ME2300: Manufacturing Processes
Jan-May 2020

Forging

Part deformation by pressing between the dies

-Dies are hard metal shapes

Temperature

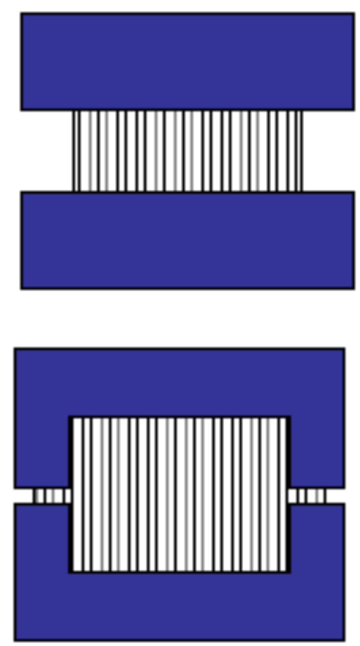
-Hot

-Cold

Processes

-Open-die forging

-Closed-die forging



Open-die forging/Upsetting

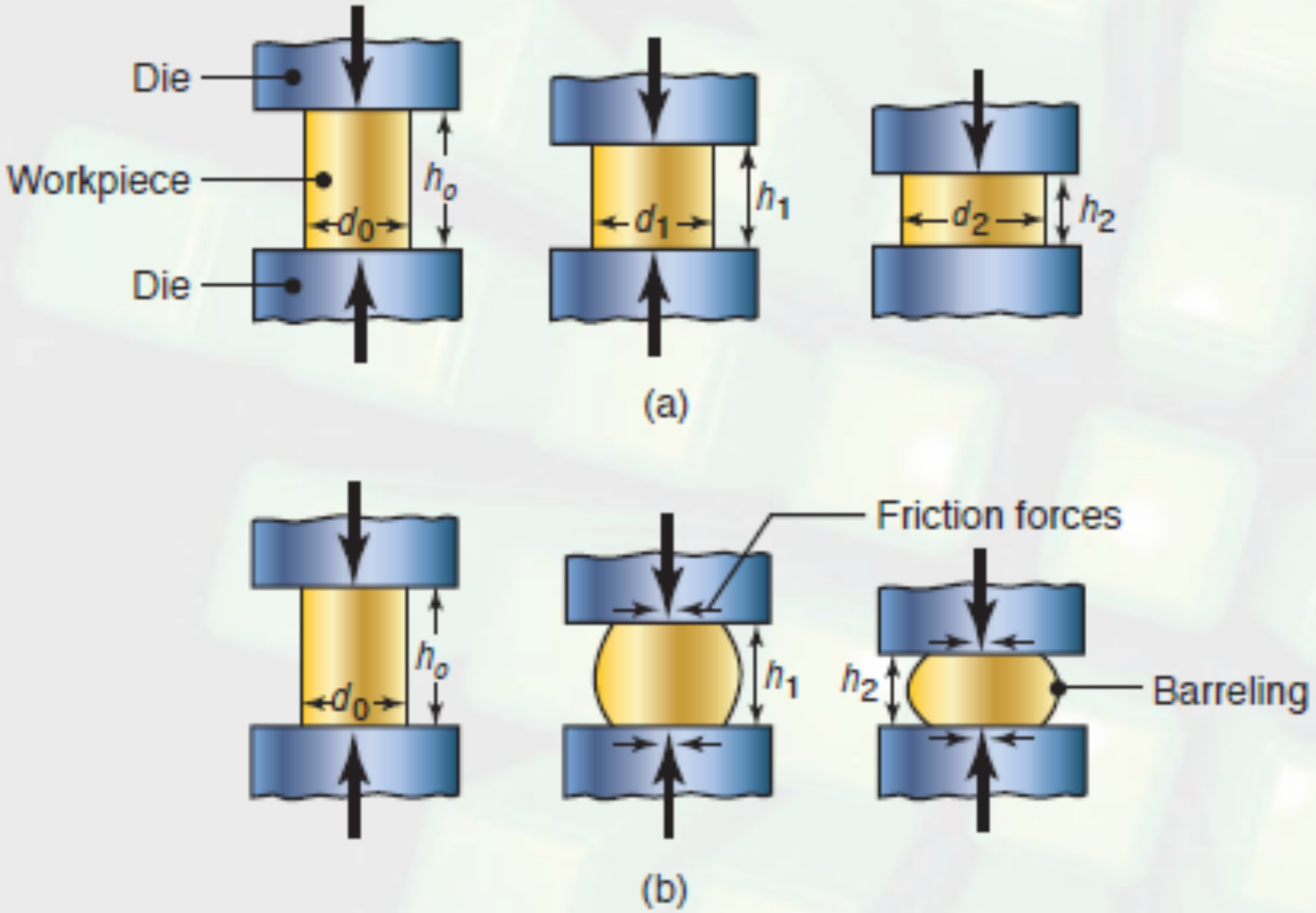
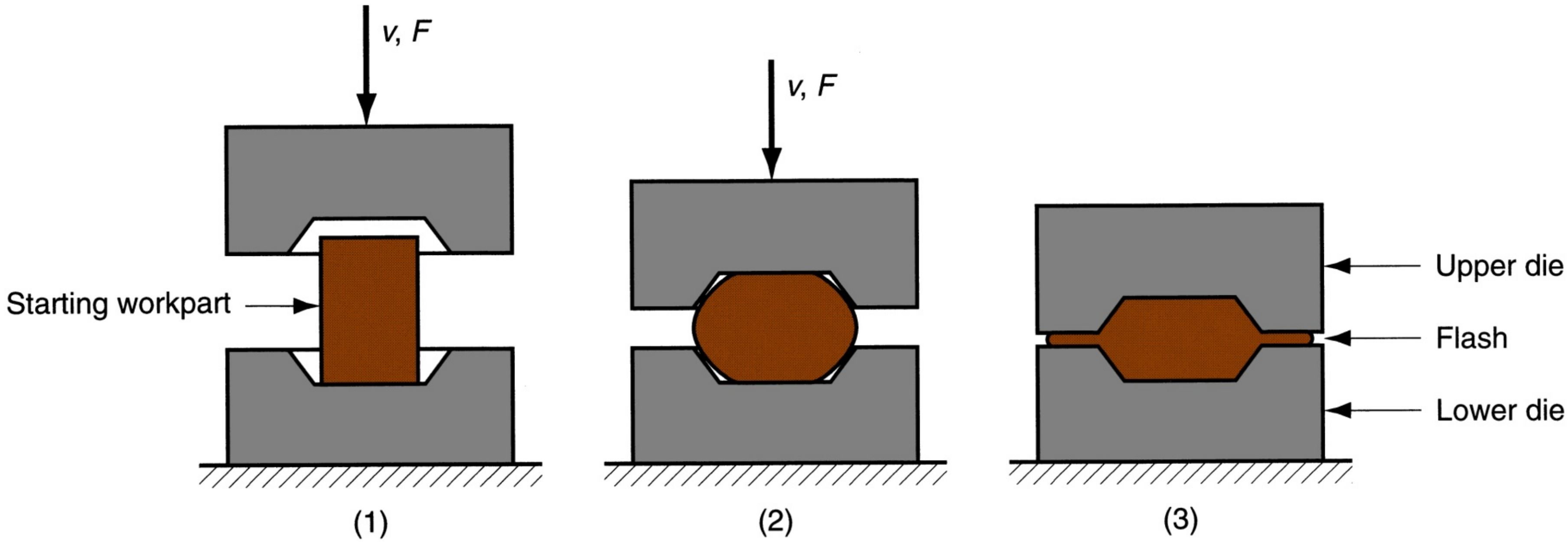


FIGURE 6.1 (a) Ideal deformation of a solid cylindrical specimen compressed between flat frictionless dies (platens), an operation known as upsetting. (b) Deformation in upsetting with friction at the die-workpiece interfaces. Note barrelling of the billet caused by friction.

Closed-die/Impression-die forging



Sequence in impression-die forging:

(1) just prior to initial contact with raw workpiece,

(2) partial compression, and

(3) final die closure, causing flash to form in gap between die plates

Grain flow

FIGURE 6.2 Grain flow lines in upsetting a solid, steel cylindrical specimen at elevated temperatures between two flat cool dies. Note the highly inhomogeneous deformation and barreling, and the difference in shape of the bottom and top sections of the specimen. The latter results from the hot specimen resting on the lower die before deformation proceeds. The lower portion of the specimen began to cool, thus exhibiting higher strength and hence deforming less than the top surface. *Source:* After J.A. Schey.

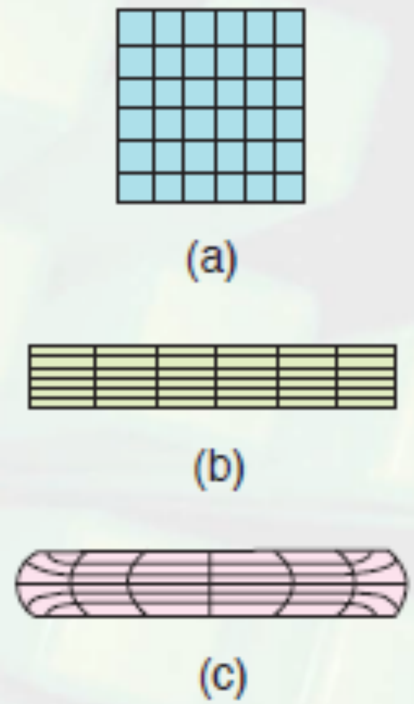
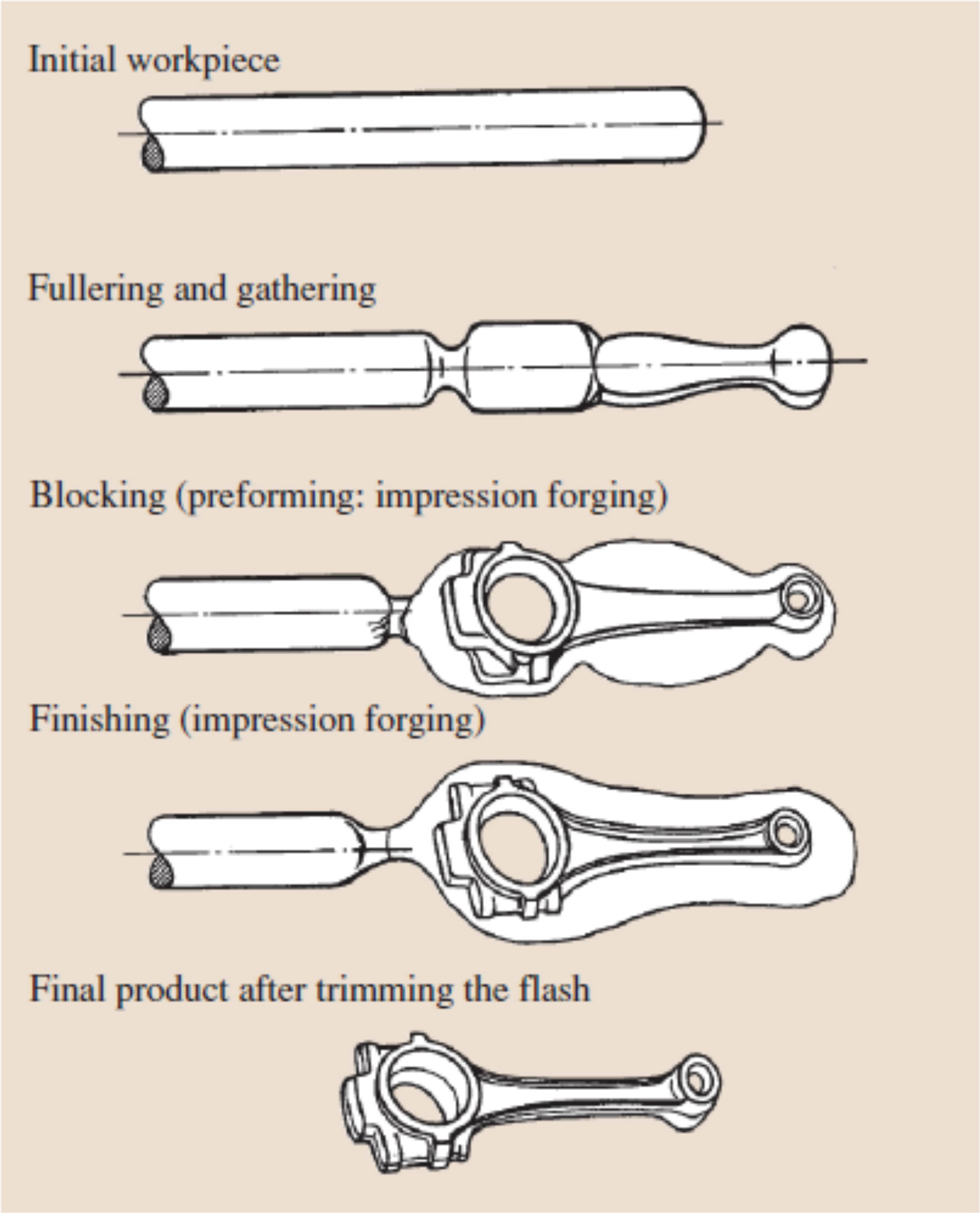


FIGURE 6.3 Schematic illustration of grid deformation in upsetting: (a) original grid pattern; (b) after deformation, without friction; (c) after deformation, with friction. Such deformation patterns can be used to calculate the strains within a deforming body.

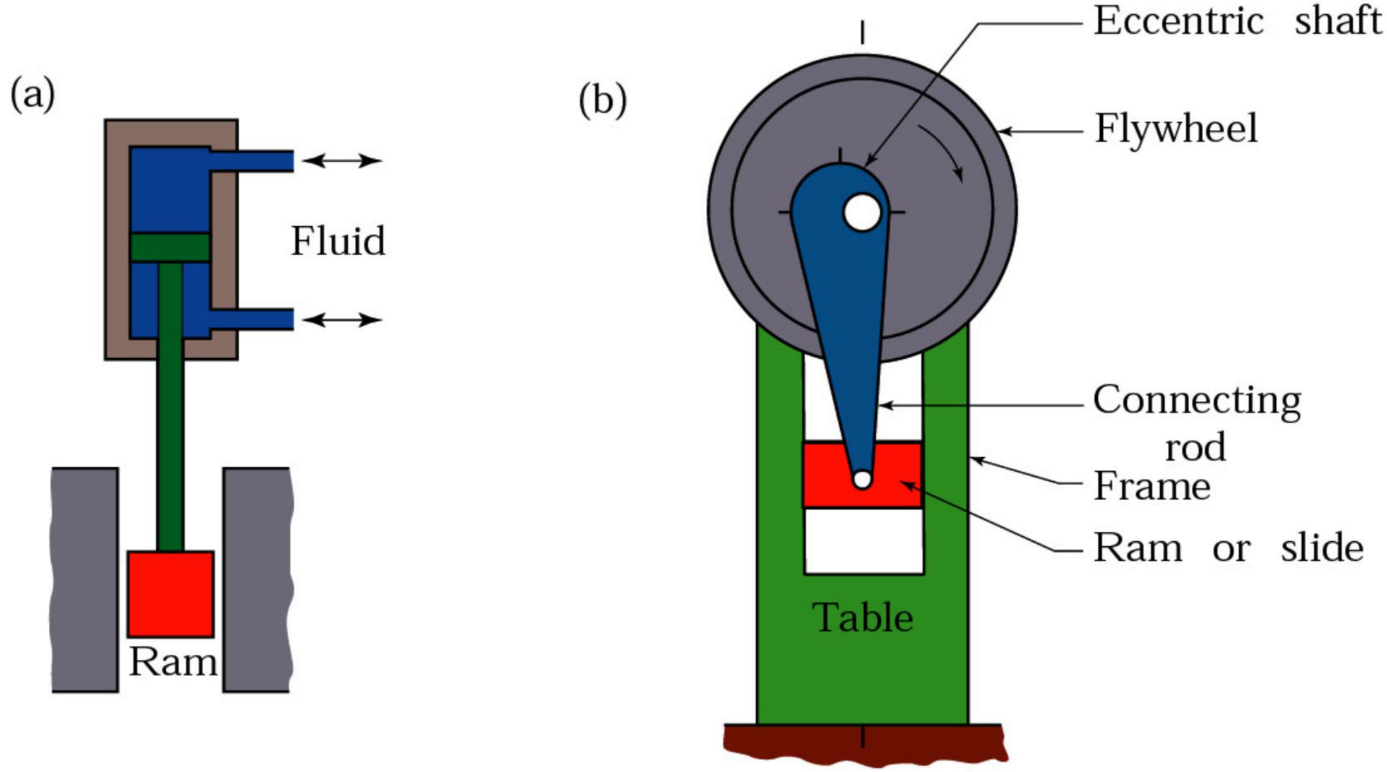
Applications

- Coins
- Gears
- Crank shaft
- Connecting rod
- Turbine shaft

Forging a connecting rod

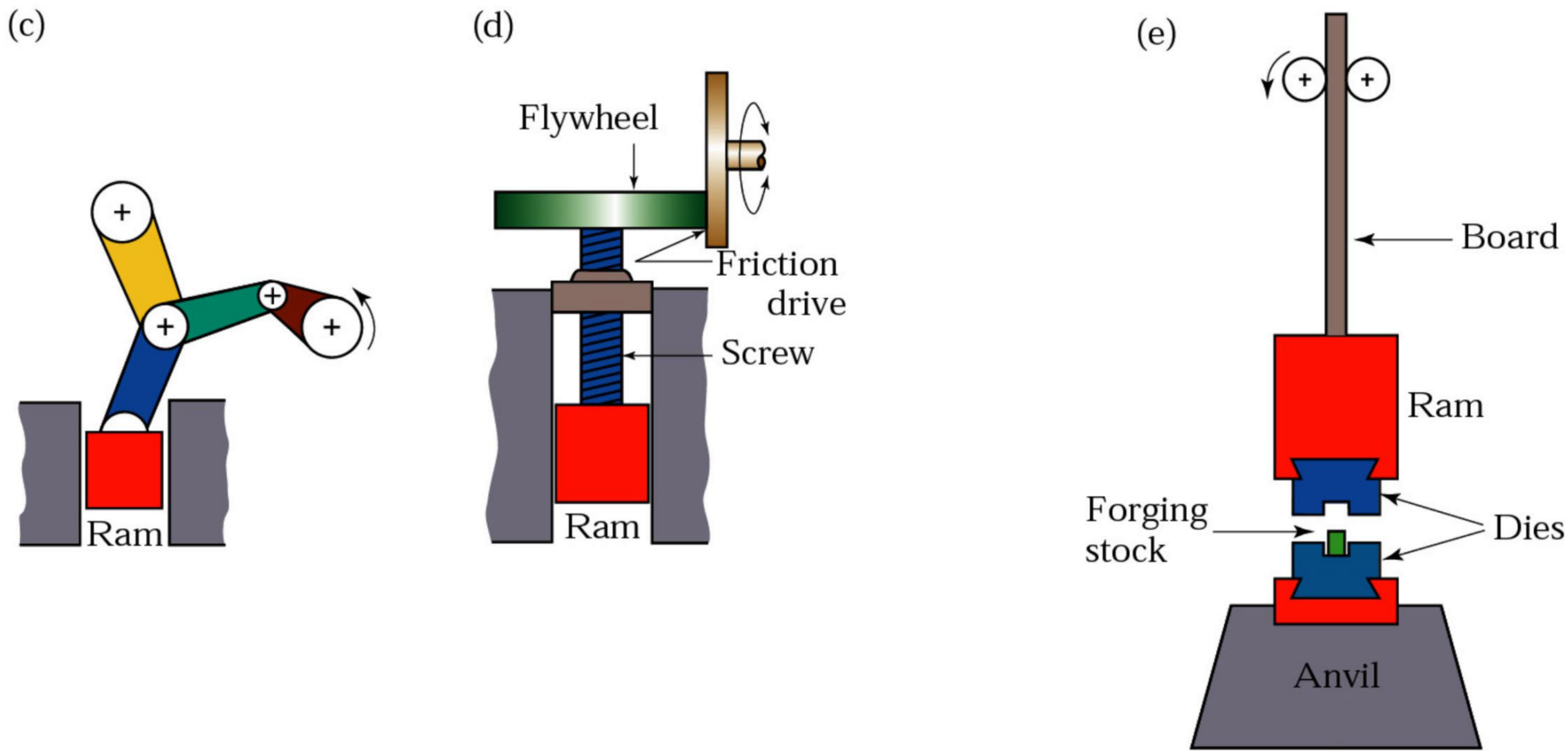


Principles of various forging machines



Schematic illustration of the principles of various forging machines. (a) Hydraulic press. (b) Mechanical press with an eccentric drive; the eccentric shaft can be replaced by a crankshaft to give the up-and-down motion to the ram. (continued)

Principles of various forging machines



(continued) Schematic illustration of the principles of various forging machines. (c) Knuckle-joint press. (d) Screw press. (e) Gravity drop hammer.

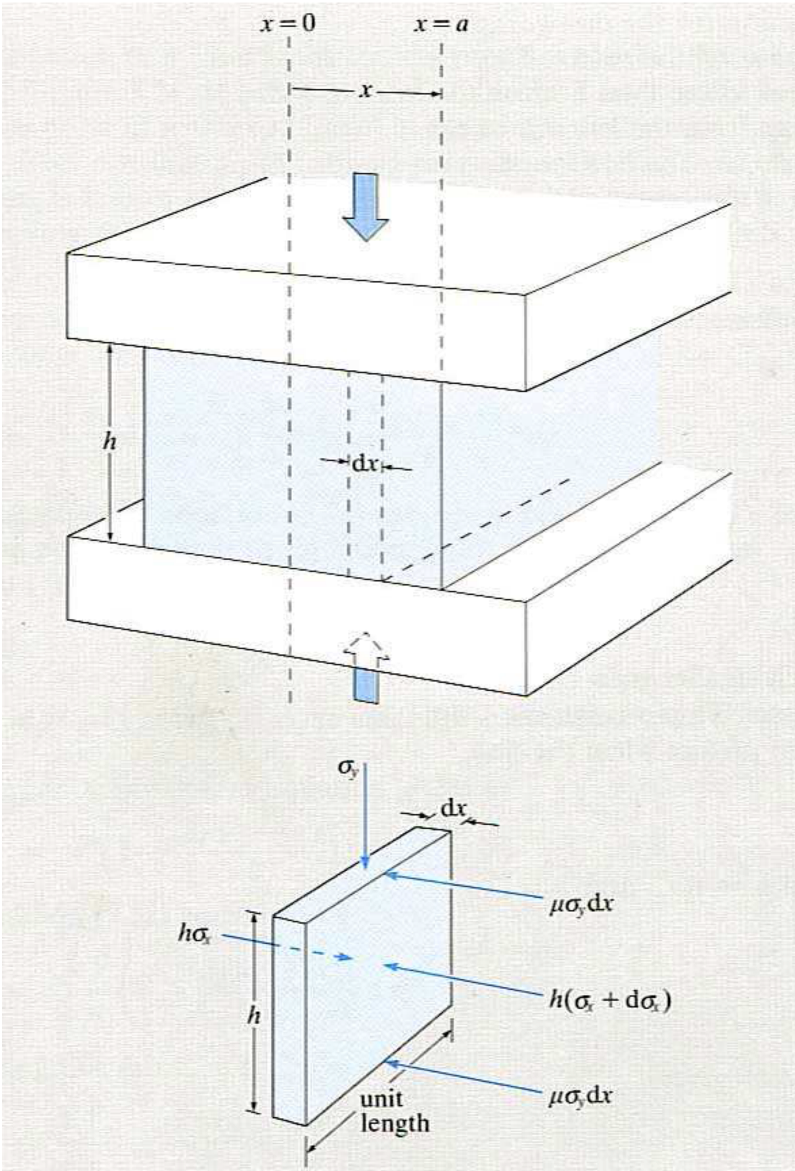
Forging temperature

Metal	°C	°F
Aluminum alloys	400-450	750-850
Copper alloys	625-950	1150-1750
Nickel alloys	870-1230	1600-2250
Alloy steels	925-1260	1700-2300
Titanium alloys	750-795	1400-1800
Refractory alloys	975-1650	1800-3000

Forging analysis (assumptions)

- Entire forging is plastic
- Material is perfectly plastic
- Friction coefficient (μ) is constant
- In any thin slab, stresses are uniform

Forging analysis (rectangular slab)



$$h(\sigma_x + d\sigma_x) + 2\mu\sigma_y dx = h\sigma_x \quad (1)$$

$$2\mu\sigma_y dx = -h d\sigma_x \quad (2)$$

$$\frac{d\sigma_x}{\sigma_y} = -\frac{2\mu}{h} dx \quad (3)$$

Forging analysis (rectangular slab)

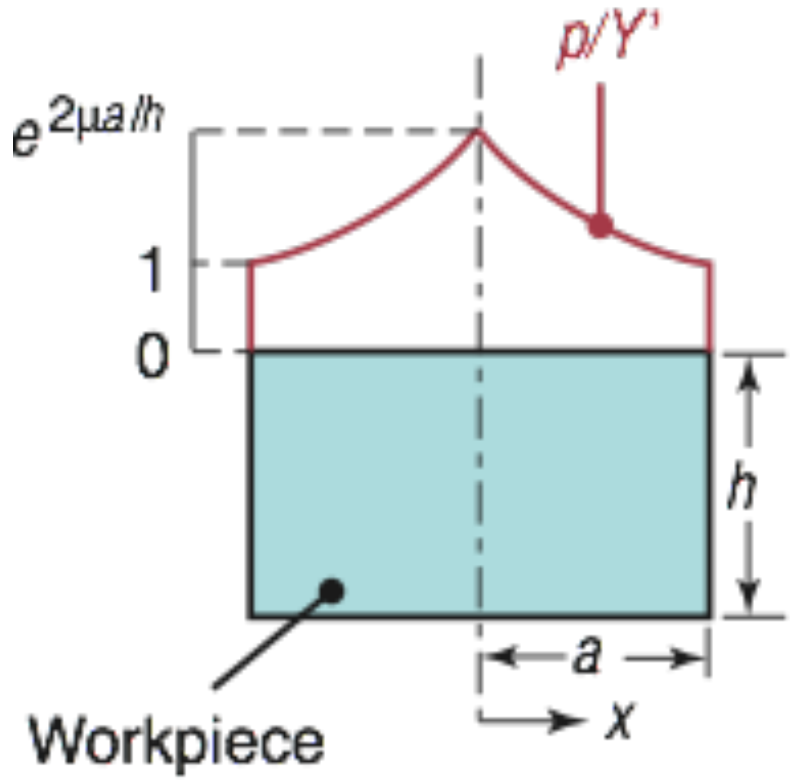
Yield criterion during deformation

$$\sigma_y - \sigma_x = \frac{2}{\sqrt{3}}\sigma_o = \sigma_o'$$

$$d\sigma_y = d\sigma_x$$

$$\frac{d\sigma_y}{\sigma_y} = -\frac{2\mu}{h}dx \quad \Rightarrow \quad \sigma_y = C\exp\left(-\frac{2\mu x}{h}\right)$$

Die Pressure



Distribution of die pressure, in dimensionless form of *p*/*Y'*, in plane-strain compression with sliding friction. Note that the pressure at the left and right boundaries is equal to the yield stress of the material in plane strain, *Y'*. Sliding friction means that the frictional stress is directly proportional to the normal stress.

Flow Stress and Work of Deformation

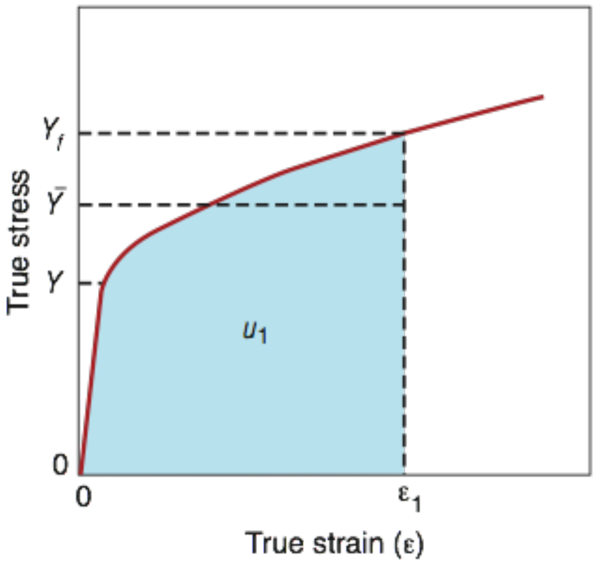


FIGURE Schematic illustration of true stress-true strain curve showing yield stress *Y*, average flow stress, specific energy u_1 and flow stress Y_f.

Flow stress:

$$\bar{Y} = \frac{K\varepsilon_1^n}{n+1}$$

Specific energy

$$u = \int_0^{\varepsilon} \bar{\sigma}\, d\bar{\varepsilon}$$

Ideal & Redundant Work

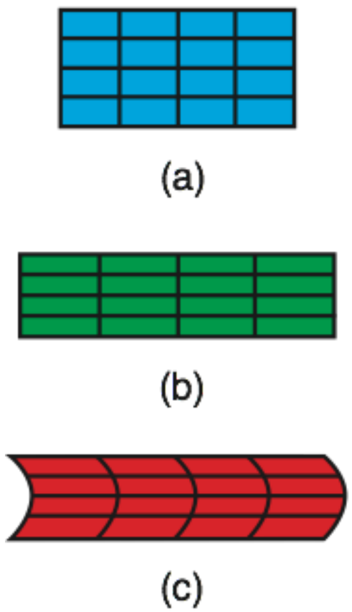


FIGURE 2.38 Deformation of grid patterns in a workpiece: (a) original pattern; (b) after ideal deformation; (c) after inhomogeneous deformation, requiring redundant work of deformation. Note that (c) is basically (b) with additional shearing, especially at the outer layers. Thus (c) requires greater work of deformation than (b). See also Figs. 6.3 and 6.49.

Total specific energy:

$$u_{total} = u_{ideal} + u_{friction} + u_{redundant}$$

Efficiency:

$$\eta = \frac{u_{ideal}}{u_{total}}$$

Average pressure and forging force (slab)

$$\bar{p} = \sigma_0'(1 + \frac{\mu a}{h})$$

Force = (Average pressure)*(2a)*(width)

h is instantaneous height

Cylindrical workpiece

$$\bar{p} = \sigma_0'(1 + \frac{2\mu r}{3h})$$

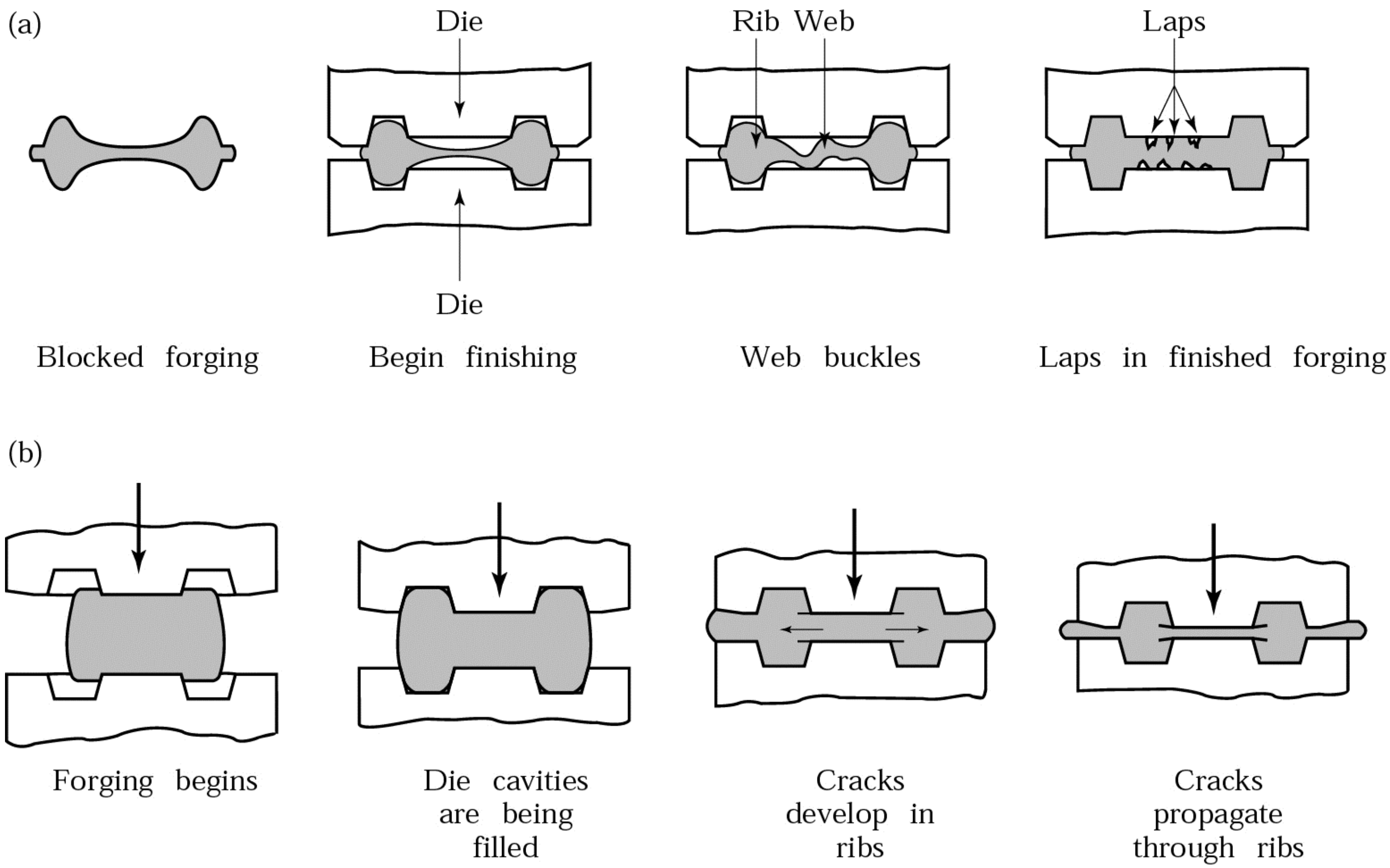
Force = (Average pressure)* πr^2

Example

Q: A cylindrical specimen made of steel has a diameter of 200 mm and is 125 mm high. It is forged at room temperature, by open die forging with flat dies to a height of 50 mm. Assuming that the coefficient of friction is 0.2, calculate the forging force required at the end of the stroke.
Strength constant, K = 760 MPa
Strain hardening exponent, n = 0.19

Answer: 8.32*10^7 N

Forging defects



Examples of defects in forged parts. (a) Laps formed by web buckling during forging; web thickness should be increased to avoid this problem. (b) Internal defects caused by oversized billet; die cavities are filled prematurely, and the material at the centre flows past the filled regions as the dies close.

Extrusion

Compression forming process in which the work metal is forced to flow through a die opening to produce a desired cross-sectional shape

- Process is similar to squeezing toothpaste out of a toothpaste tube
- In general, extrusion is used to produce long parts of uniform cross-sections
- Two basic types of extrusion:
  - Direct extrusion
  - Indirect extrusion

Extruded products

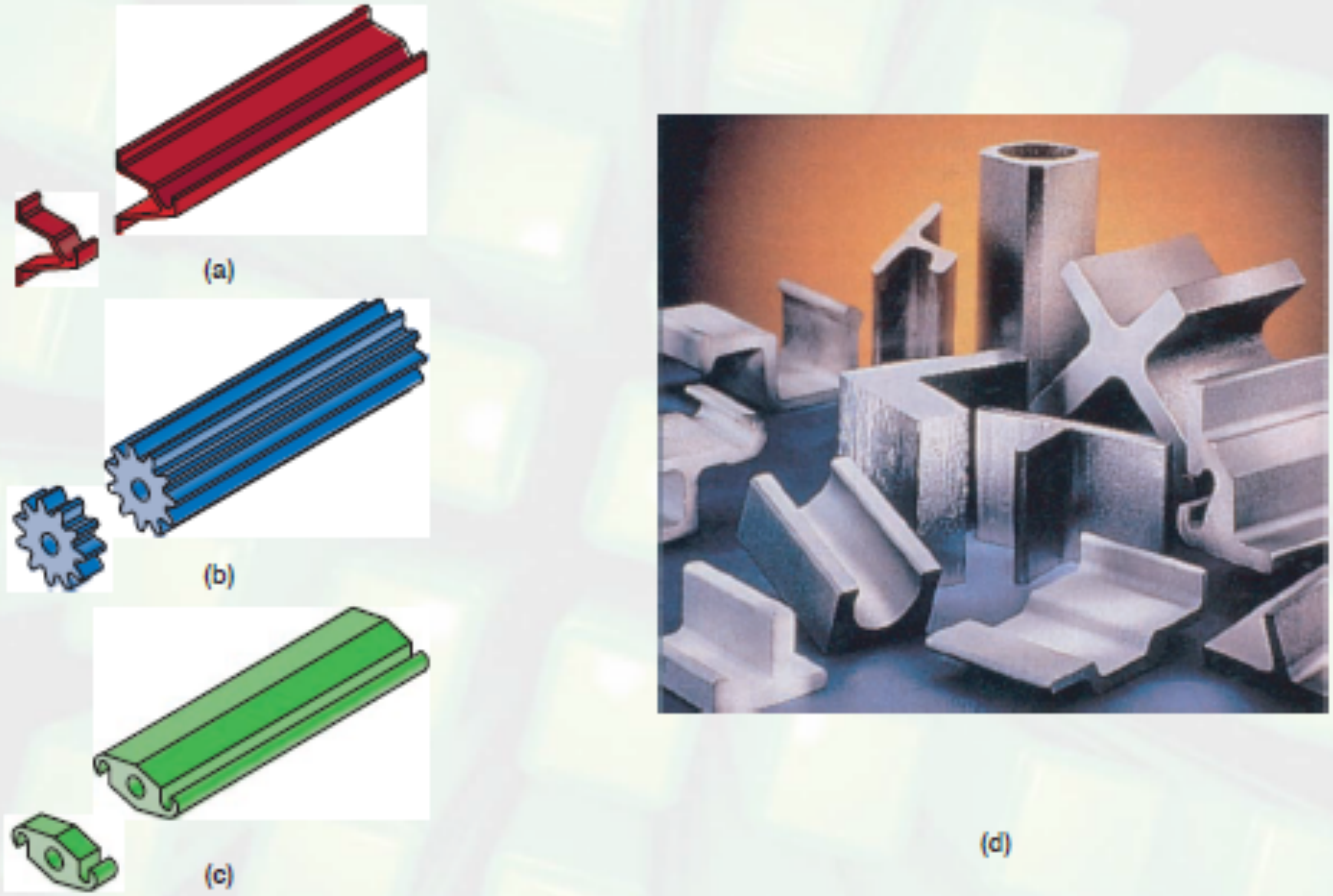
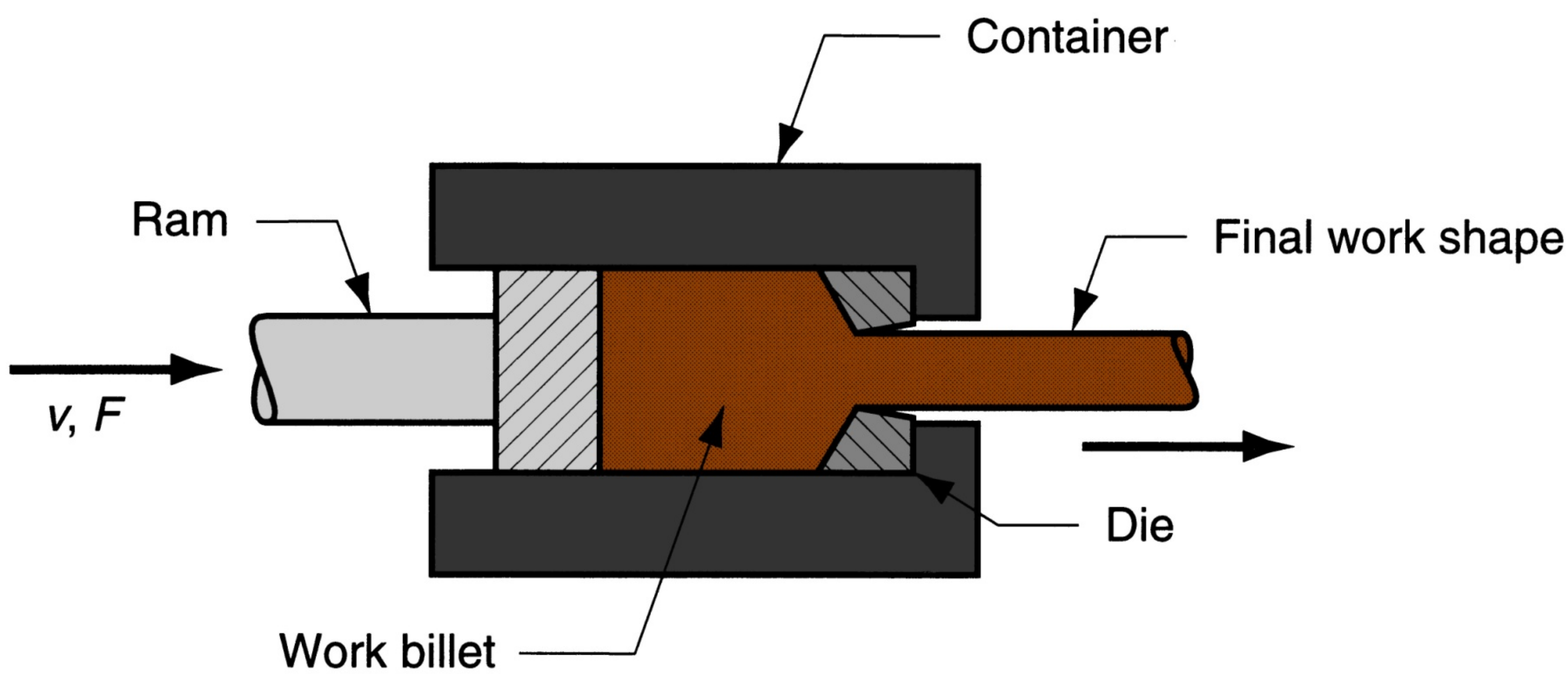


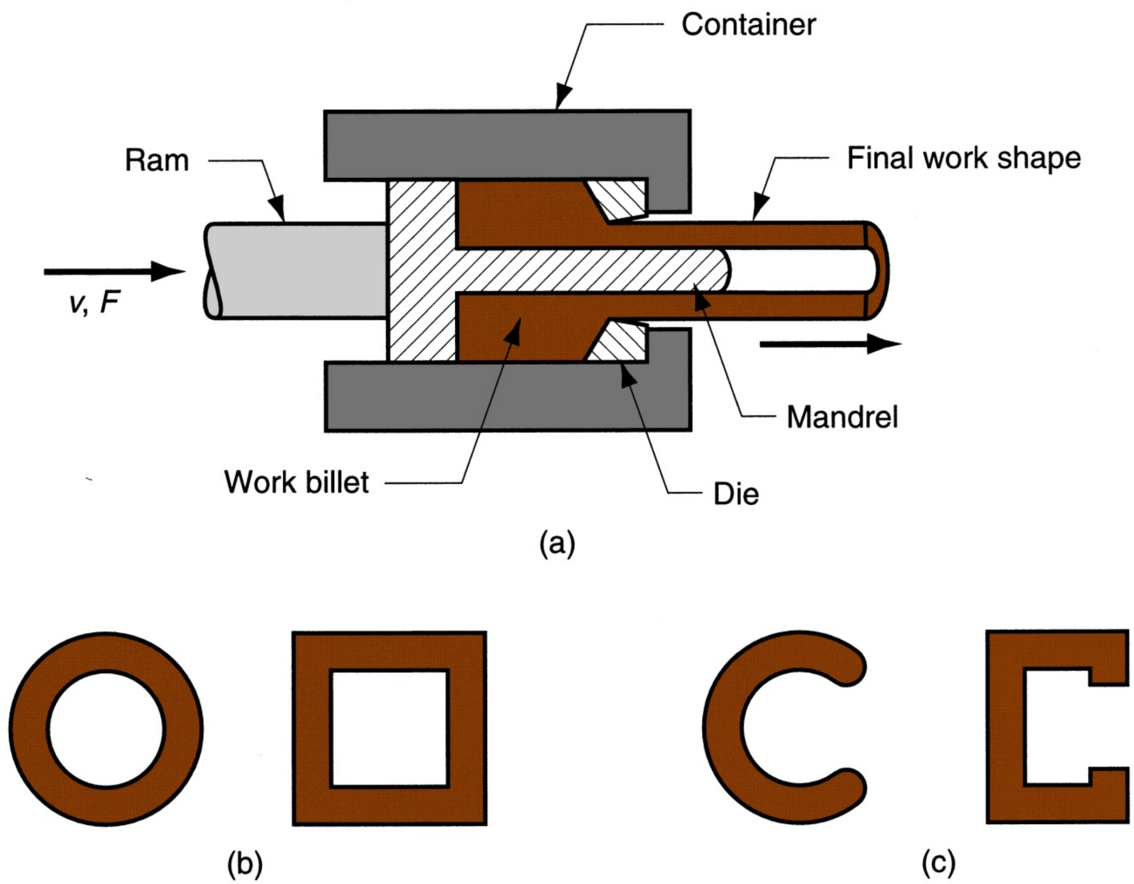
FIGURE 6.48 (a)-(c) Examples of extrusions and products made by sectioning them. *Source:* Kaiser Aluminum. (d) Examples of extruded cross-sections. *Source:* (d) Courtesy of Plymouth Extruded Shapes.

Direct extrusion



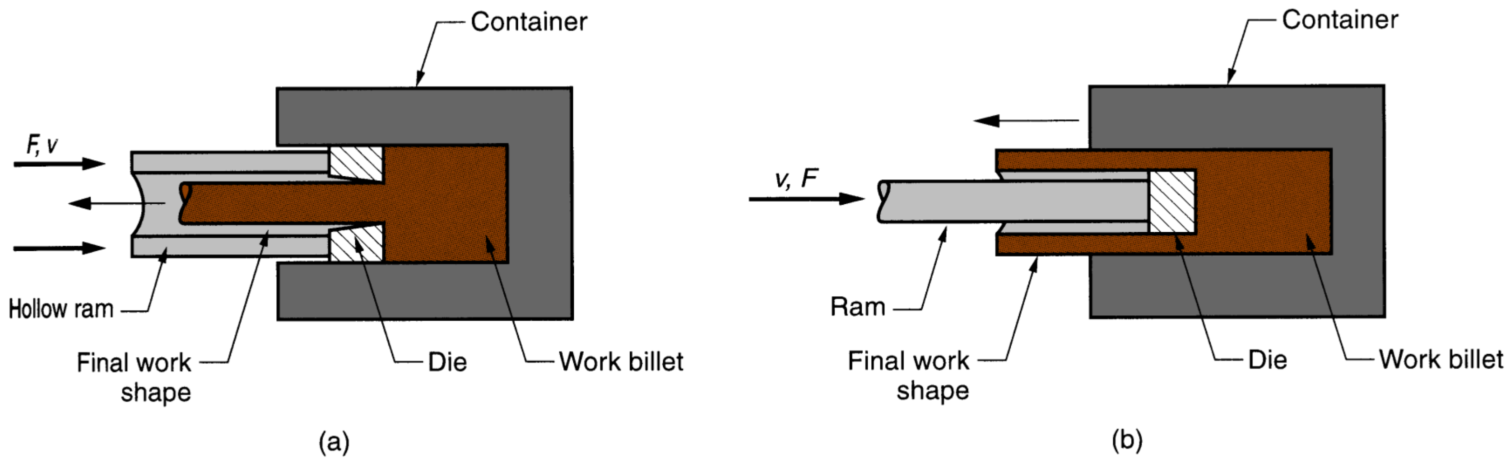
Direct extrusion

Direct extrusion



(a) Direct extrusion to produce a hollow or semi-hollow cross-section; (b) hollow and (c) semi-hollow cross- sections

Indirect extrusion



Indirect extrusion to produce

(a) a solid cross-section and (b) a hollow cross-section

Extrusion ratio

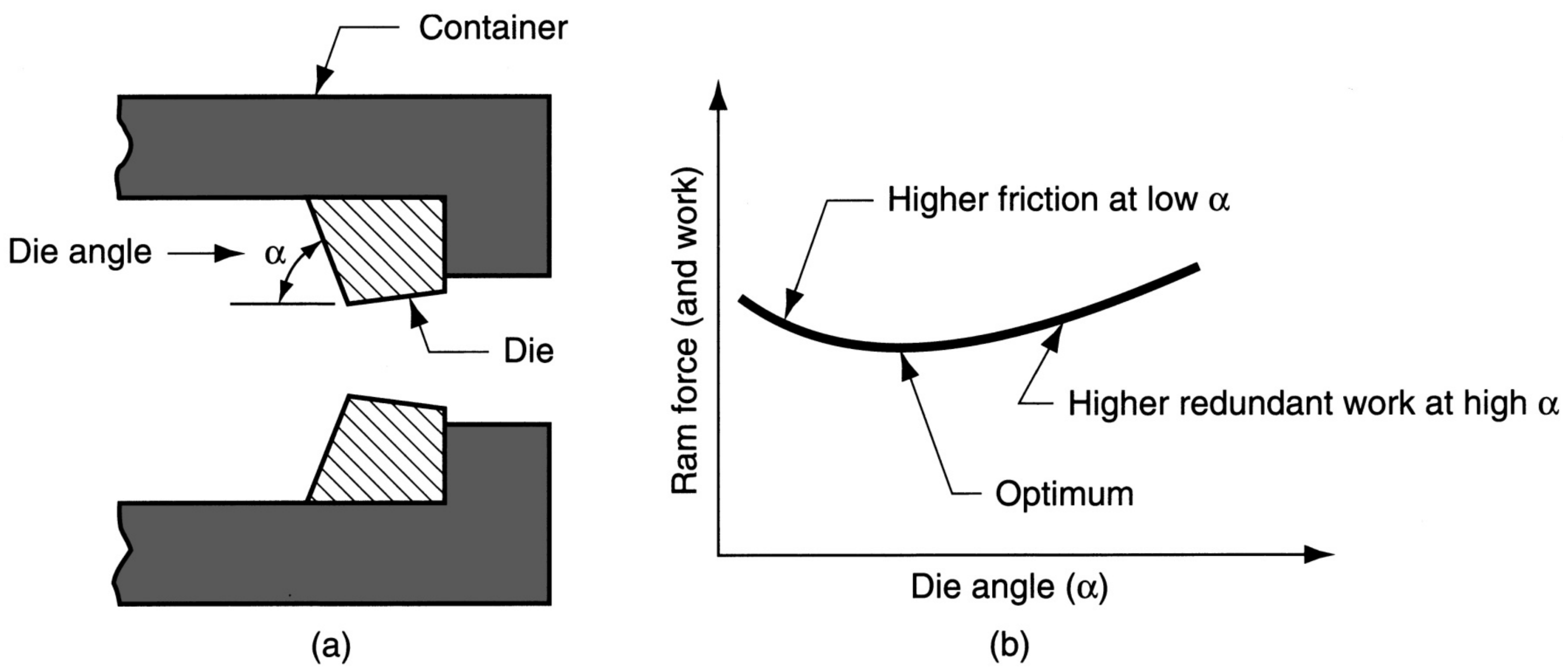
Also called the *extrusion ratio*, it is defined as

$$R = \frac{A_o}{A_f}$$

Where R = extrusion ratio; A_o = cross-sectional area of the starting billet; and A_f = final cross-sectional area of the extruded section

- Applies to both direct and indirect extrusion

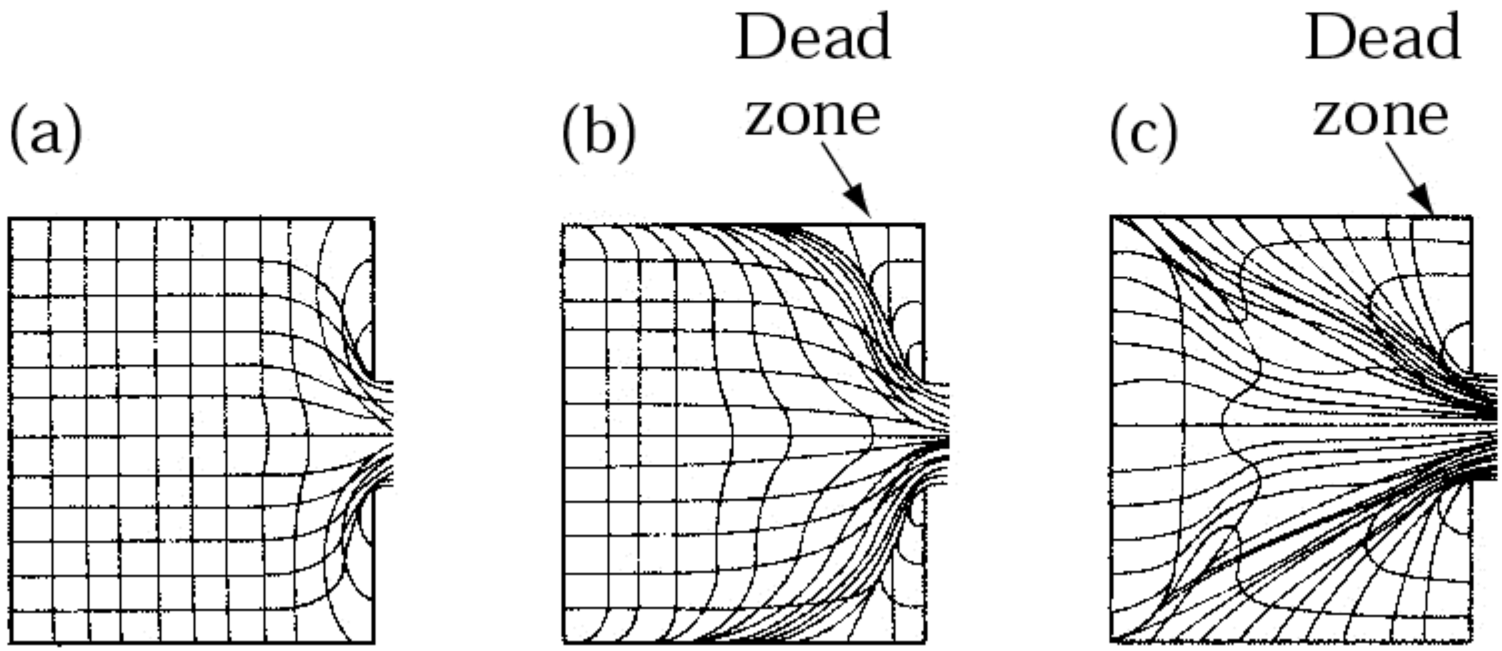
Process variables in direct extrusion



(a) Definition of die angle in direct extrusion;
(b) effect of die angle on ram force

The die angle, reduction in cross-section, extrusion speed, billet temperature, and lubrication all affect the extrusion pressure.

Metal flow in extrusion



Types of metal flow in extruding with square dies. (a) Flow pattern obtained at low friction, or in indirect extrusion. (b) Pattern obtained with high friction at the billet-chamber interfaces. (c) Pattern obtained at high friction, or with cooling of the outer regions of the billet in the chamber. This type of pattern, observed in metals whose strength increases rapidly with decreasing temperature, leads to a defect known as pipe, or extrusion defect.

Mechanics of extrusion

1. Ideal force, no friction

$$\varepsilon = \ln\left(\frac{A_o}{A_f}\right) = \ln\left(\frac{L_f}{L_o}\right) = \ln R$$

Assumption: perfectly plastic material, u=Yε

For a perfectly plastic material with a yield stress, Y the energy dissipated in plastic deformation per unit volume, u is, **u=Yε**

Work $= uA_oL_o = FL_0 = pA_oL_o$ (p: extrusion pressure)

$$p = u = Y\ln\left(\frac{A_o}{A_f}\right) = Y\ln\left(\frac{L_f}{L_o}\right) = Y\ln R$$

Mechanics of extrusion

1. Ideal force, no friction

$$\varepsilon = \ln(\frac{A_o}{A_f}) = \ln(\frac{L_f}{L_o}) = \ln R$$

Assumption: strain hardening material, u=?

Work $= uA_oL_o = FL_0 = pA_oL_o$ (p: extrusion pressure)

$$p = u = \bar{Y}\ln(\frac{A_o}{A_f}) = \bar{Y}\ln(\frac{L_f}{L_o}) = \bar{Y}\ln R$$

Mechanics of extrusion

2. Ideal force, with friction

$$p = Y\left(1 + \frac{\tan\alpha}{\mu}\right)\left[R^{\mu\cot\alpha} - 1\right]$$

3. Actual forces

$$p = Y(a + b\ln R)$$

Coefficient of friction, flow stress (temperature & strain rate and work during deformation)

Extrusion constant

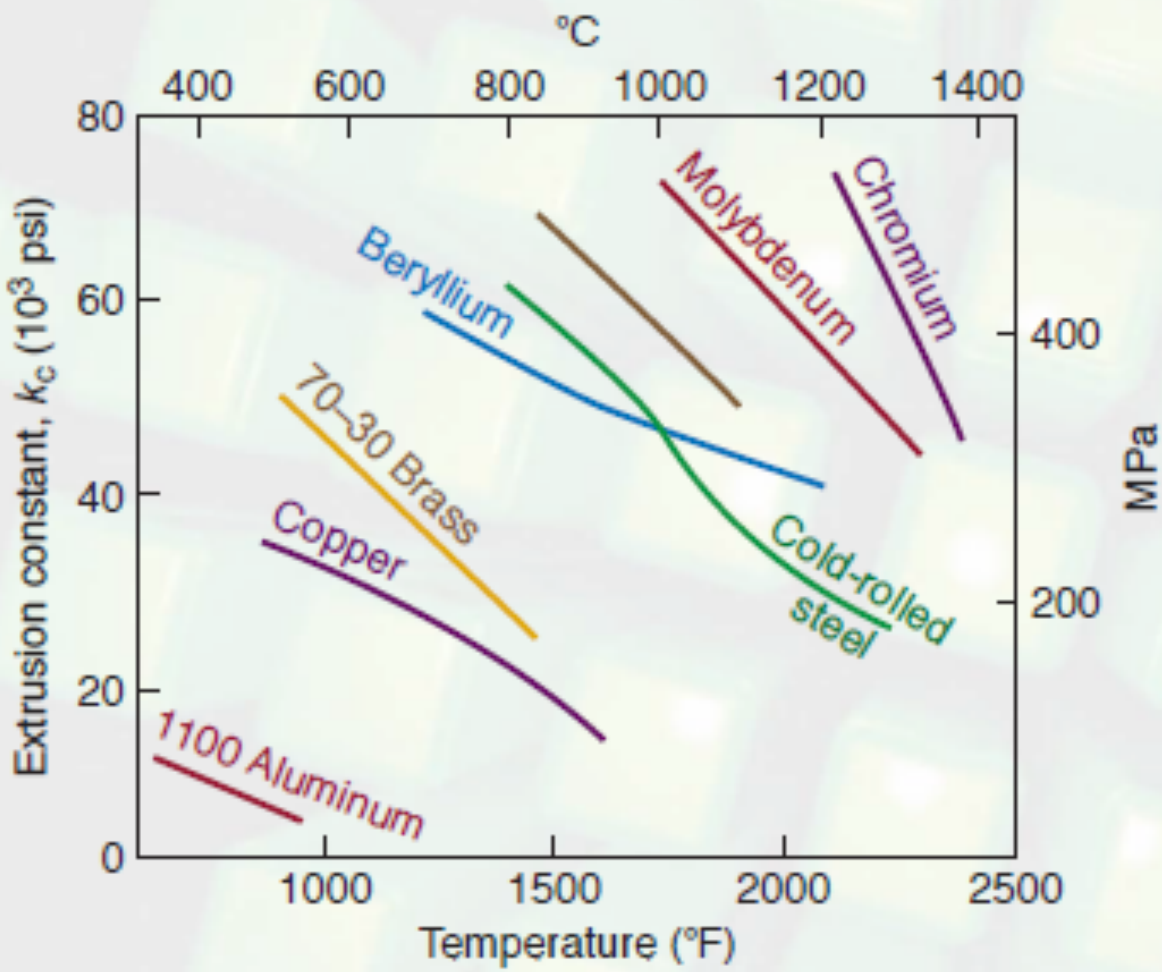


FIGURE 6.51 Extrusion constant, K_e, for various materials as a function of temperature. *Source:* After P. Loewenstein.

$$p = K_e \ln R$$

Extrusion force and pressure

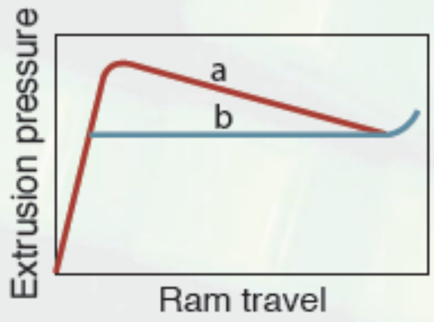


FIGURE 6.50 Schematic illustration of typical extrusion pressure as a function of ram travel: (a) direct extrusion and (b) indirect extrusion. The pressure in direct extrusion is higher because of frictional resistance at the container-billet interfaces, which decreases as the billet length decreases in the container.

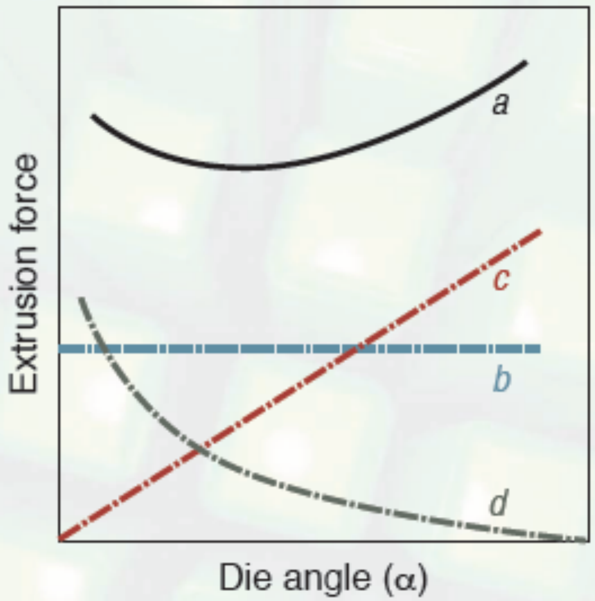


FIGURE 6.51 Schematic illustration of extrusion force as a function of die angle: (a) total force; (b) ideal force; (c) force required for redundant deformation; (d) force required to overcome friction. Note that there is a die angle where the total extrusion force is a minimum (optimum die angle).

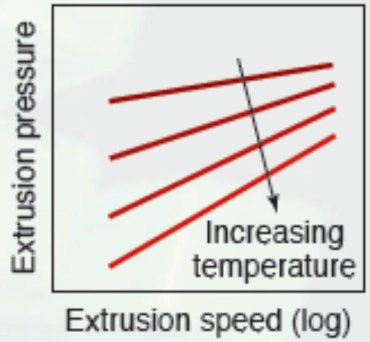
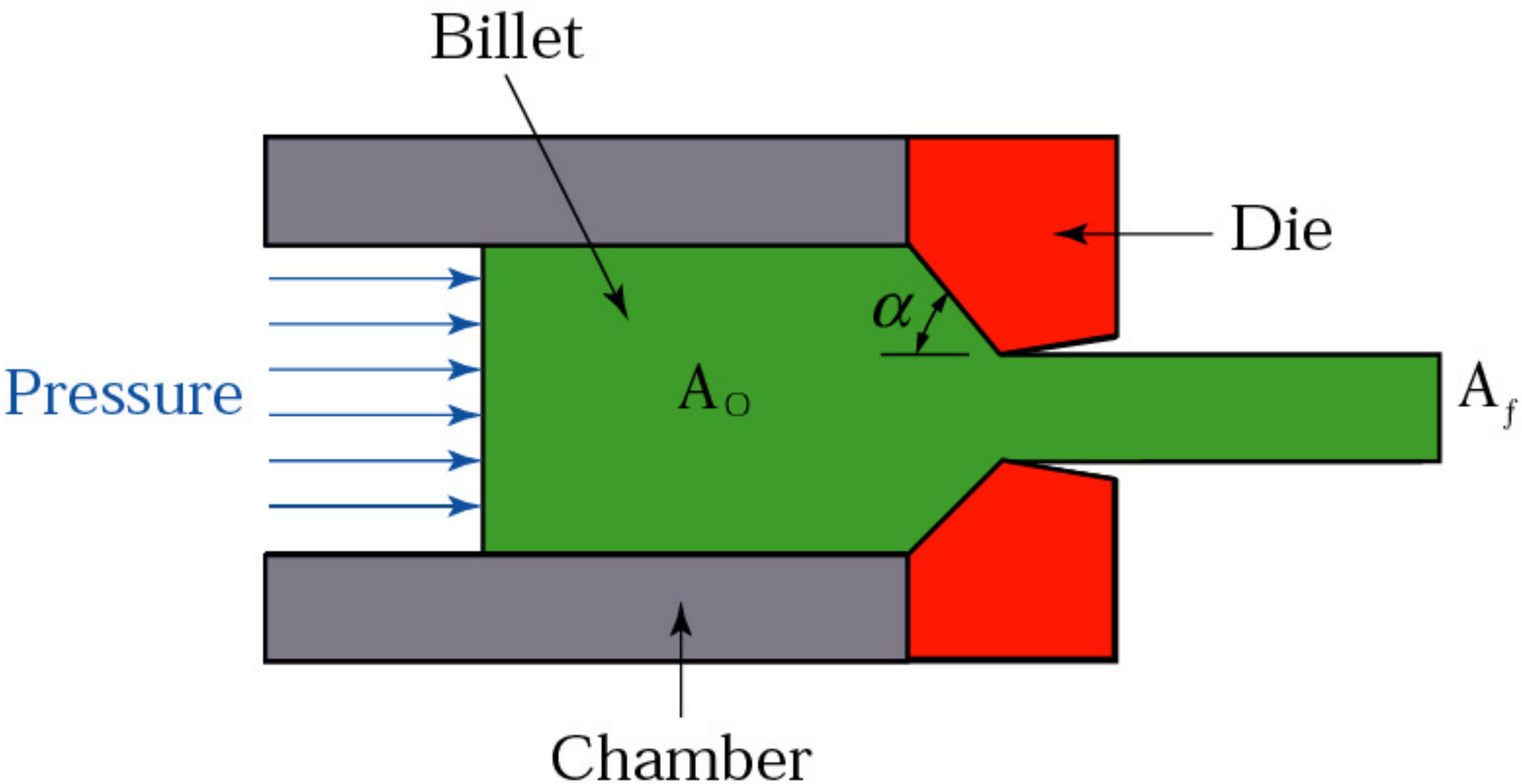


FIGURE 6.52 Schematic illustration of the effect of temperature and ram speed on extrusion pressure. Note the similarity of this figure with Fig. 2.10.

Example

Q: Determine the true strain rate in extruding a round billet of radius r_o as a function of distance x from the entry of a conical die.



Example

Q: A copper billet 150 mm in diameter and 300 mm long is extruded at 1123 K at a speed of 0.3 m/s. Using square dies and assuming poor lubrication, estimate the force required in this operation if the extruded diameter is 75 mm (C = 240 MPa, m = 0.06, a=0.8 & b=1.5).

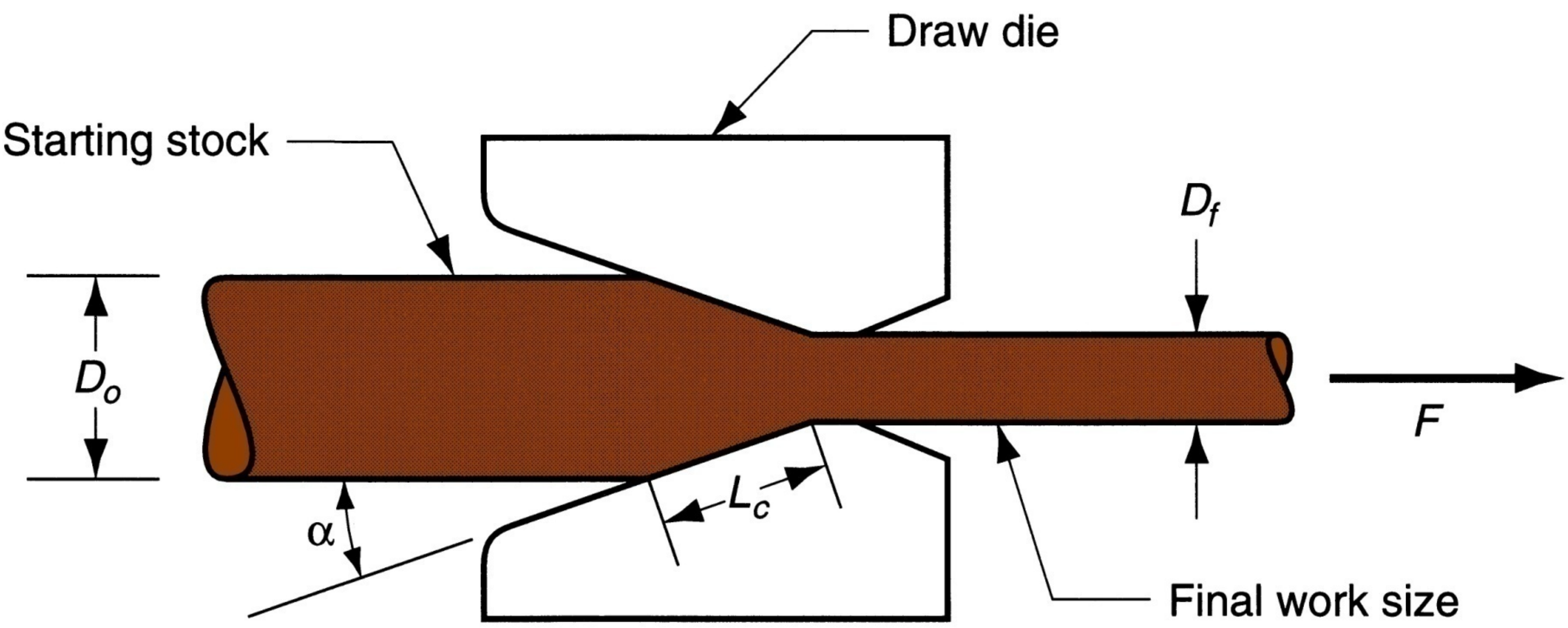
$$\overline{\dot{\varepsilon}} = \frac{6V_o}{D_o} \ln R$$

$$p = Y(a + b \ln R)$$

Wire and bar drawing

- Drawing operations involve pulling metal through a die by means of a tensile force applied to the exit side of the die.
- The plastic flow is caused by compression force, arising from the reaction of the metal with the die.
- Starting materials: hot rolled stock (ferrous) and extruded (nonferrous).
- Materials should have high ductility and good tensile strength
- Wire and bar drawing are usually carried out at room temperature
- The metal usually has a circular symmetry (but not always, depending on requirements).

Wire and bar drawing



Drawing of bar, rod, or wire

Area reduction in drawing

Change in size of work is usually given by area reduction:

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

where r = area reduction in drawing; A_o = original area of work; and A_r = final work

Wire drawing vs. bar drawing

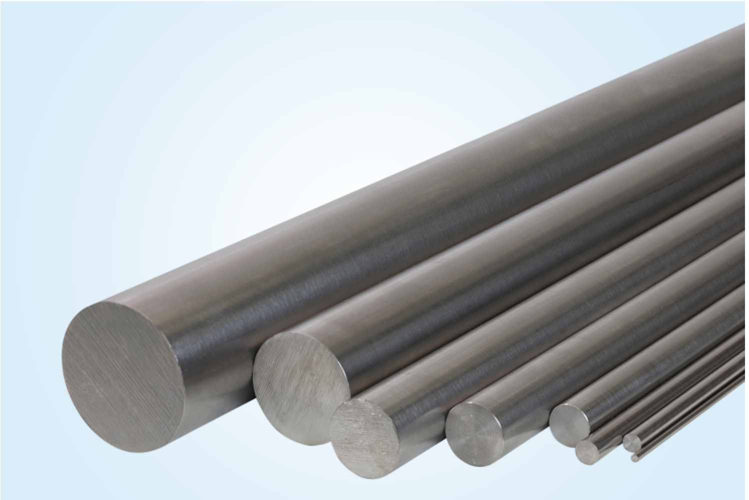
- Difference between bar drawing and wire drawing is stock size
  - *Bar drawing* - large diameter bar and rod stock
  - *Wire drawing* - small diameter stock - wire sizes down to 0.03 mm (0.001 in.) are possible
- Although the mechanics are the same, the methods, equipment, and even terminology are different

Drawing practice and products

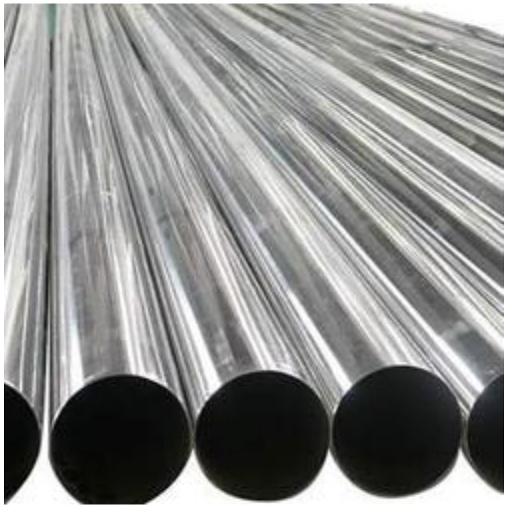
- Drawing practice:
  - Usually performed as cold working
  - Most frequently used for round cross-sections
- Products:
  - *Wire*: electrical wire; wire stock for fences, coat hangers, and shopping carts
  - *Rod stock* for nails, screws, rivets, and springs
  - *Bar stock*: metal bars for machining, forging, and other processes

Drawing practice and products

Metal wires

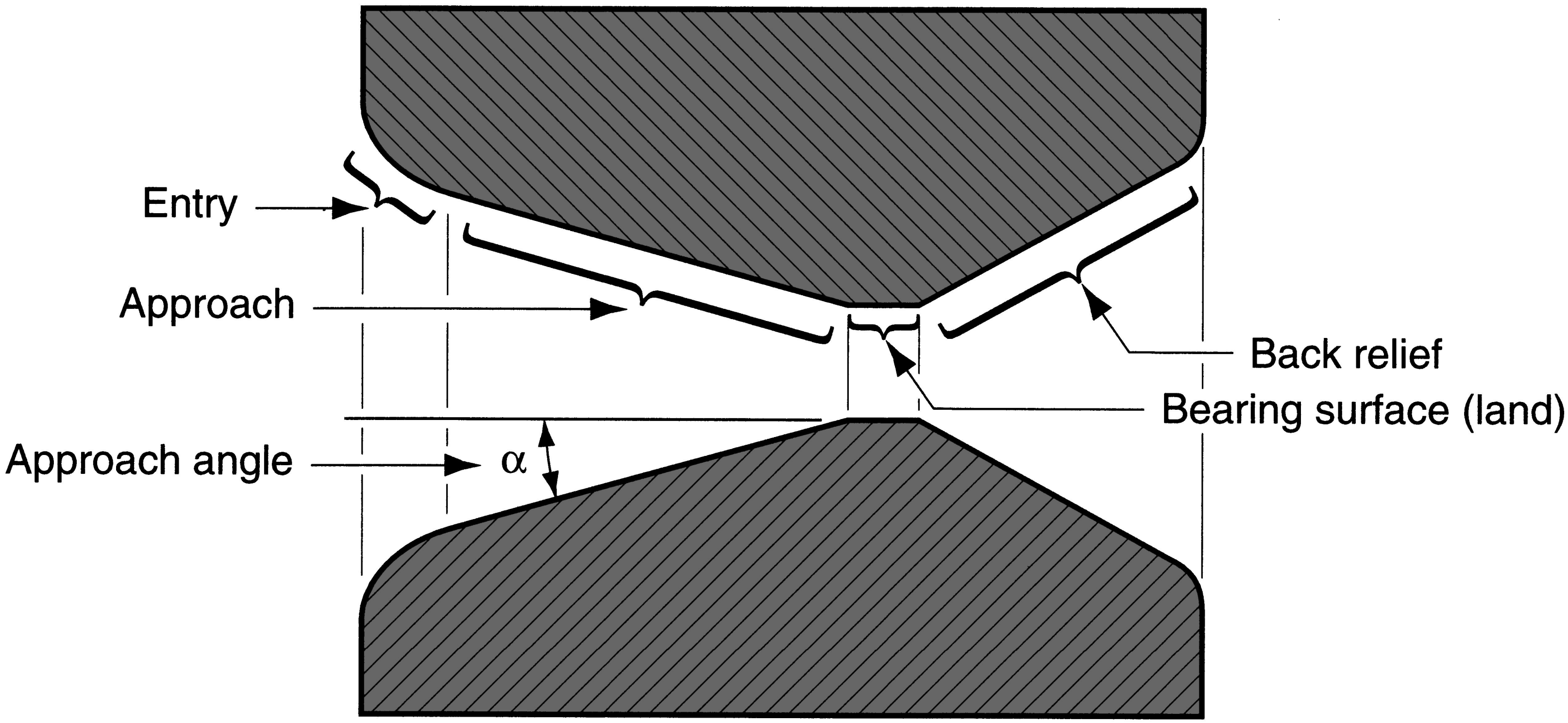


Metal rods



Pipes

Features of draw die



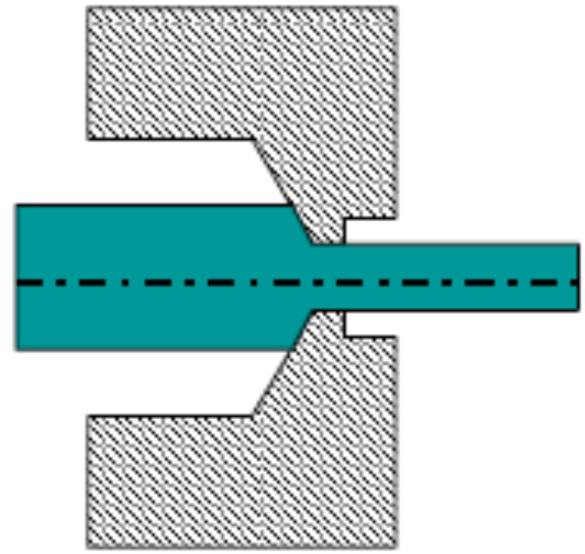
Draw die for drawing of round rod or wire

Die materials

- Large diameter
  – high carbon steel
  – high speed steel

- Moderate diameter
  – tungsten carbide (WC)

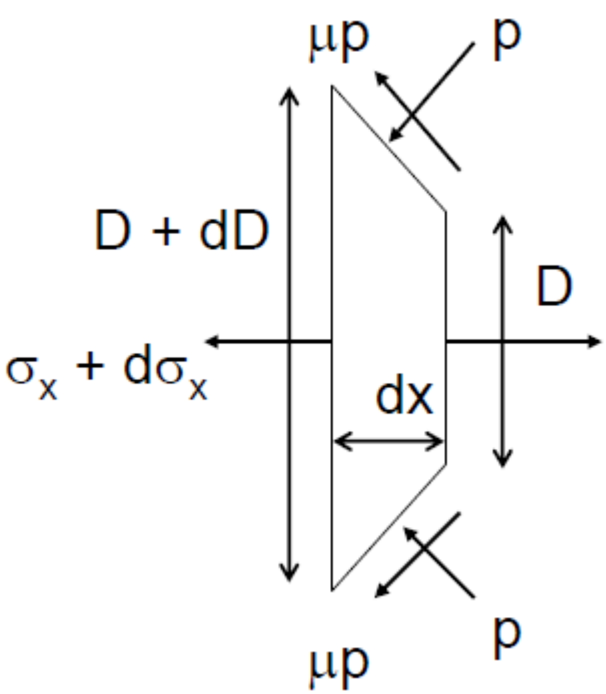
- Small diameter
  – diamond inserts

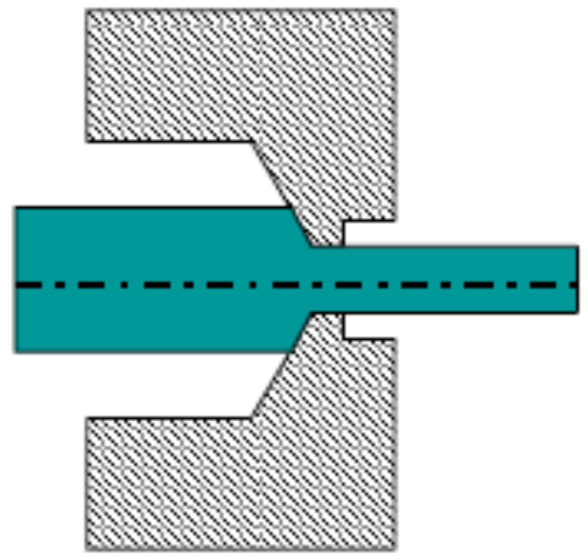


Workpiece preparation

- *Annealing* – to increase ductility of stock
- *Cleaning* - to prevent damage to work surface and draw die
- *Pointing* – to reduce diameter of starting end to allow insertion through draw die

Mechanics of wire and bar drawing





Assume p, σ_x are uniform

$$(\sigma_x + d\sigma_x)\frac{\pi}{4}(D + dD)^2 - \sigma_x \frac{\pi}{4} D^2$$
$$+ p\frac{\pi D \cdot dx}{\cos\alpha}\sin\alpha + \mu p \frac{\pi D \cdot dx}{\cos\alpha}\cos\alpha = 0$$

Mechanics of wire and bar drawing

Case 1: Ideal deformation, no friction

External work = work done during plastic deformation

$$\sigma_d (A_f l) = u(A_f l)$$

$$\sigma_d = u = \int_0^{\varepsilon_t} \sigma_t d\varepsilon_t$$

$$\boxed{\sigma_d = \frac{K\varepsilon_t^n}{n+1}\varepsilon_t = \bar{Y}_f \varepsilon_t = \bar{Y}_f \ln\left(\frac{A_0}{A_f}\right)}$$

Drawing force, $F_d = \sigma_d A_f$

Drawing power, $P_d = F_d V_f$

Maximum reduction per pass

Perfectly plastic material

Drawing stress = yield stress of the material

$$\sigma_d = Y \ln\left(\frac{A_o}{A_f}\right) = Y$$

r = 0.63

Maximum reduction per pass

Strain hardening material

Drawing stress = yield stress of the material

$$\sigma_d = \bar{Y} \ln\left(\frac{A_o}{A_f}\right) = \bar{Y}\varepsilon$$

$$r = 1 - e^{-(n+1)}$$

Mechanics of wire and bar drawing

Case 2: Ideal deformation, with friction

$$\sigma_d = Y\left(1+\frac{\tan\alpha}{\mu}\right)\left[1-\left(\frac{A_f}{A_o}\right)^{\mu\cot\alpha}\right]$$

Residual stresses in drawing

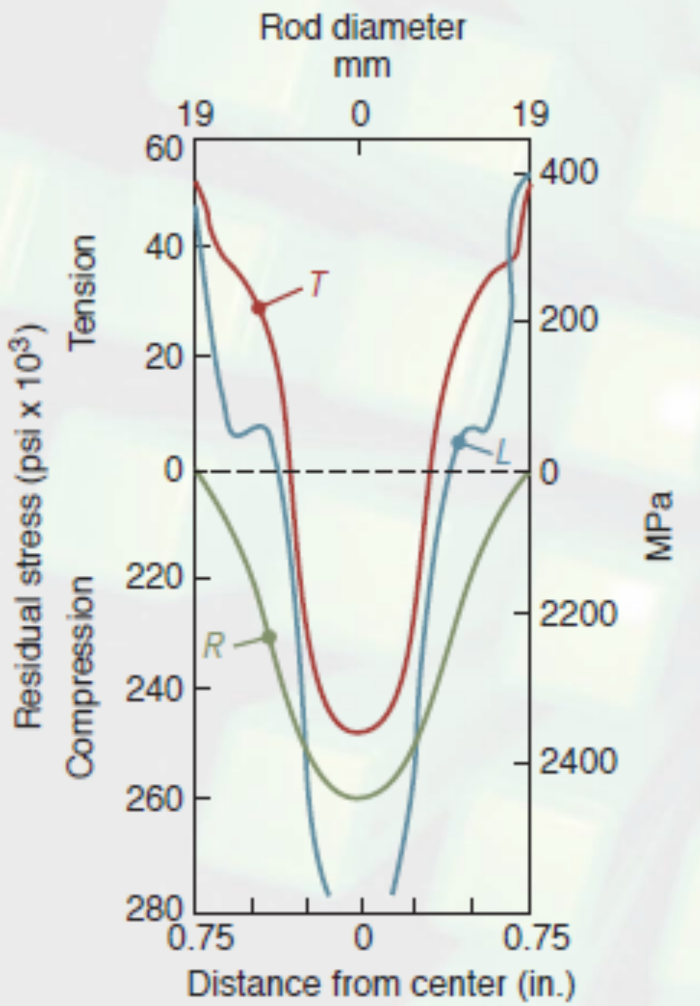


FIGURE 6.65 Residual stresses in cold-drawn 1045 carbon steel round rod: *T* = transverse direction, *L* = longitudinal direction and *R* = radial direction. *Source:* After E.S. Nachtman.

Drawing stresses

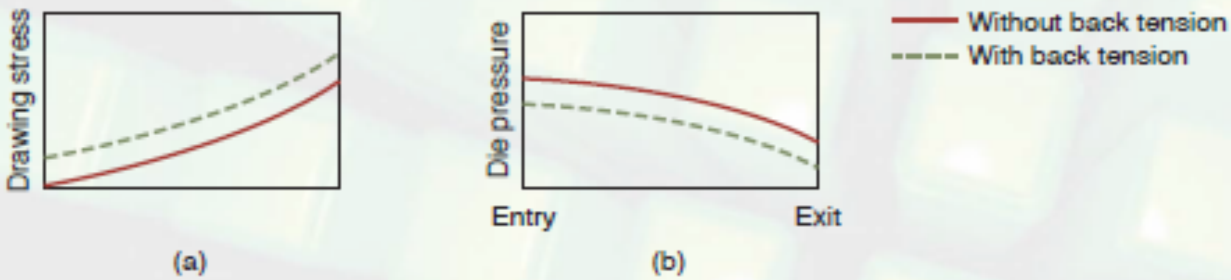


FIGURE 6.62 Variation in the (a) drawing stress and (b) die contact pressure along the deformation zone. Note that as the drawing stress increases, the die pressure decreases (see also yield criteria, described in Section 2.11). Note the effect of back tension on the stress and pressure.

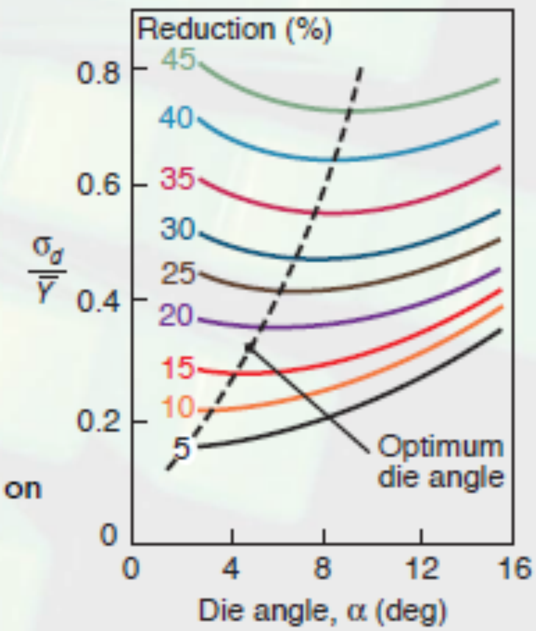


FIGURE 6.63 The effect of reduction in cross-sectional area on the optimum die angle in drawing. *Source:* After J.G. Wistreich.

$$p = Y_f - \sigma_d$$

Example

Q: Assuming zero redundant work and frictional work to be 20% of the ideal work, derive an expression for the maximum reduction in area per pass for a wire drawing operation for a material with a true-stress strain curve of $\sigma = K\varepsilon^n$

$$r = 1 - e^{-(n+1)/1.2}$$

Example

Q: A round rod of annealed brass 70-30 is being drawn from a diameter of 6 mm to 3 mm at a speed of 0.6 m/s. Assume that the frictional and redundant work together constitute 35% of the ideal work of deformation. (a) Calculate power required and die pressure at the exit of die.

K = 895 MPa and n = 0.49

Power = 1.992 kW