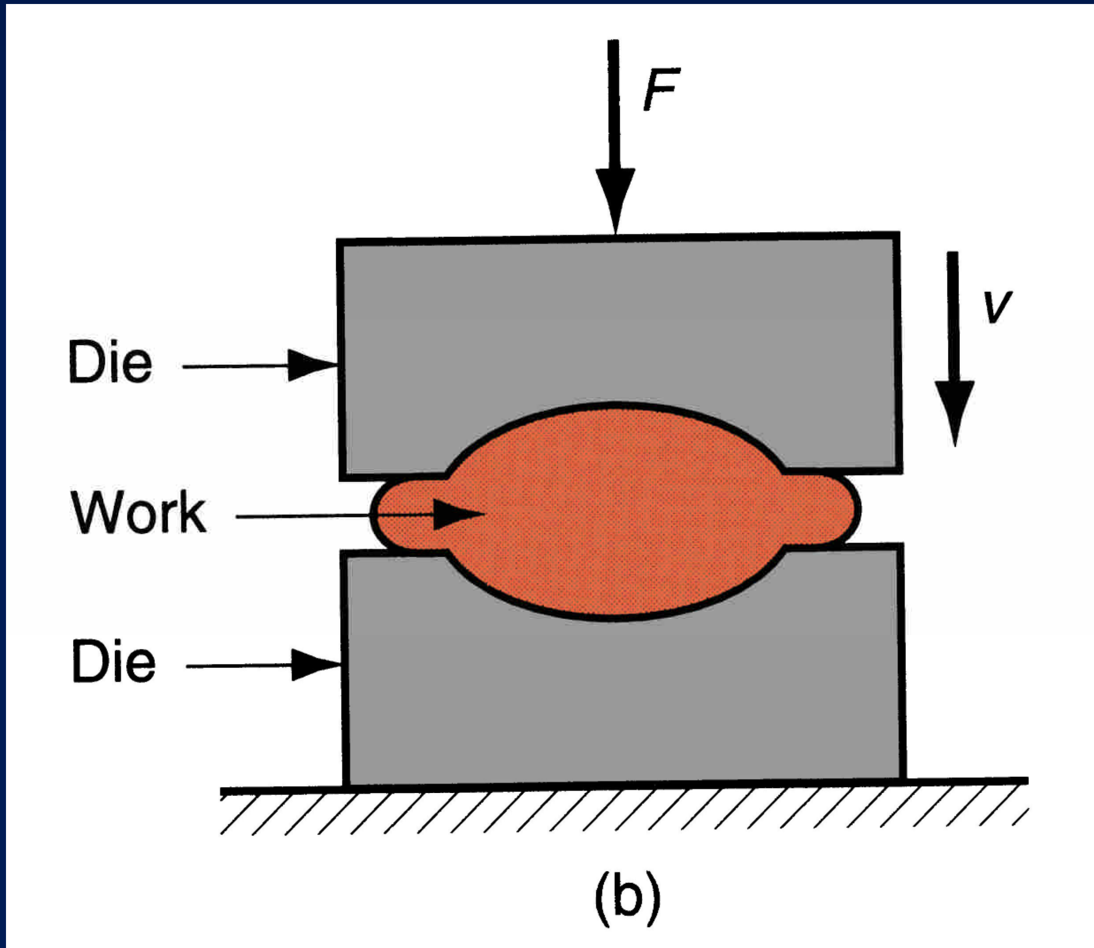

Figure 18.2 – Basic bulk deformation processes: (b) forging

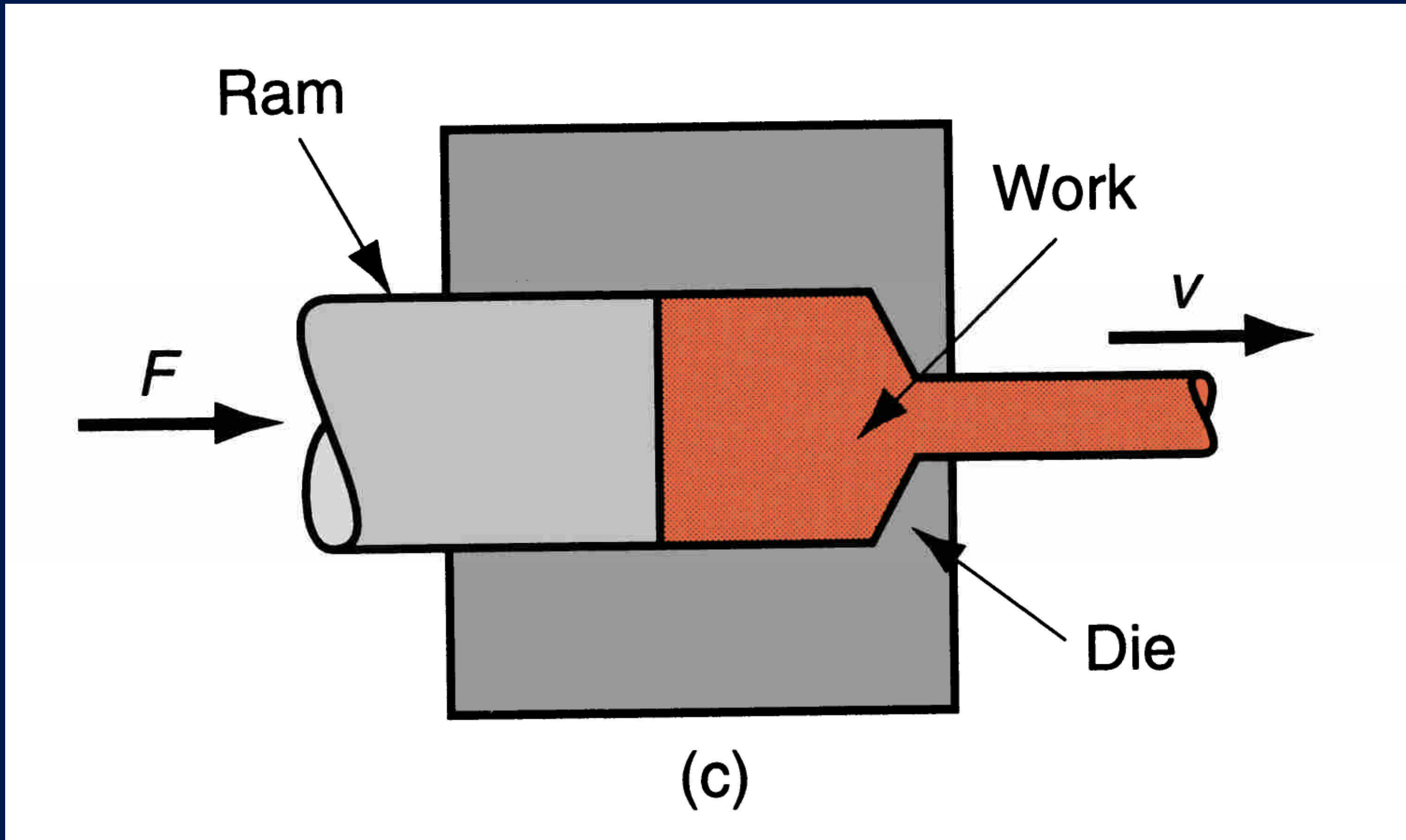

Figure 18.2 – Basic bulk deformation processes: (c) extrusion

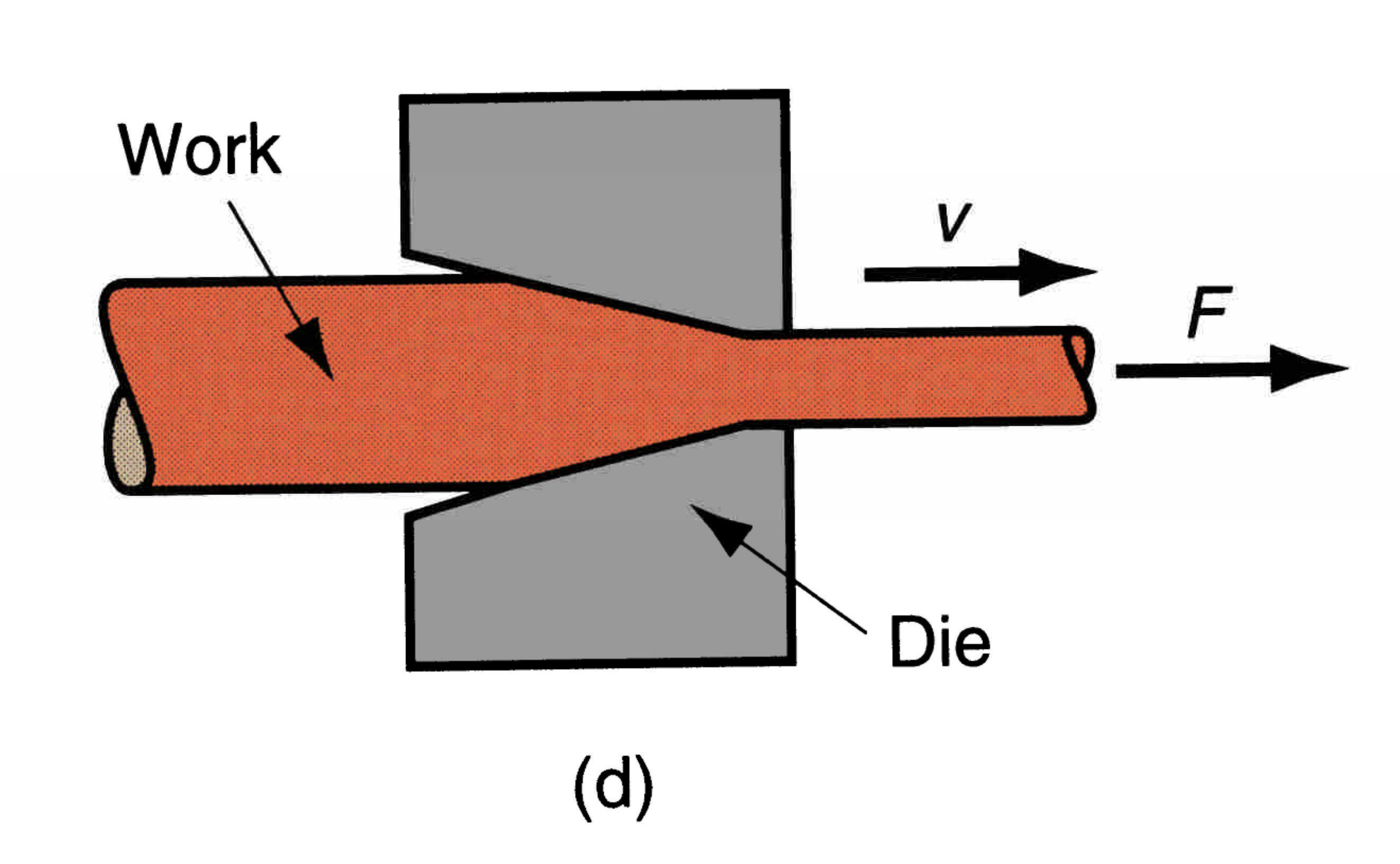

Figure 18.2 – Basic bulk deformation processes: (d) drawing

Sheet Metalworking

- 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*

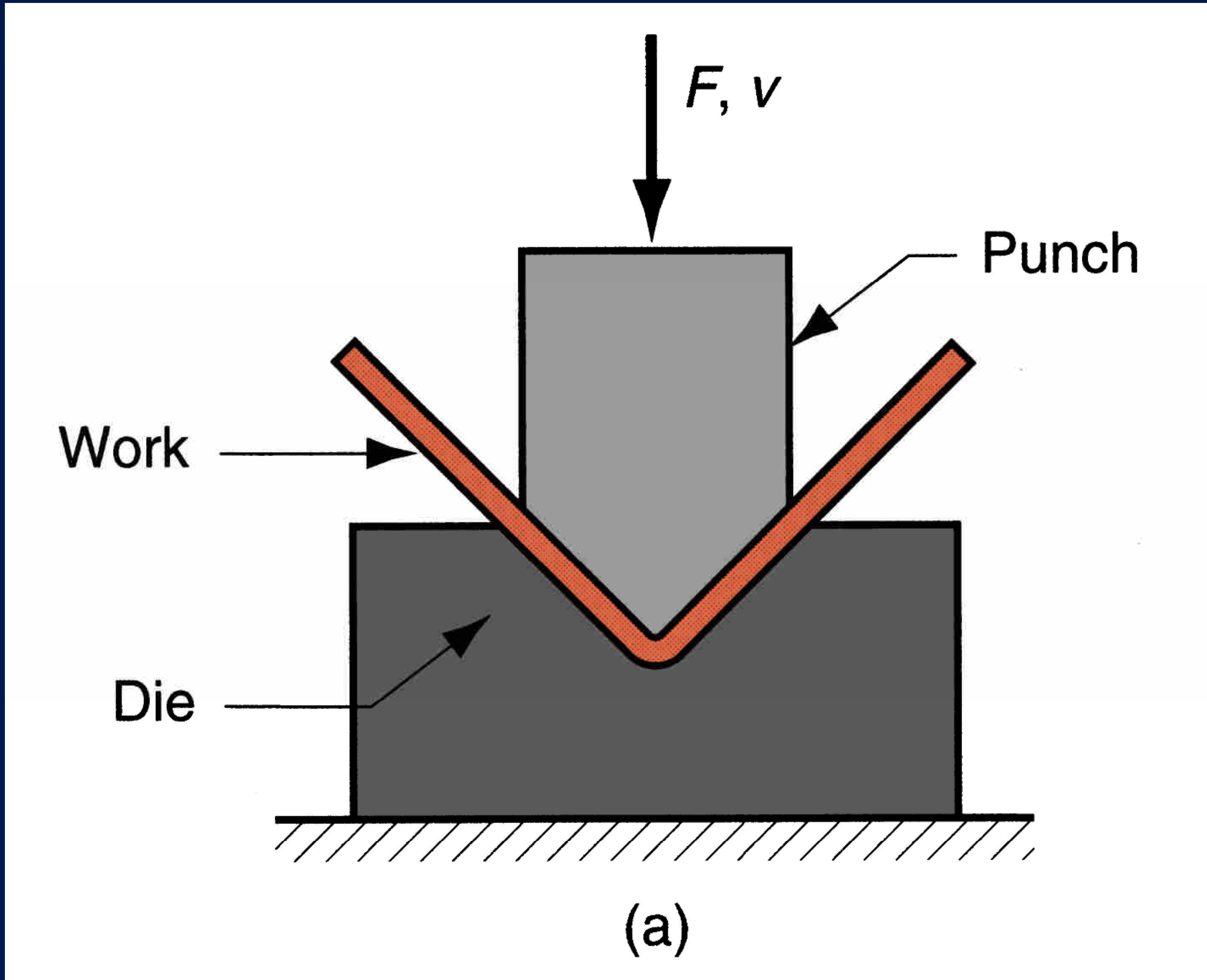

Figure 18.3 - Basic sheet metalworking operations: (a) bending

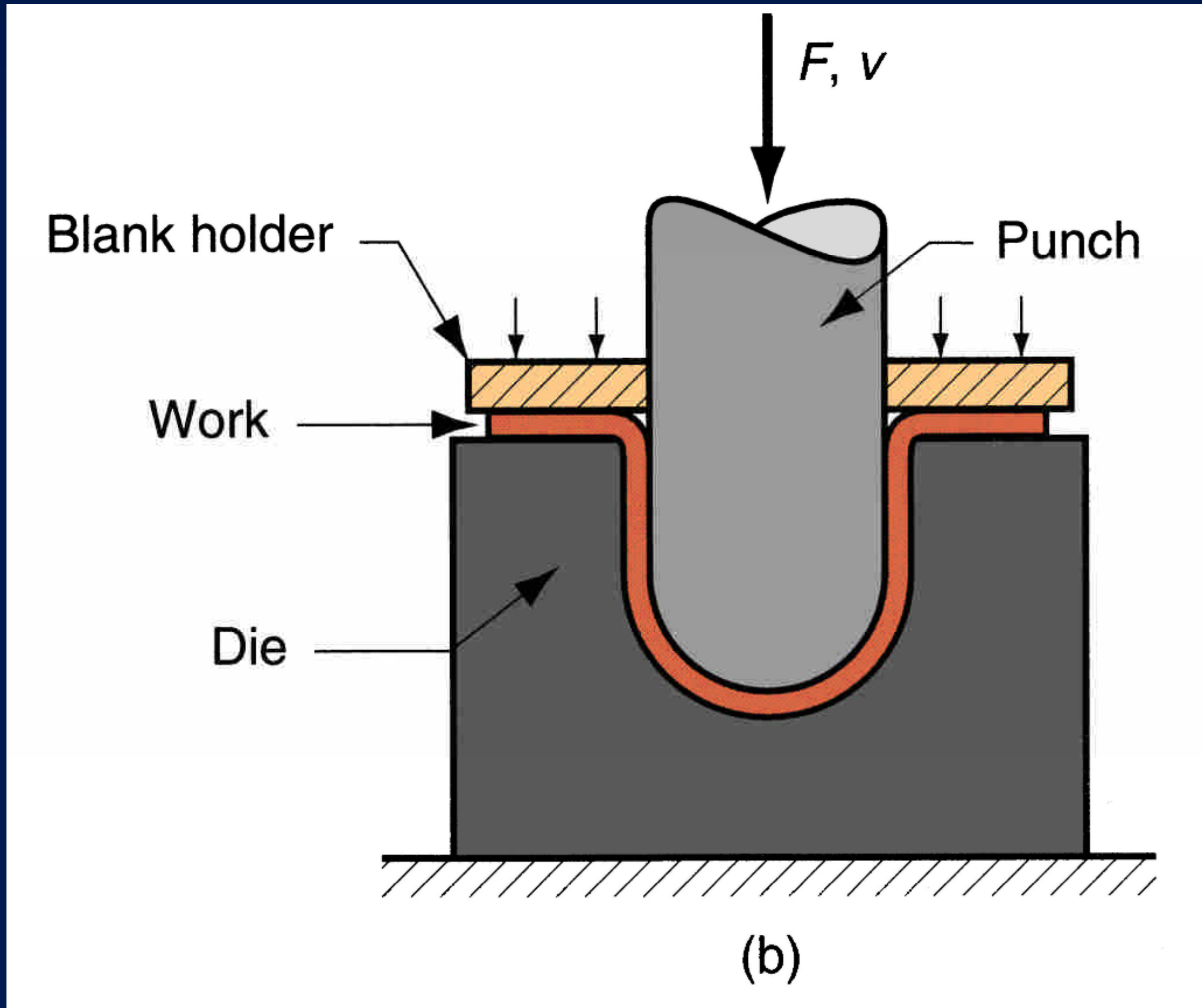

Figure 18.3 - Basic sheet metalworking operations: (b) drawing

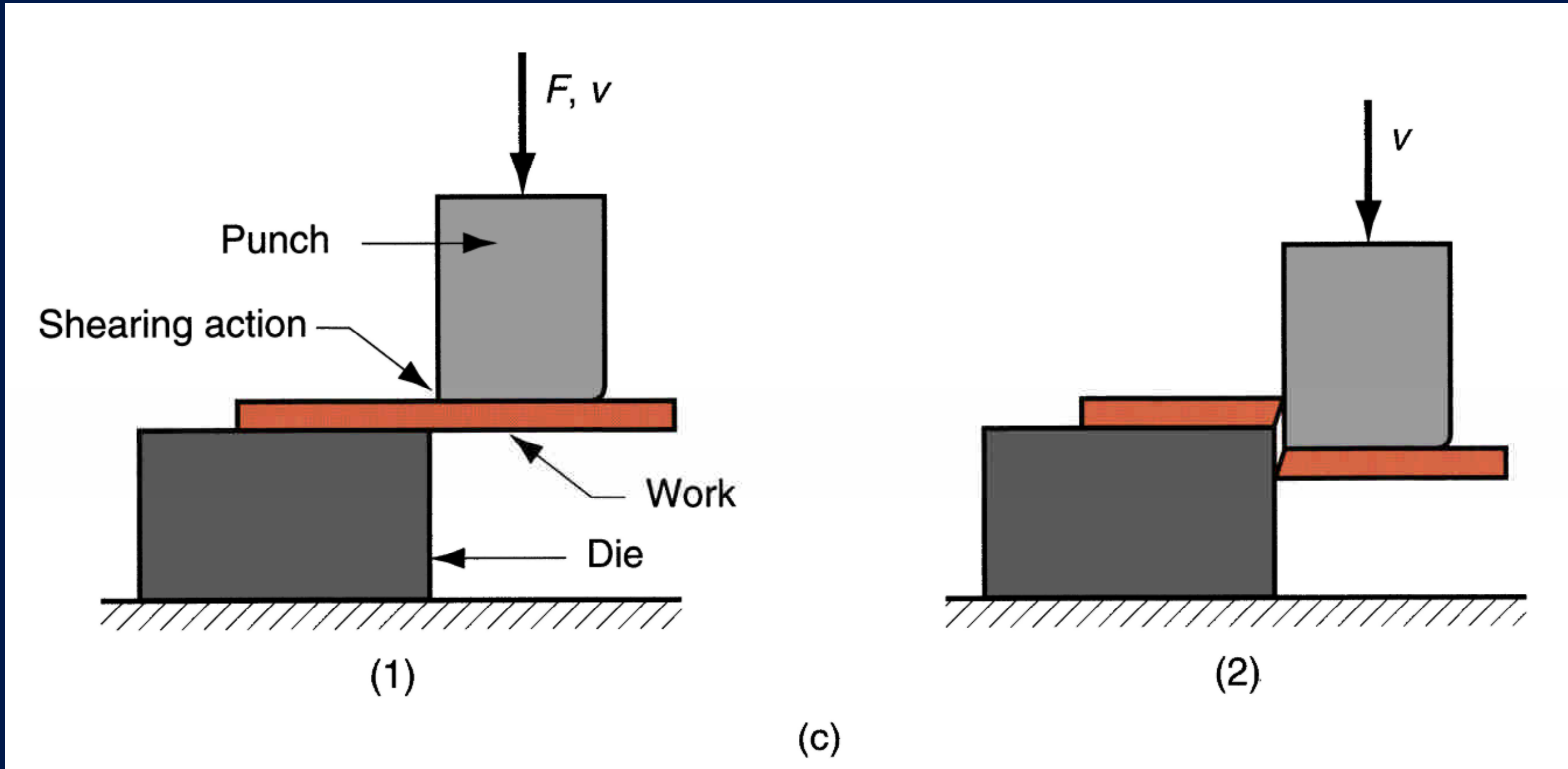

Figure 18.3 - Basic sheet metalworking operations: (c) shearing

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

- 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

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 vs. 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*

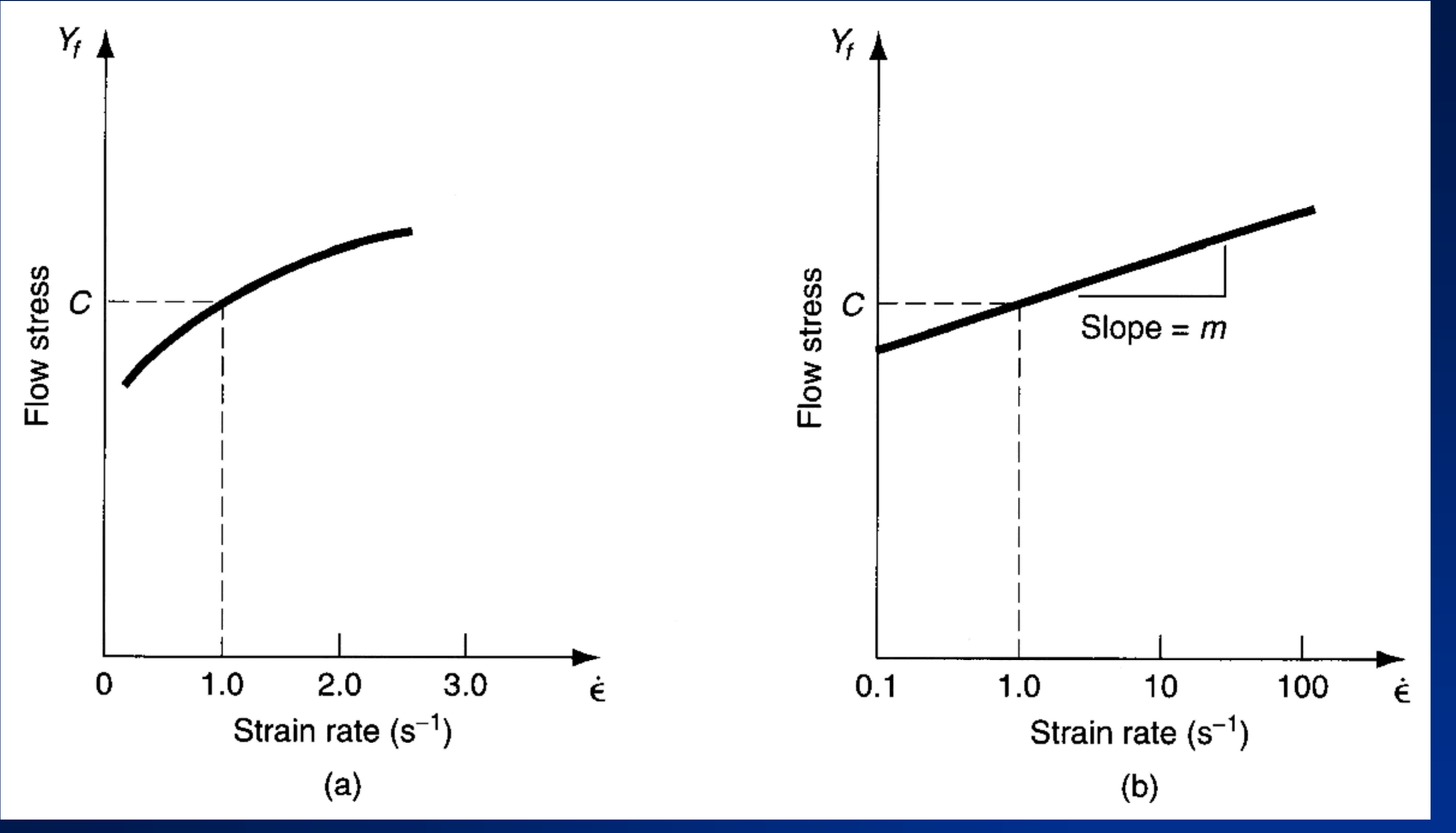

Figure 18.5 - (a) Effect of strain rate on flow stress at an elevated work temperature. (b) Same relationship plotted on log-log coordinates

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

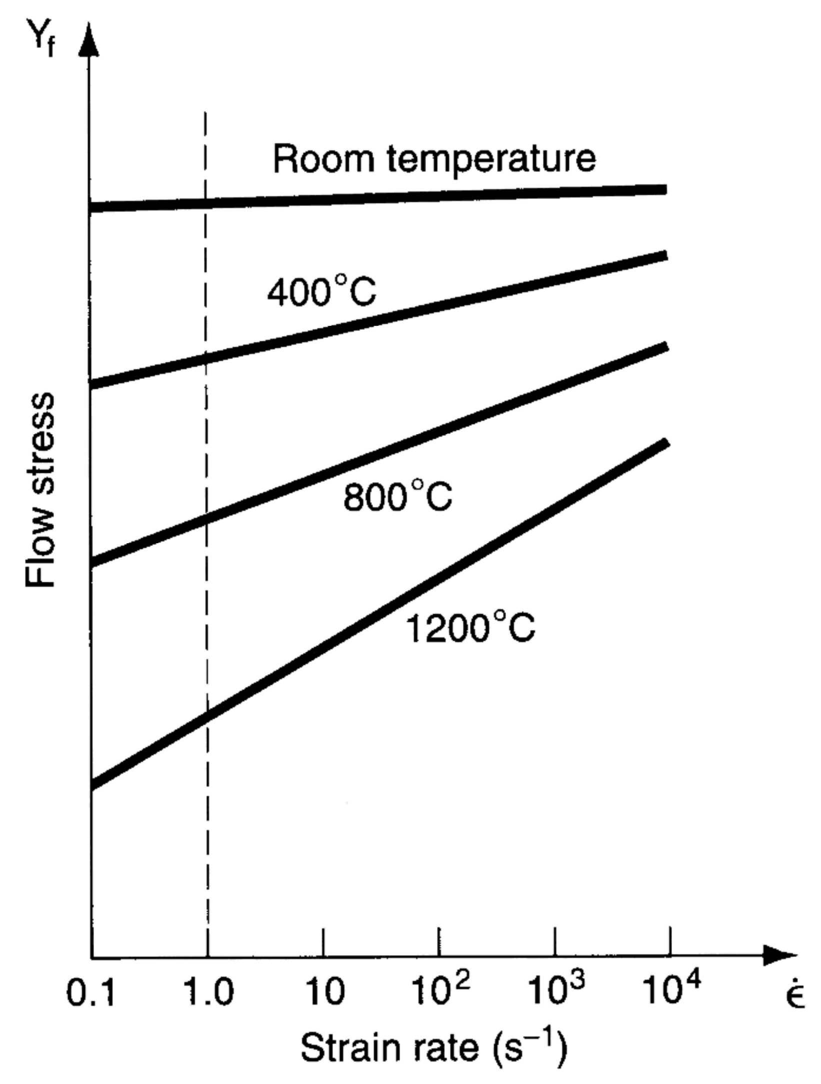

Figure 18.6 - Effect of temperature on flow stress for a typical metal. The constant *C* in Eq. (18.4), indicated by the intersection of each plot with the vertical dashed line at strain rate = 1.0, decreases, and *m* (slope of each plot) increases with increasing temperature

Observations about Strain Rate Sensitivity

- Increasing temperature decreases *C,* 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

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