4 4 6 . 3 0 5 A M A N U F A C T U R I N G P R O C E S S E S

Chapter 6. Bulk Deformation Processes

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Classification of Deformation Processes

- **Temperature**
  - Hot working(열간가공) $T > 0.6T_m$
  - Warm working(온간가공) $T = 0.3 \sim 0.5T_m$
  - Cold working(냉간가공) $T < 0.3T_m$

- **Type of operation**
  - Primary working(1차가공) : solid piece of metal(금속괴) → slabs(슬래브), plates(후판), billets(빌렛).
  - Secondary working(2차가공) : products from primary working(1차가공품) → bolts(볼트), sheet metal parts(금속판재품), wire(선재).

- **Size and shape of the workpiece**
  - Bulk deformation(부피성형가공) : thickness or cross section of the work-piece changes(forging(단조), rolling(압연), extrusion(압출), drawing(인발)).
  - Sheet forming(판재성형가공) : generally shape changes, thickness changes are undesirable.

Forging (단조) (1)

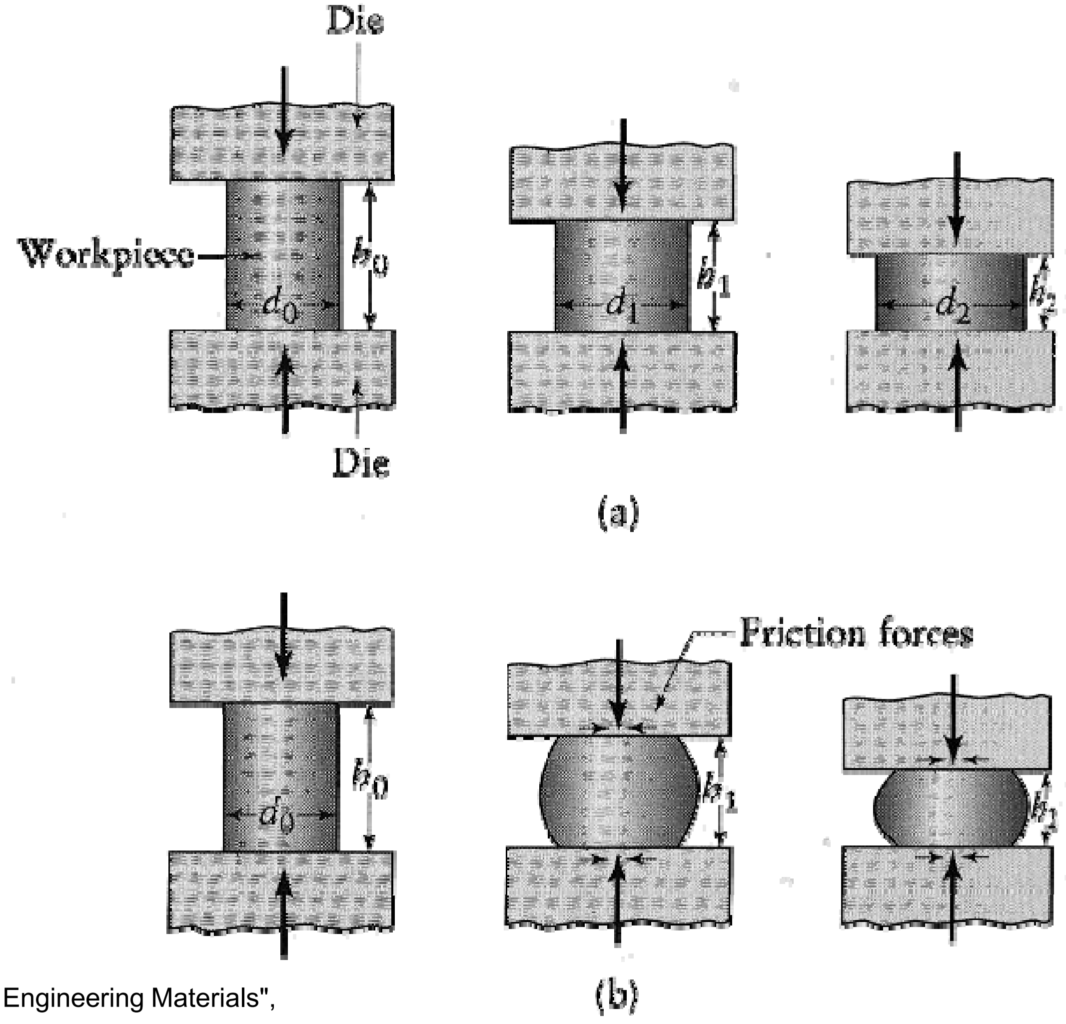
Forging (단조) (2)

- **Plastic deformation of the workpiece is carried out by compressive forces.**
- **Crankshafts, connecting rods, turbine disks, gears, wheels, bolt heads, hand tools, etc.**
- **The recrystallization temperature(재결정온도) for metals :** $T / T_m \sim 0.5$
- **Basic categories of forging**
    - Open die(자유단조)
    - Impression die(형단조)
    - Closed die(폐쇄단조)

Open-die forging (자유단조)

- **Reducing the height of workpiece between two flat dies by compressing it.**

FIGURE 6.1 (a) Ideal deformation of a solid cylindrical specimen compressed between flat frictionless dies. This process is known as *upsetting*. (b) Deformation in upsetting with friction at the die–workpiece interfaces.



Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Forces and work of deformation

Reduction in height

$$= \frac{h_0 - h_1}{h_0} \times 100\%$$

$$e_1 = \frac{h_0 - h_1}{h_0}, \quad \varepsilon_1 = \ln\left(\frac{h_0}{h_1}\right)$$

$$\dot{e}_1 = -\frac{v}{h_0}, \quad \dot{\varepsilon}_1 = -\frac{v}{h_1}$$

← **Relative velocity between the plates**

$$F = YA_1, \quad A_1 = \frac{A_0 h_0}{h_1}$$

$$\text{Work} = \text{volume}\int_0^{\varepsilon_1} \sigma\, d\varepsilon, \quad \sigma = K\varepsilon^n$$

$$F = Y_f A_1, \quad \text{Work} = (\text{volume})\left(\bar{Y}\right)\left(\varepsilon_1\right)$$

$$\bar{Y} = \frac{K\int_0^{\varepsilon_1} \varepsilon^n d\varepsilon}{\varepsilon_1} = \frac{K\varepsilon_1^n}{n+1}$$

(**Y_f : Flow stress, $\bar{Y}$: Average flow stress**)

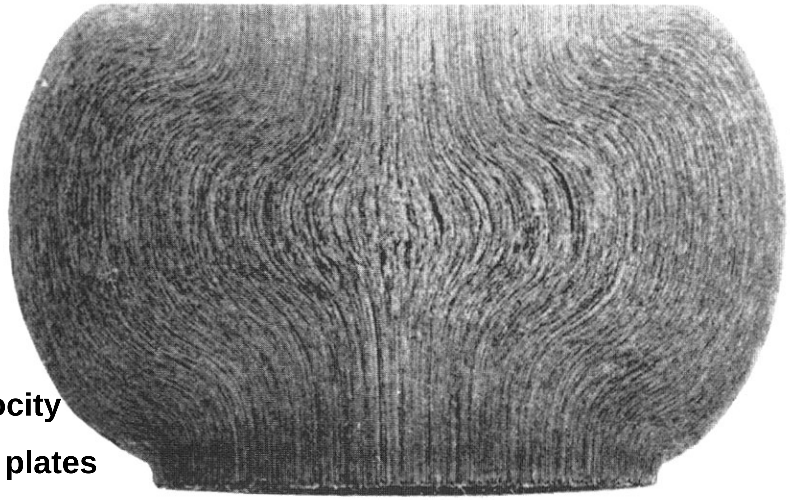


FIGURE 6.2 Grain flow lines in upsetting a solid steel cylinder at elevated temperatures. Note the highly inhomogeneous deformation and barreling. The different shape of the bottom section of the specimen (as compared with the top) results from the hot specimen resting on the lower, cool die before deformation proceeded. The bottom surface was chilled; thus it exhibits greater strength and hence deforms less than the top surface. *Source*: J. A. Schey et al., IIT Research Institute.

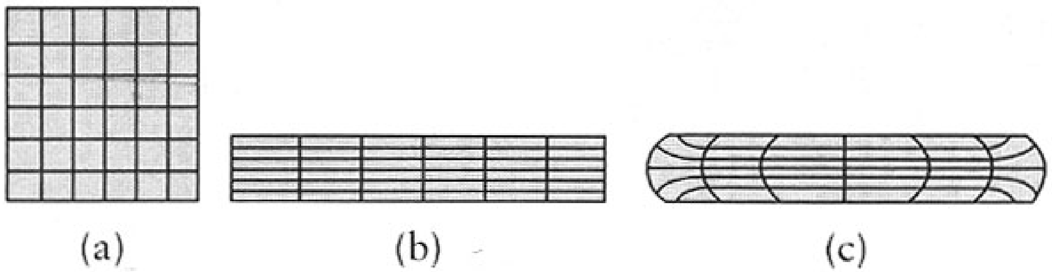


FIGURE 6.3 Schematic illustration of grid deformation in upsetting: (a) original grid pattern; (b) after deformation, without friction; (c) after deformation, with friction. Such deformation patterns can be used to calculate the strains within a deforming body.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Methods of analysis - Slab method (1)

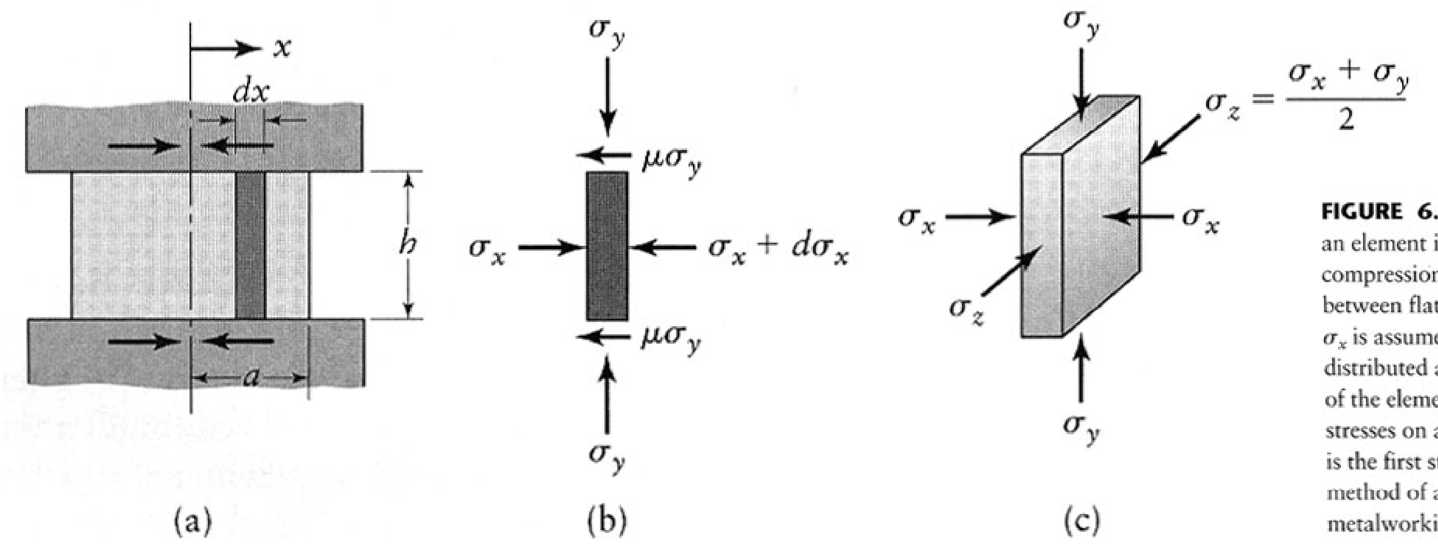


FIGURE 6.4 Stresses on an element in plane-strain compression (forging) between flat dies. The stress σ_x is assumed to be uniformly distributed along the height h of the element. Identifying the stresses on an element (slab) is the first step in the slab method of analysis for metalworking processes.

Horizontal forces : $(\sigma_x + d\sigma_x)h + 2\mu\sigma_y dx - \sigma_x h = 0$

$$d\sigma_x + \frac{2\mu\sigma_y}{h}dx = 0 \qquad \text{ⓐ}$$

Using distortion-energy criterion for plane strain

$$\sigma_y - \sigma_x = \frac{2}{\sqrt{3}}Y = Y'$$ **: Average flow stress**

$$d\sigma_y = d\sigma_x \qquad \text{ⓑ}$$

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Methods of analysis - Slab method (2)

ⓐ & ⓑ give

$$d\sigma_y + \frac{2\mu\sigma_y}{h}dx = 0$$

$$\frac{d\sigma_y}{\sigma_y} = -\frac{2\mu}{h}dx \xrightarrow{\text{O.D.E}} \sigma_y = Ce^{-2\mu x/h}$$

Boundary conditions : $x = a, \ \ \sigma_x = 0 \longrightarrow \ \sigma_y = Y'$ at the edges of the specimen

$$C = Y' e^{2\mu a/h}$$

$$p = \sigma_y = Y' e^{2\mu(a-x)/h}$$

$$\sigma_x = \sigma_y - Y' = Y'[e^{2\mu(a-x)/h} - 1]$$

$$p_{av} \approx Y'\left(1 + \frac{\mu a}{h}\right)$$: Average pressure

$$F = (p_{av})(2a)(width)$$: Forging force

Methods of analysis - Slab method (3)

Rectangular Specimen | **Die pressure**

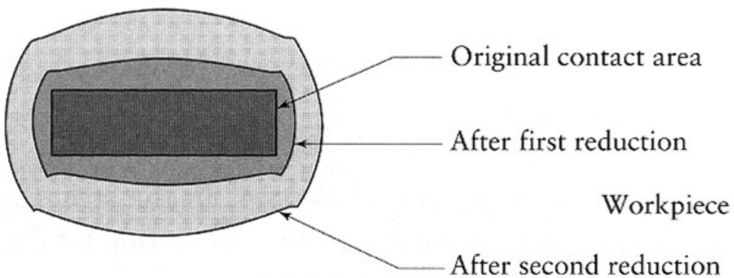


FIGURE 6.7 Increase in contact area of a rectangular specimen (viewed from the top) compressed between flat dies with friction. Note that the length of the specimen has increased proportionately less than its width. Likewise, a specimen in the shape of a cube acquires the shape of a pancake after deformation with friction.

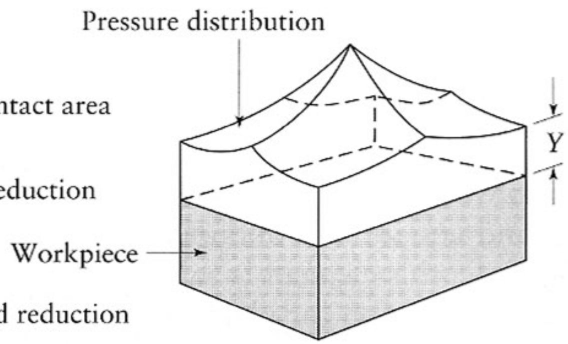


FIGURE 6.6 Normal stress (pressure) distribution in the compression of a rectangular workpiece with sliding friction under conditions of plane stress, using the *distortion-energy criterion*. Note that the stress at the corners is equal to the uniaxial yield stress, Y, of the material.

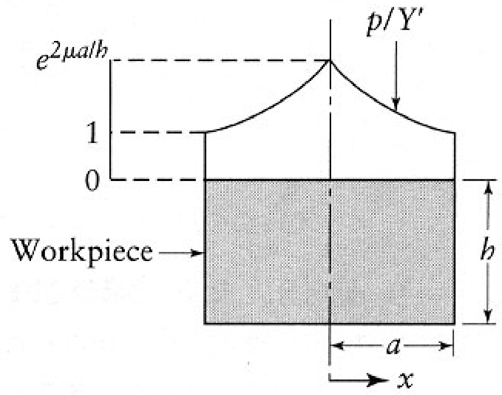


FIGURE 6.5 Distribution of die pressure, in terms of p/Y', in plane-strain compression with sliding friction. Note that the pressure at the left and right boundaries is equal to the yield stress in plane strain, Y'. Sliding friction means that the frictional stress is directly proportional to the normal stress.

Question : What should be the shape before deformation to make a rectangular part?

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Methods of analysis - others

- **Slip-line analysis(미끄럼선 해석)**
- **Upper-bound technique(상계해법)**
- **Finite element method(유한요소법)**

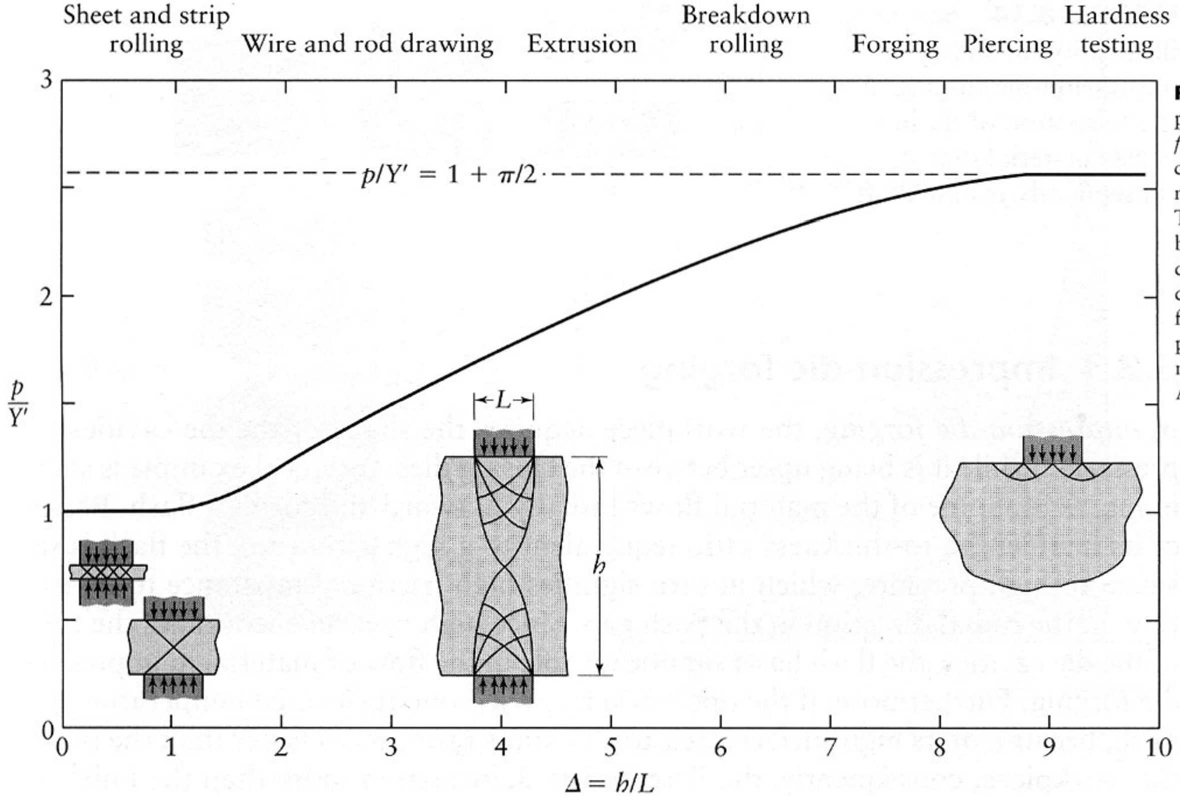


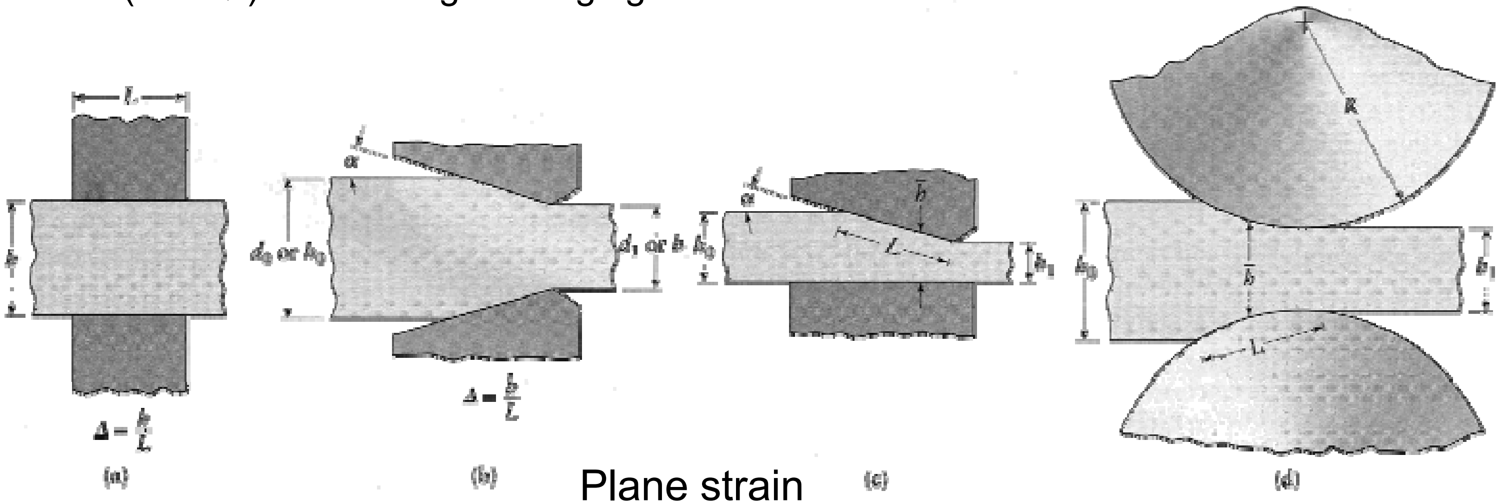
FIGURE 6.12 Die pressures required in *frictionless* plane-strain conditions for a variety of metalworking operations. The geometric relationship between contact area of the dies and workpiece dimensions is an important factor in predicting forces in plastic deformation of materials. *Source*: After W. A. Backofen.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Impression-die/closed-die forging(형단조)(1)

- **Impression-die forging : the workpiece acquires the shape of the die cavities (impressions) while it is being upset between the closing dies.**
  - Flash(플래쉬) : significant role in the flow of material.
  - Forces in impression-die forging : depending on its position, $F=K_pY_fA$.
  - Land(랜드부) : controlling the forging load not to be excessive.

$\frac{h}{L}$ ratio

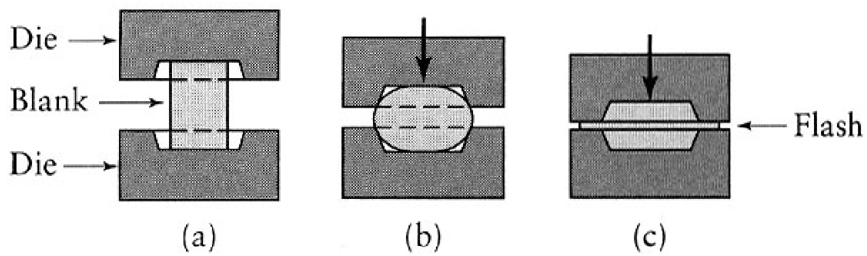


Plane strain

FIGURE 6.13 Examples of plastic deformation processes in plane strain, showing the h/L ratio. (a) Indenting with flat dies. This operation is similar to cogging, shown in Fig. 6.10. (b) Drawing or extrusion of strip with a wedge-shaped die, described in Sections 6.4 and 6.5. (c) Ironing; see also Fig. 7.34. (d) Rolling, described in Section 6.3. As shown in Fig. 6.12, the larger the h/L ratio, the higher the die pressure becomes. In actual processing, however, the smaller this ratio, the greater is the effect of friction at the die–workpiece interface. The reason is that contact area, and hence friction, increases with a decreasing h/L ratio.

$$F=(K_p)(Y_f)(A)$$

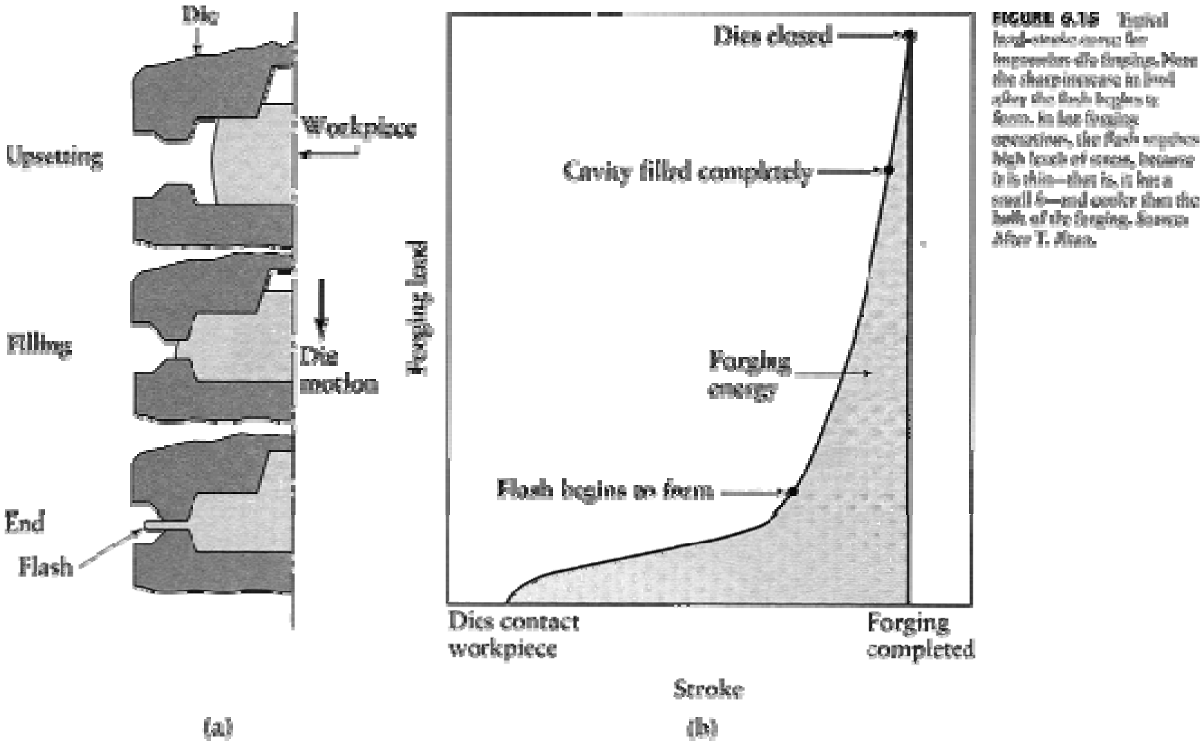
FIGURE 6.14 Schematic illustration of stages in impression-die forging. Note the formation of flash, or excess material that is subsequently trimmed off.



Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Impression-die/closed-die forging(형단조)(2)

- **Closed-die forging(폐쇄단조) : no flash is formed and the workpiece is completely surrounded by the dies.**
  - Precision forging(정밀단조), flashless forging(밀폐단조) : the part formed is close to the final dimensions, high forging load & capacity equipment needed.
  - Isothermal forging(등온단조), hot-die forging(가열금형단조) : the dies are heated to the same temperature as the hot blank.



Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", $3^{rd}/4^{th}$ ed. Addison Wesley

Closed-die forging (폐쇄단조)

- **Orbital forging(궤도단조)**

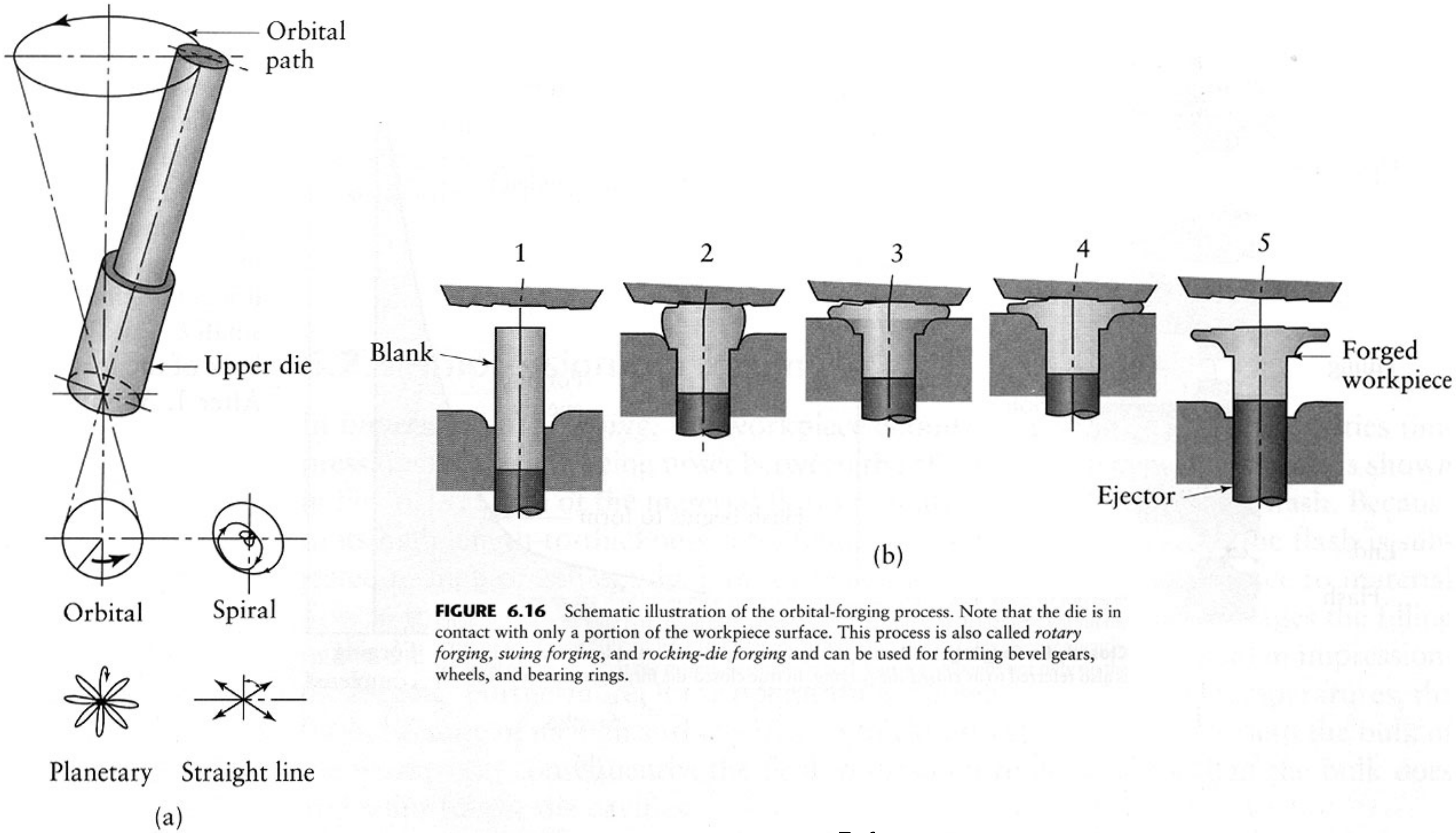


FIGURE 6.16 Schematic illustration of the orbital-forging process. Note that the die is in contact with only a portion of the workpiece surface. This process is also called *rotary forging, swing forging*, and *rocking-die forging* and can be used for forming bevel gears, wheels, and bearing rings.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", $3^{rd}/4^{th}$ ed. Addison Wesley

Miscellaneous forging operations (1)

- Coining(코이닝)
  - **an example of closed-die forging**
  - **minting of coins.**
- Heading(헤딩) – Fig 6.17
- Piercing(천공) – Fig 6.18
- Hubbing(허빙)
- Cogging(코깅)
- Fullering and edging(풀러링, 에징)
- Role forging(압연단조)
- Skew-rolling(강구전조작업)

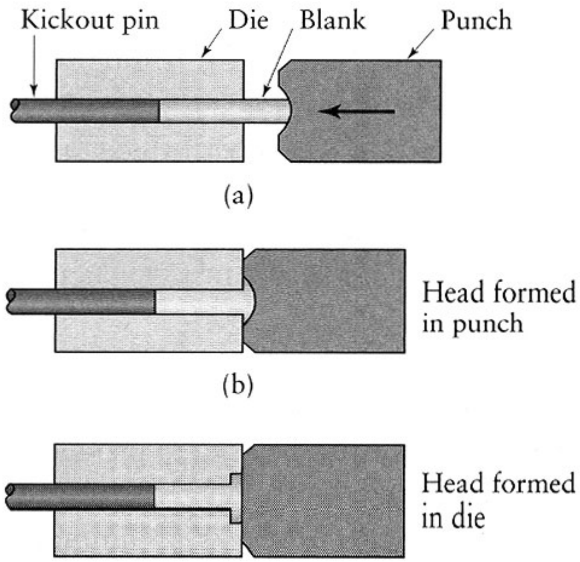


FIGURE 6.17 Forming heads on fasteners such as bolts and rivets. These processes are called *heading*.

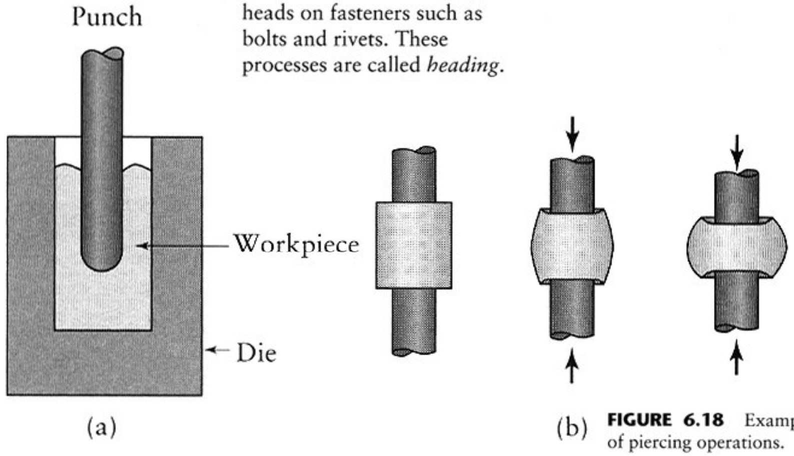


FIGURE 6.18 Examples of piercing operations.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Miscellaneous forging operations (2)

Cogging

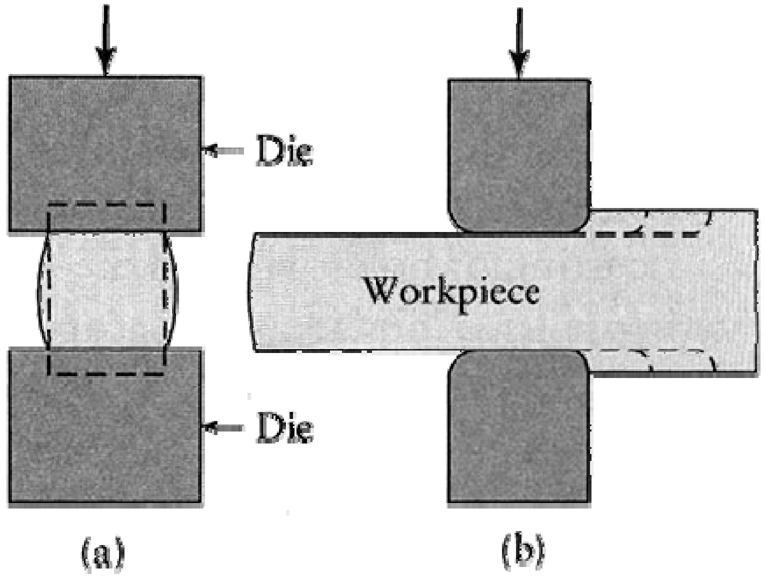


FIGURE 6.19 Schematic illustration of a cogging operation on a rectangular bar. With simple tools, the thickness and cross-section of a bar can be reduced by multiple cogging operations. Note the barreling after cogging. Blacksmiths use a similar procedure to reduce the thickness of parts in small increments by heating the workpiece and hammering it numerous times.

Roll forging(Cross rolling)

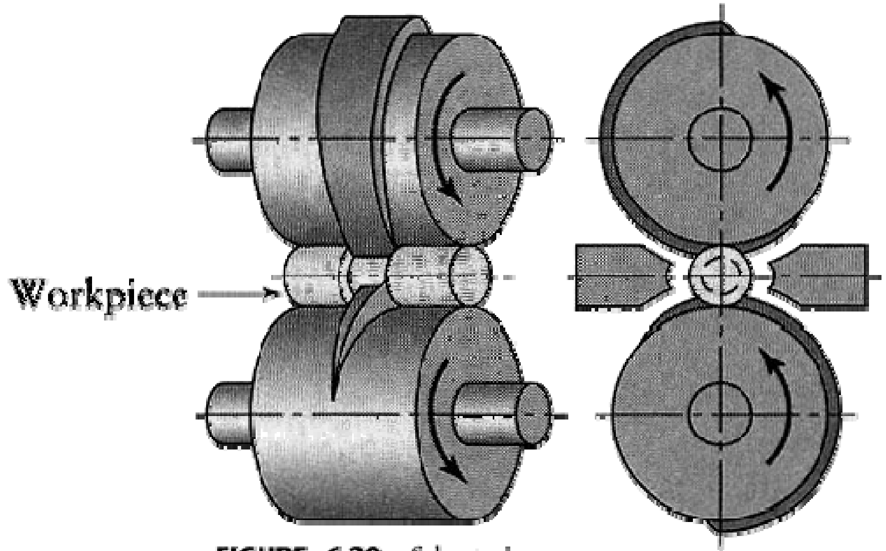


FIGURE 6.20 Schematic illustration of a roll forging (cross-rolling) operation. Tapered leaf springs and knives can be made by this process with specially designed rolls. *Source:* After J. Holub.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Miscellaneous forging operations (3)

Steel balls by skew-rolling

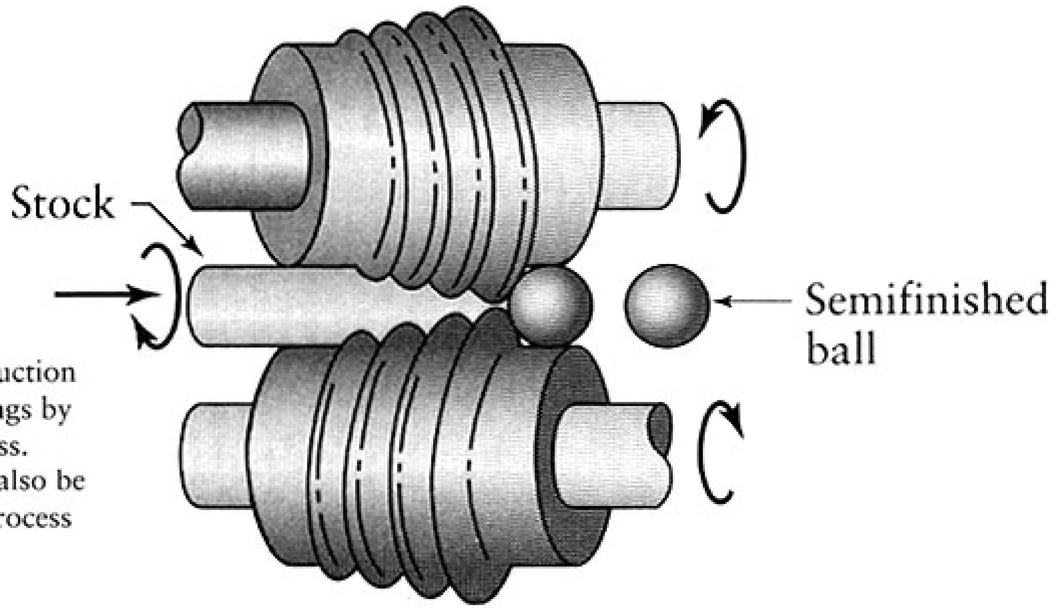


FIGURE 6.21 Production of steel balls for bearings by the skew-rolling process. Balls for bearings can also be made by the forging process shown in Fig. 6.22.

Steel balls by upsetting

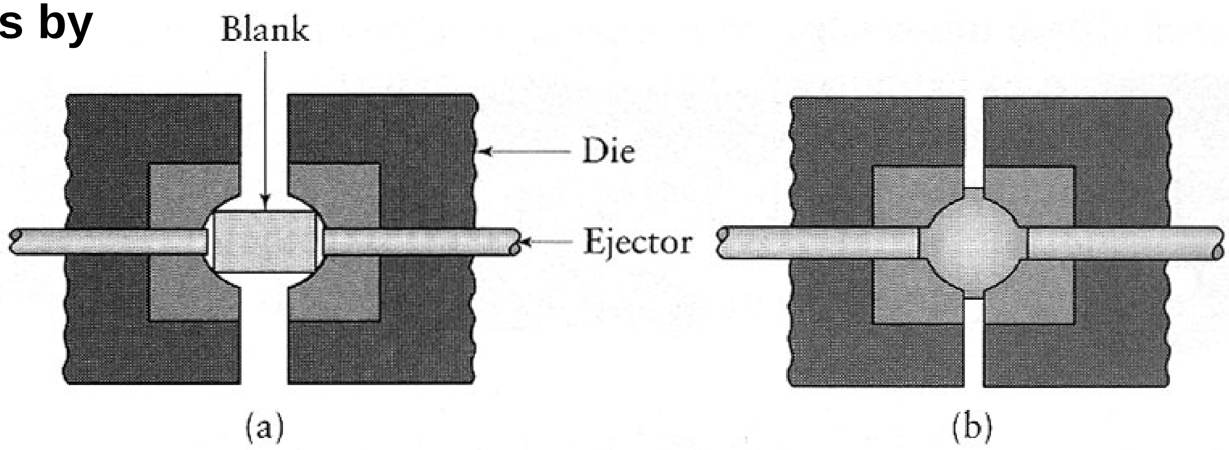


FIGURE 6.22 Production of steel balls by upsetting of a cylindrical blank. Note the formation of flash. The balls are subsequently ground and polished for use as ball bearings and in other mechanical components.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Defects in forging (1)

- **Caused by the material flow patterns in the die cavity.**
- **Cold shut.**
- **Grain flow pattern, end grain.**

Buckling

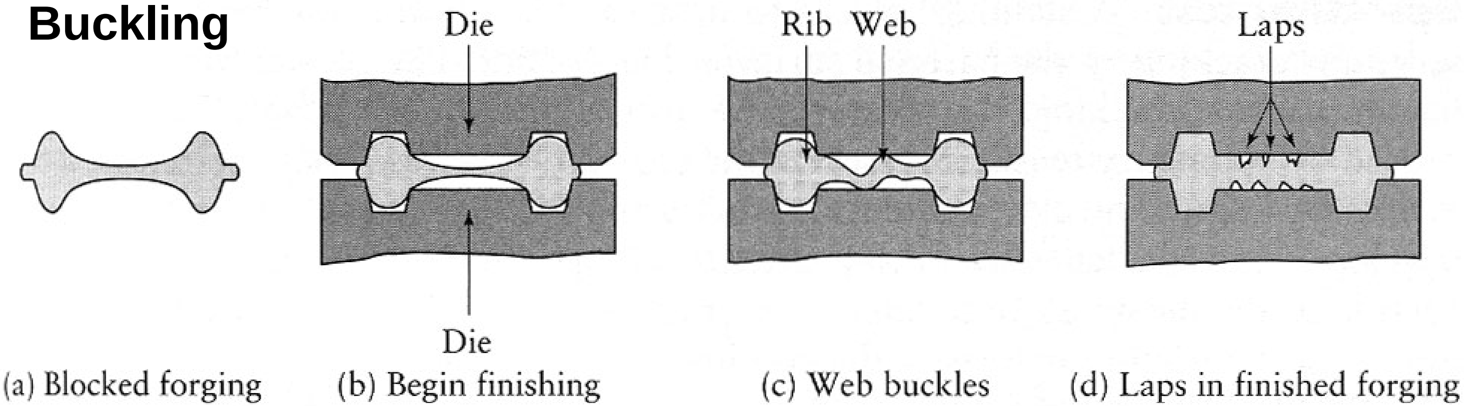


FIGURE 6.23 Laps formed by buckling of the web during forging.

Over sized billet

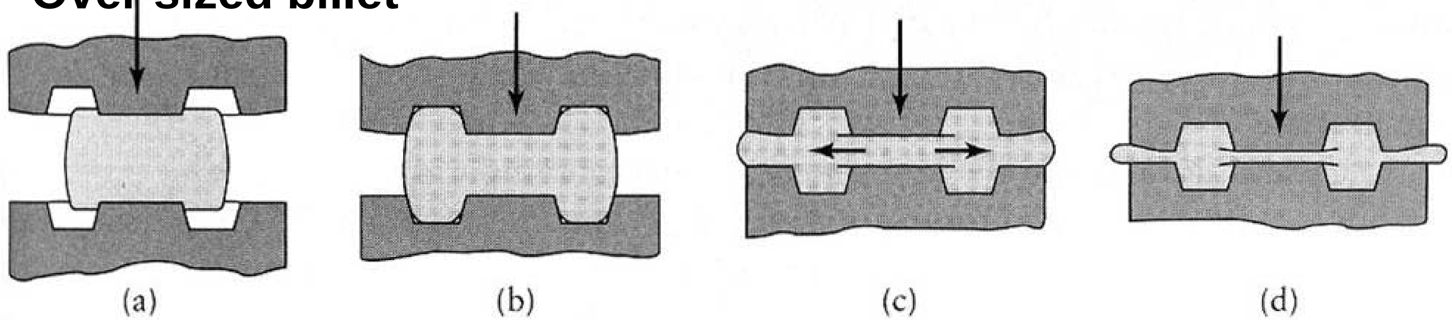


FIGURE 6.24 Internal defects produced in a forging because of an oversized billet. The die cavities are filled prematurely, and the material at the center of the part flows past the filled regions as deformation continues.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Defects in forging (2)

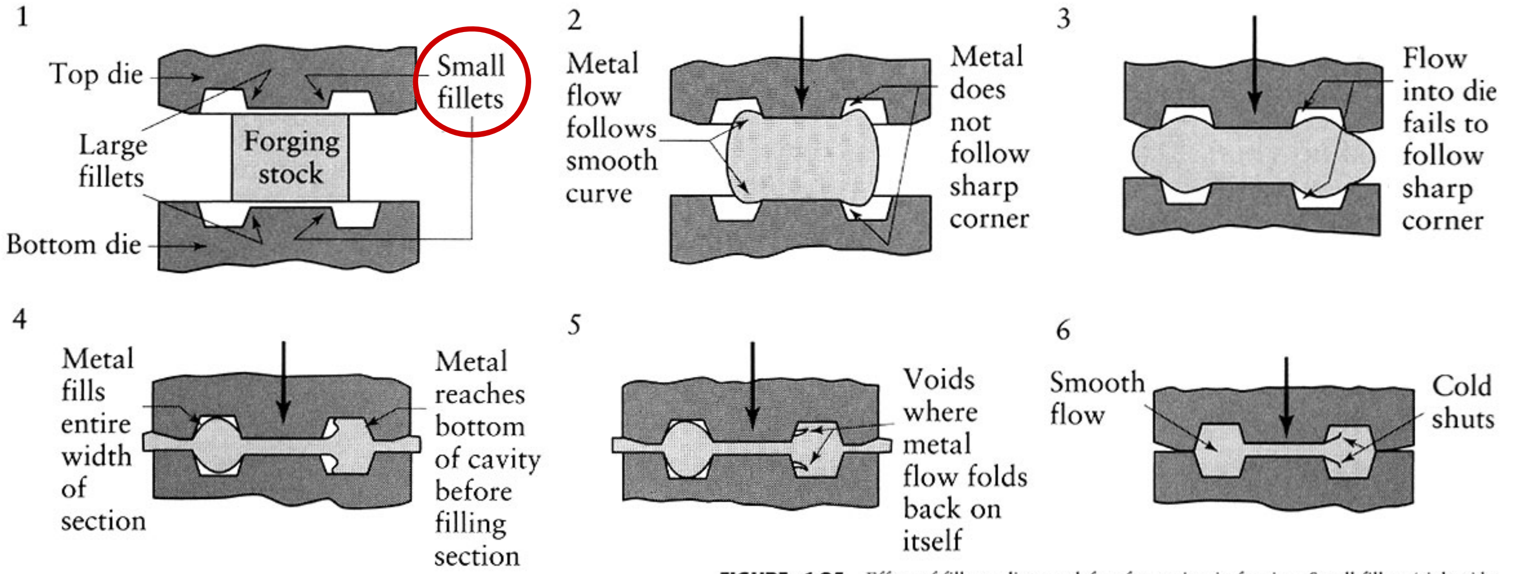
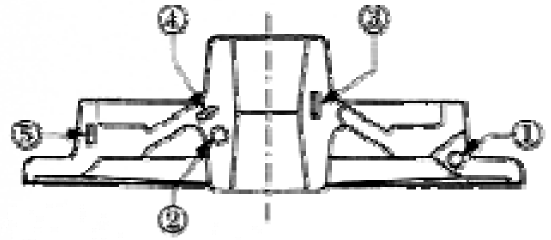


FIGURE 6.25 Effect of fillet radius on defect formation in forging. Small fillets (right side of drawings) cause the defects. *Source*: Aluminium Company of America.

Grain flow pattern
(단류선 영향)



Specimen location	Yield strength, psi	Ultimate tensile strength, psi	Elongation, %
1.	26,500	41,200	20.0
2.	23,000	39,400	17.7
3.	13,800	38,000	18.6
4.	25,400	40,400	16.2
5.	17,100	37,500	14.0

FIGURE 6.26 Mechanical properties of five tensile-test specimens taken at various locations and directions in an AZ61 magnesium alloy forging. Note the anisotropy of properties caused by inhomogeneous deformation during forging. *Source*: After S. M. Jablonski, Modern Metals, vol. 16, 1963, pp. 62-70.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Die design (1)

- The most important rule in die design : the workpiece material flow in the direction of least resistance.

- **Considerations**
  - Strength and ductility of the workpiece material.
  - Strain rate and temperature.
  - Frictional characteristics.
  - Die distortion under high forging loads.

- **Die design parameters**
  - Flash clearance between the dies : 3% of the max. thickness.
  - Length of the land : 5 times of the flash clearance.
  - Proper radii for corners and fillets.

- **Die materials**
  - Tool and die steel(공구강 및 다이강) containing Cr, Ni, Mo and V.

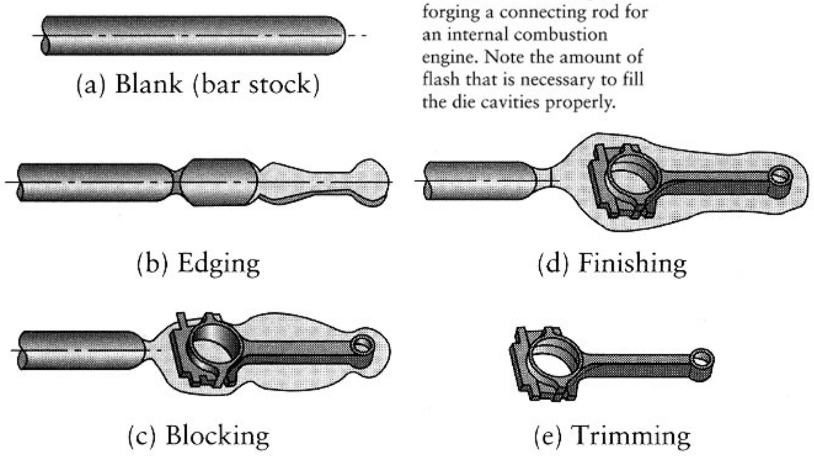


FIGURE 6.26 Stages in forging a connecting rod for an internal combustion engine. Note the amount of flash that is necessary to fill the die cavities properly.

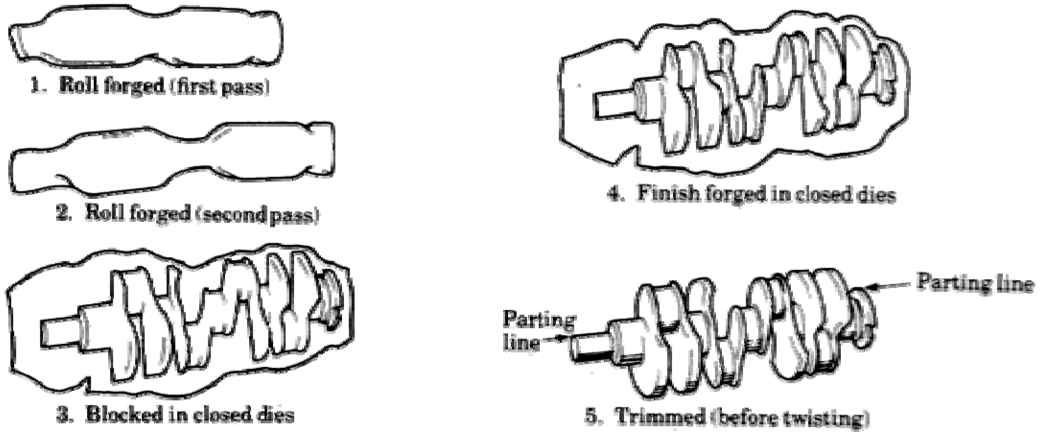


FIGURE 6.28 Intermediate stages in forging a crankshaft. These intermediate stages are important for distributing the material and filling the die cavities properly.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Die design (2)

- **Draft angles : Internal angles(7~10°) > External angles(3~5°)**

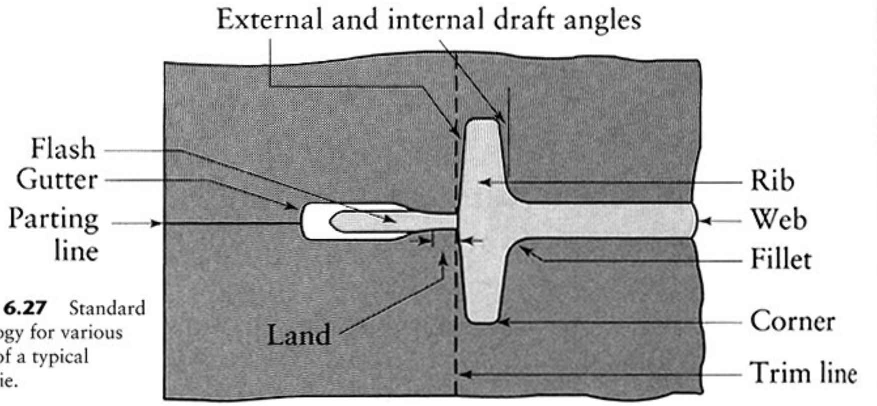


FIGURE 6.27 Standard terminology for various features of a typical forging die.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Forging equipment

- Hydraulic presses(유압프레스)
- Mechanical presses(기계프레스)
- Screw presses(나사프레스) : for parts requiring precision(turbine blades) and control of ram speed.
- Hammers(해머) : potential energy of the ram is converted to kinetic energy.
- Counterblow hammers(카운터블로해머)

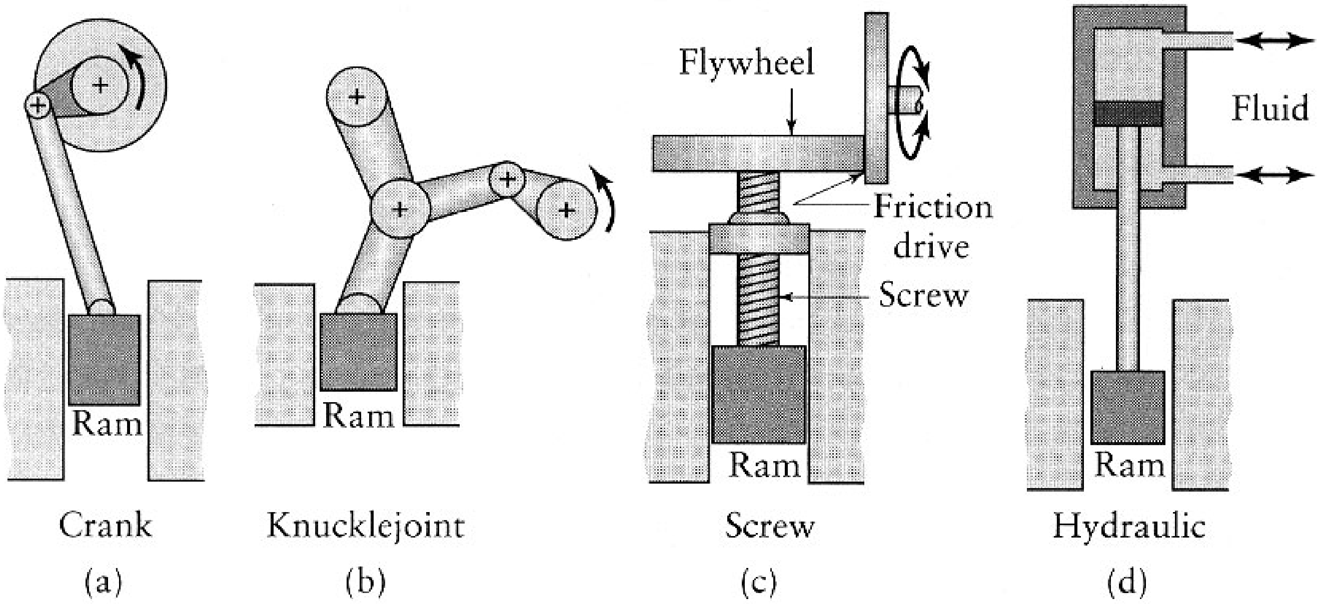


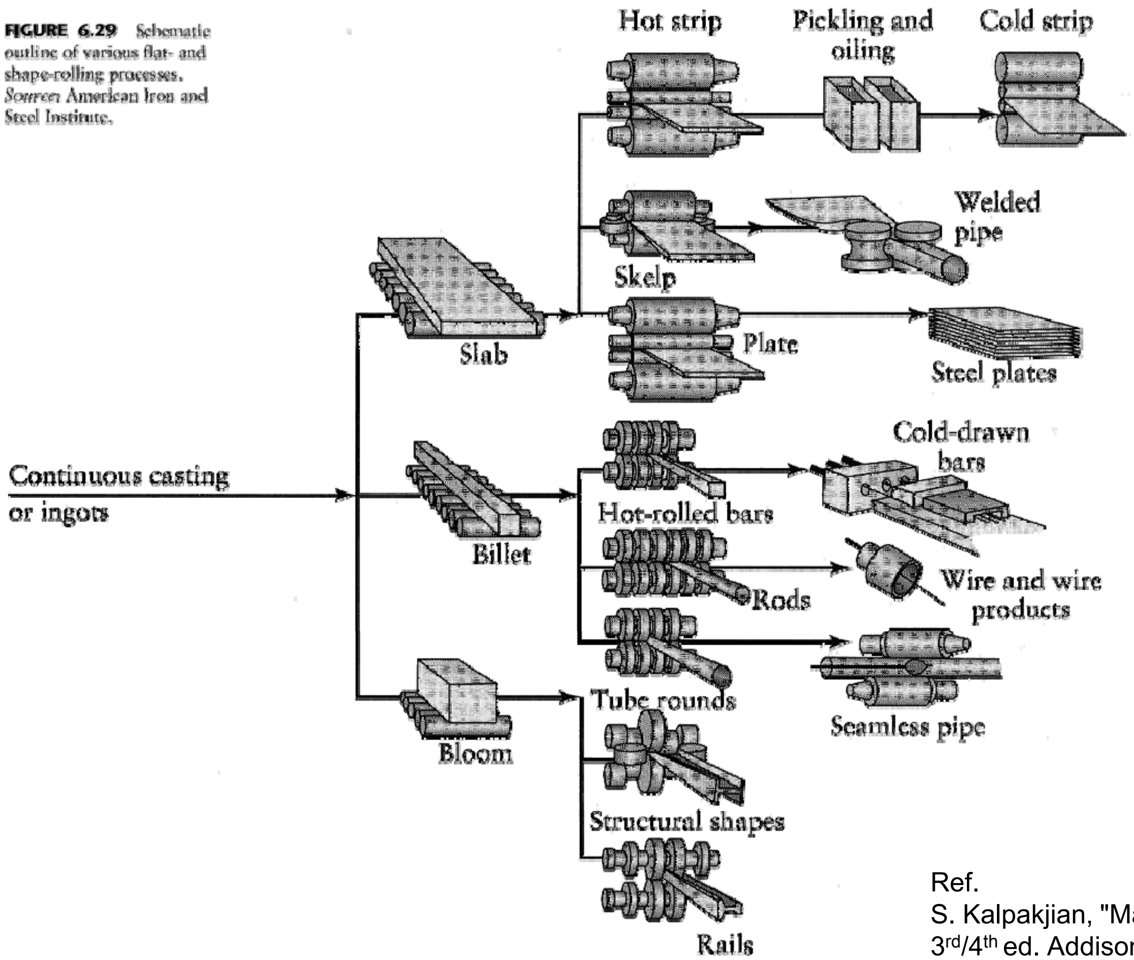
FIGURE 6.28 Schematic illustration of various types of presses used in metalworking. The choice of the press is an important factor in the overall operation.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Rolling (압연)

- The process of reducing the thickness or changing the cross-section of a long workpiece by compressive forces applied through a set of rolls.
- Plate(후판) : t ≥6mm / sheet (박판) : t ≤ 6mm

FIGURE 6.29 Schematic outline of various flat- and shape-rolling processes. *Source:* American Iron and Steel Institute.



Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Changes in the grain structure

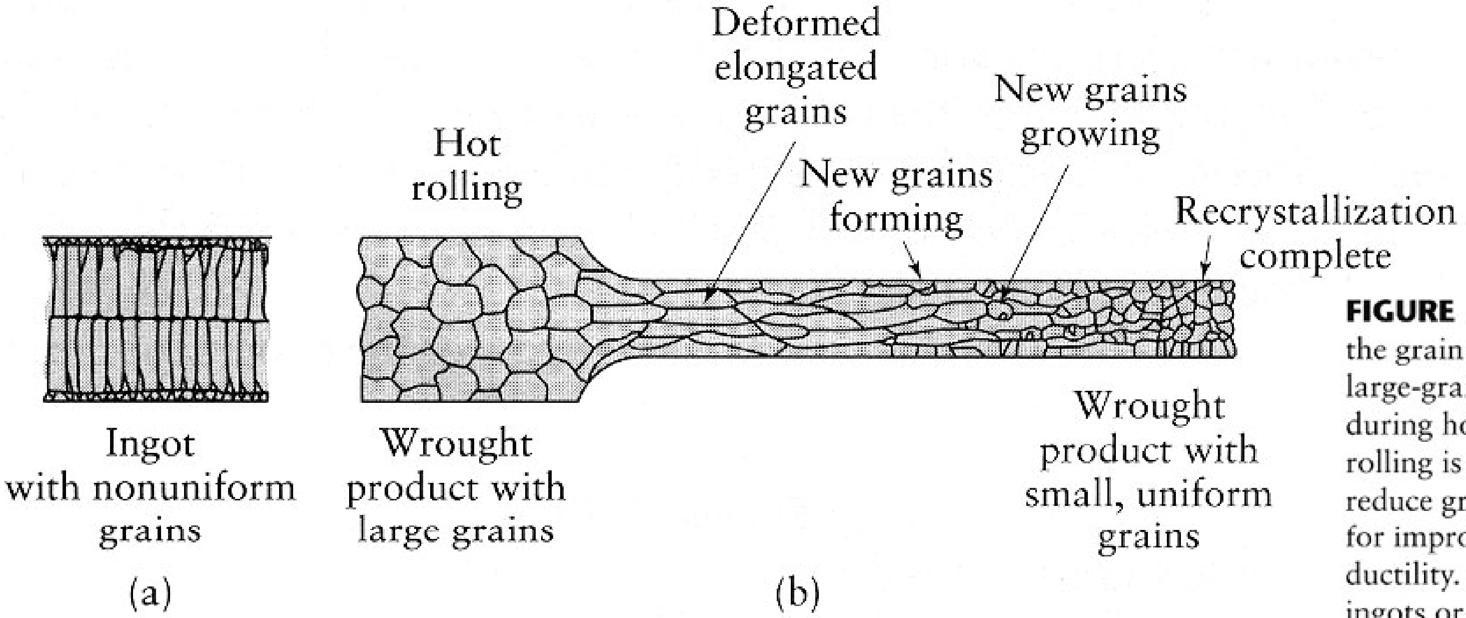


FIGURE 6.30 Changes in the grain structure of cast or large-grain wrought metals during hot rolling. Hot rolling is an effective way to reduce grain size in metals for improved strength and ductility. Cast structures of ingots or continuous castings are converted to a wrought structure by hot working.

Wrought structure
(단련 구조)

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Mechanics of flat rolling

- The velocity of strip must increase as it moves through the roll gap.
- Sliding occurs between the roll and the strip due to the surface speed of the roll is constant.
- Neutral point or no slip point(중립점)
  - Left of neutral point : workpiece velocity < roll velocity
  - Right of neutral point : workpiece velocity > roll velocity
- The frictional forces oppose each other at the neutral point. ($F_{friction\_left} > F_{friction\_right}$)
  → yielding a net frictional force to the right.

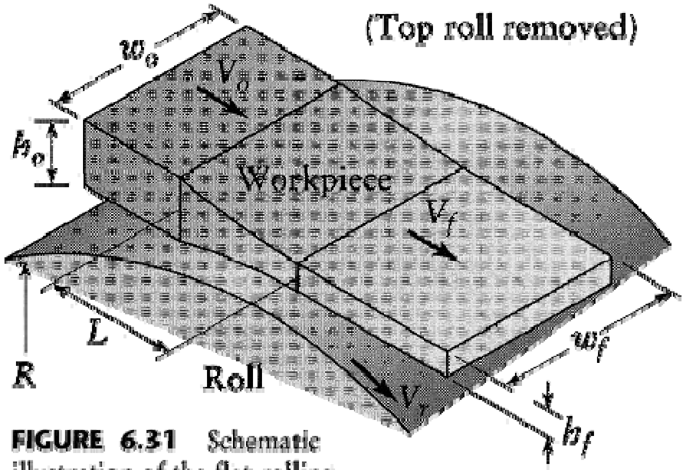


FIGURE 6.31 Schematic illustration of the flat-rolling process. A greater volume of metal is formed by rolling than by any other metalworking process.

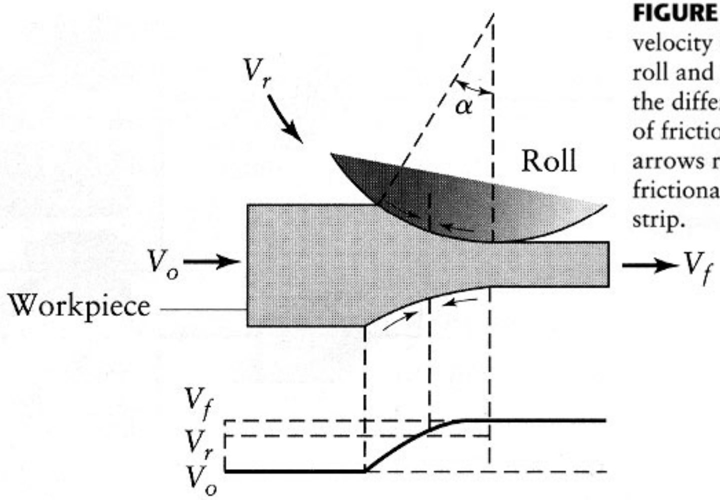


FIGURE 6.32 Relative velocity distribution between roll and strip surfaces. Note the difference in the direction of frictional forces. The arrows represent the frictional forces acting on the strip.

$$\text{Forward slip} = \frac{V_f - V_r}{V_r}$$

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Roll pressure distribution (1)

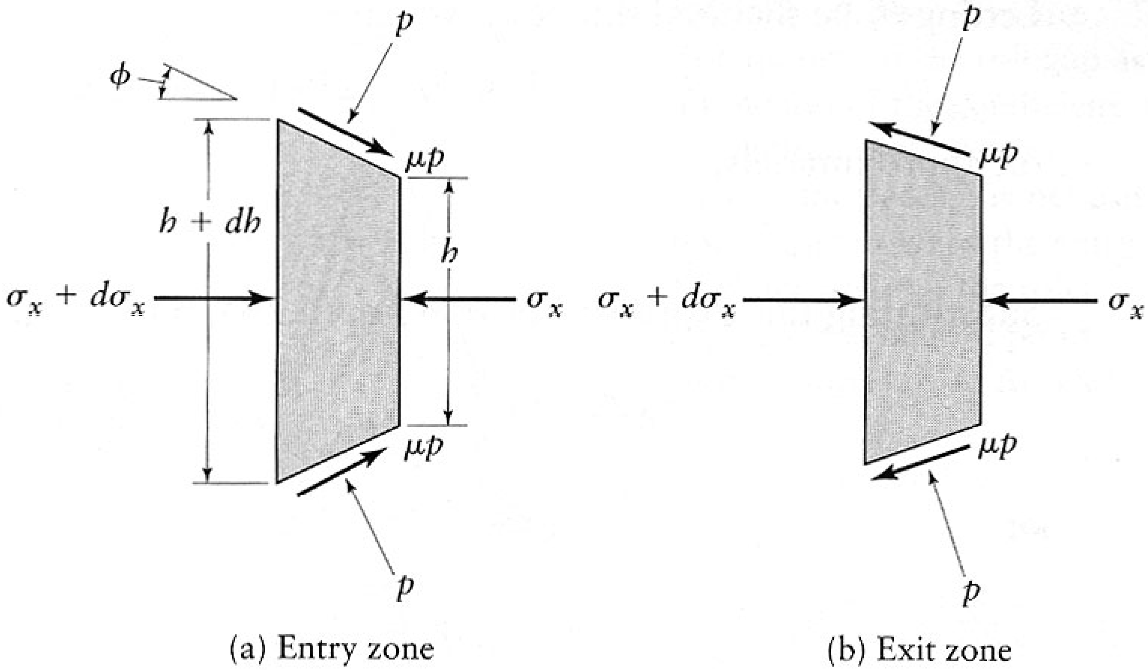


FIGURE 6.33 Stresses on an element in rolling: (a) entry zone and (b) exit zone.

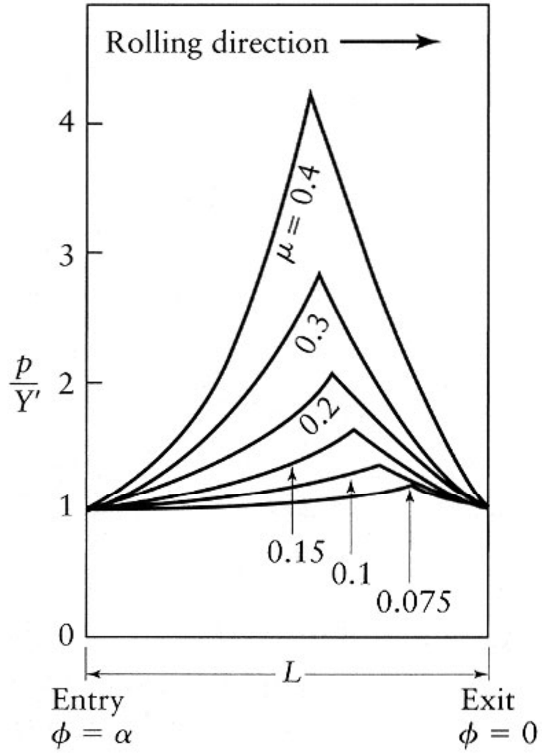


FIGURE 6.34 Pressure distribution in the roll gap as a function of the coefficient of friction. Note that as friction increases, the neutral point shifts toward the entry. Without friction, the rolls slip, and the neutral point shifts completely to the exit.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Roll pressure distribution (2)

$$(\sigma_x + d\sigma_x)(h+dh) - 2pRd\phi\sin\phi - \sigma_x h \pm 2\mu pRd\phi\cos\phi = 0$$

$$\frac{d(\sigma_x h)}{d\phi} = 2pR(\sin\phi \mp \mu\cos\phi)$$

$$\frac{d(\sigma_x h)}{d\phi} = 2pR(\phi \mp \mu) \ , \ (\because \sin\phi \approx \phi \, , \cos\phi \approx 1)$$

$$p - \sigma_x = \frac{2}{\sqrt{3}} Y_f = Y_f'$$

$$\frac{d[(p - Y_f')h]}{d\phi} = 2pR(\phi \mp \mu)$$

$$\frac{d}{d\phi}\left[Y_f'\left(\frac{p}{Y_f'} - 1\right)h\right] = 2pR(\phi \mp \mu)$$

$$Y_f' h \frac{d}{d\phi}\left(\frac{p}{Y_f'}\right) + \left(\frac{p}{Y_f'} - 1\right)\frac{d}{d\phi} Y_f' h = 2pR(\phi \mp \mu)$$

$$\frac{\frac{d}{d\phi}\left(\frac{p}{Y_f'}\right)}{p / Y_f'} = \frac{2R}{h}(\phi \mp \mu)$$

$$h = h_f + 2R(1 - \cos\phi)$$

$$h = h_f + R\phi^2$$

$$\ln\frac{p}{Y_f'} = \ln\frac{h}{R} \mp 2\mu\sqrt{\frac{R}{h_f}}\tan^{-1}\sqrt{\frac{R}{h_f}}\phi + \ln C$$

$$p = CY_f'\frac{h}{R}e^{\mp\mu H}$$

$$H = 2\sqrt{\frac{R}{h_f}}\tan^{-1}\left(\sqrt{\frac{R}{h_f}}\phi\right)$$

In the entry zone : $C = \frac{R}{h_f}e^{\mu H_i}$

$$p = Y_f'\frac{h}{h_o}e^{\mu(H_o - H)}$$

In the exit zone : $C = \frac{R}{h_f}$

$$p = Y_f'\frac{h}{h_f}e^{\mu H}$$

Neutral point / front and back tension

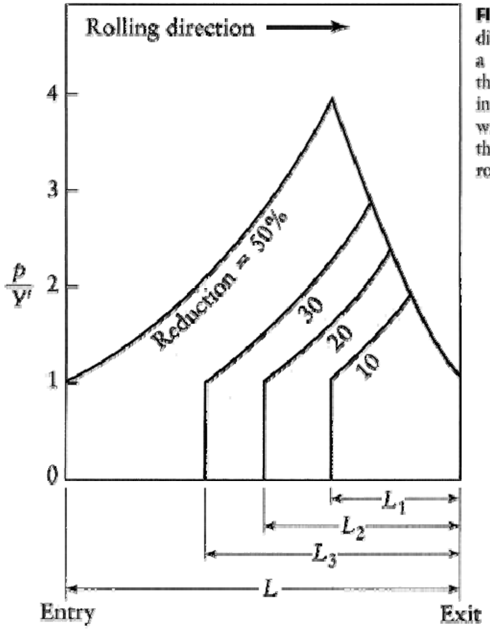
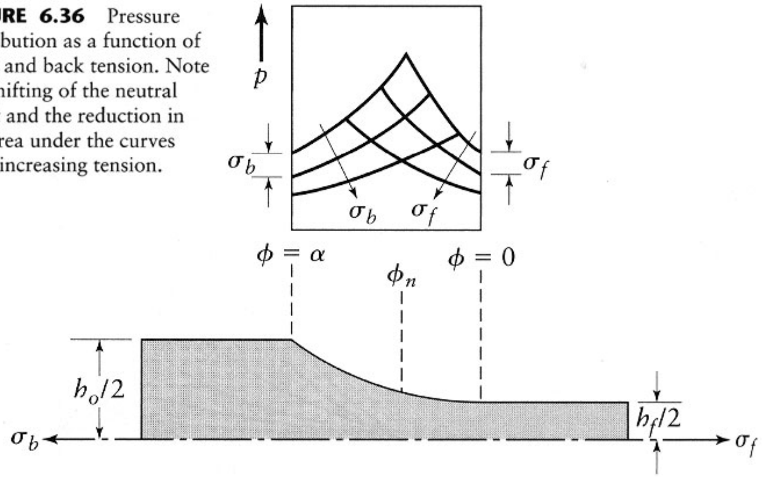


FIGURE 6.35 Pressure distribution in the roll gap as a function of reduction in thickness. Note the increase in the area under the curves with increasing reduction in thickness, thus increasing the roll force.

FIGURE 6.36 Pressure distribution as a function of front and back tension. Note the shifting of the neutral point and the reduction in the area under the curves with increasing tension.



$$\frac{h_o}{h_f} = \frac{e^{\mu H_o}}{e^{2\mu H_n}} = e^{\mu(H_o - 2H_n)}$$

$$H_n = \frac{1}{2}\left(H_o - \frac{1}{\mu}\ln\frac{h_o}{h_f}\right)$$

$$\phi_n = \sqrt{\frac{h_f}{R}}\tan\left(\sqrt{\frac{h_f}{R}}\cdot\frac{H_n}{2}\right)$$

$$\text{Entry zone}: p = (Y'_f - \sigma_b)\frac{h}{h_o}e^{\mu(H_o - H)}$$

$$\text{Exit zone}: p = (Y'_f - \sigma_f)\frac{h}{h_f}e^{\mu H}$$

Exmple 6.3 Back tension required to cause roll slip

$$p_{\phi=0} = (Y'_f - \sigma_b)\frac{h_f}{h_o}e^{\mu H_o}$$

$$\sigma_b = Y'_f\left[1 - \left(\frac{h_o}{h_f}\right)(e^{-\mu H_o})\right]$$

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Defects in rolling

- **Surface defects**
- **Structural defects**
- **Residual stresses**
    - In the case of small-diameter rolls or small reductions, plastic deformation occurs on the surfaces.
      → compressive stresses(surfaces), tensile stresses(bulk).
    - In the case of large-diameter rolls or high reduction, plastic deformation of the bulk is greater than the surfaces.
      → tensile stresses(surfaces), compressive stresses(bulk)

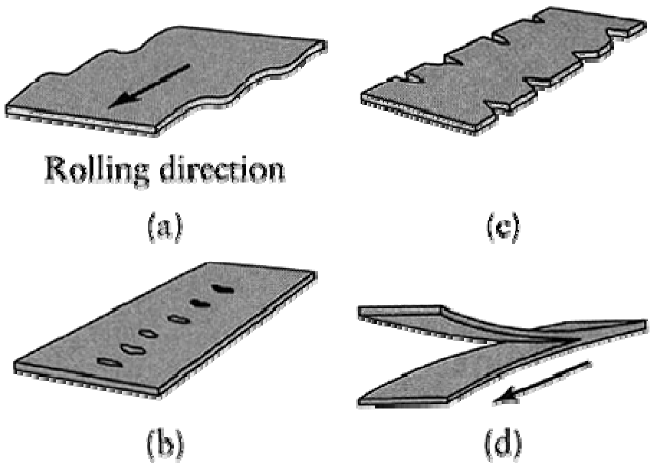


FIGURE 6.39 Schematic illustration of typical defects in flat rolling: (a) wavy edges; (b) zipper cracks in the center of strip; (c) edge cracks; (d) alligatoring.

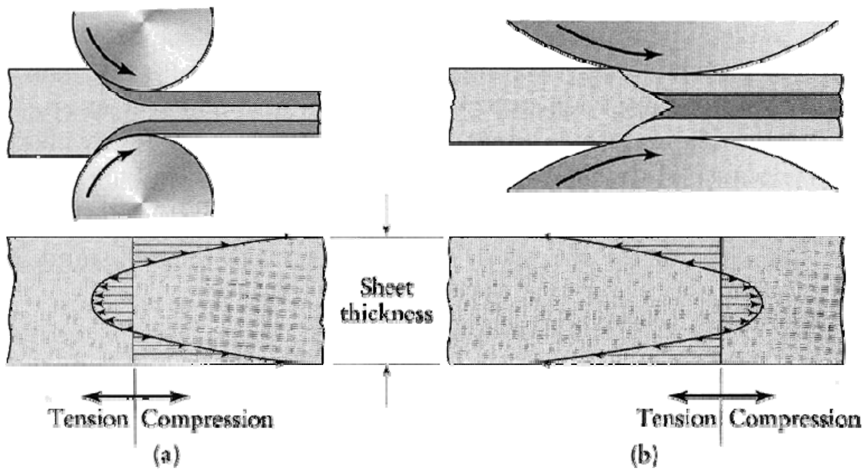


FIGURE 6.40 The effect of roll radius on the type of residual stresses developed in flat rolling: (a) small rolls, or small reduction in thickness; and (b) large rolls, or large reduction in thickness.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Flat-rolling practice (평판 압연 작업)

- **Hot rolling : converts the coarse-grained, brittle and porous cast structure to wrought structure(finer grains and enhanced ductility).**

- **Products of the first hot-rolling operation**
  - Bloom : square cross-section(정사각형), at least 150mm side, structural shapes by shape rolling(e.g. I-beam and railroad rails).
  - Slab : rectangular in cross-section(직사각형), plates and sheet.
  - Billet : square cross-section(정사각형) smaller than bloom, various shapes (e.g. round rods(환봉강) and bars)

- **Rolling equipment**
  - Small-diameter rolls are preferable, because the smaller the roll radius the lower the roll force. However, small rolls deflect under roll forces and have to be supported by other rolls. The cluster mill, or Sendzimir(다단압연기), is particularly suitable for cold rolling thin strips of high-strength metals.

Rolling equipment

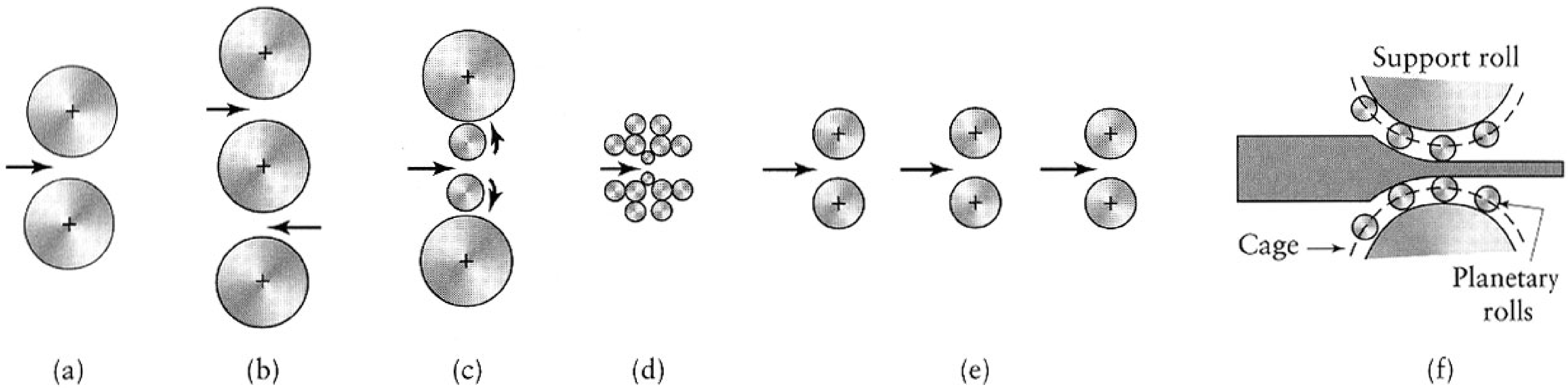


FIGURE 6.42 Schematic illustration of various roll arrangements: (a) two high; (b) three high; (c) four high; (d) cluster; (e) tandem rolling with three stands; (f) planetary.

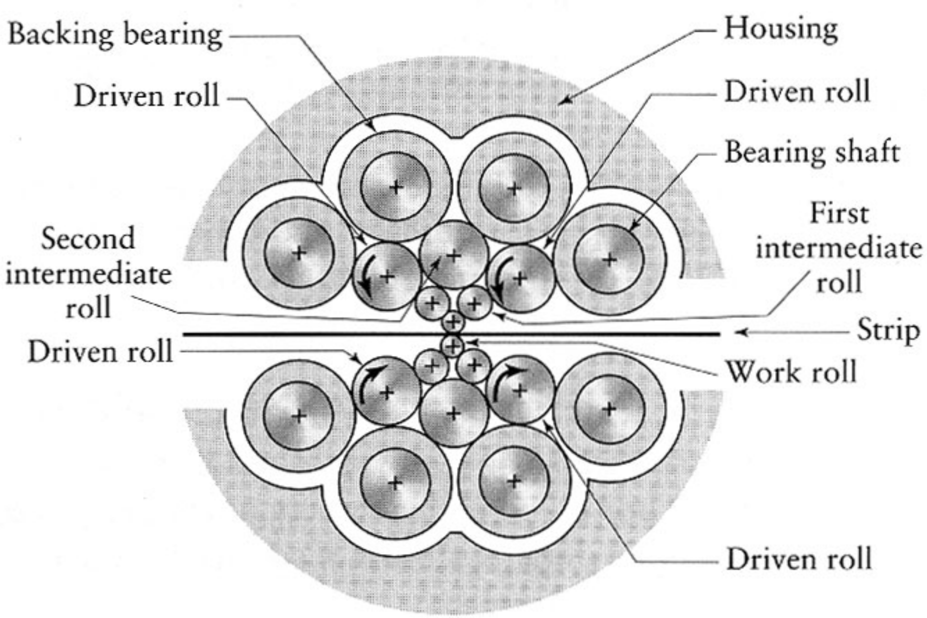


FIGURE 6.43 Schematic illustration of a cluster (*Sendzimir*) mill. These mills are very rigid and are used in rolling thin sheets of high-strength materials, with good control of dimensions.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Miscellaneous rolling operations (1)

- Shape rolling(형상압연) : H-section part, I-Beam and channels.
- Ring rolling(링압연) : rings for rocket, turbines and gearwheel rims.
- Thread and gear rolling(나사 및 기어전조) : high production rates, great strength, improved fatigue life.
- Rotary tube piercing(회전천공) : hot-working process to make long, thick-walled seamless tubing.

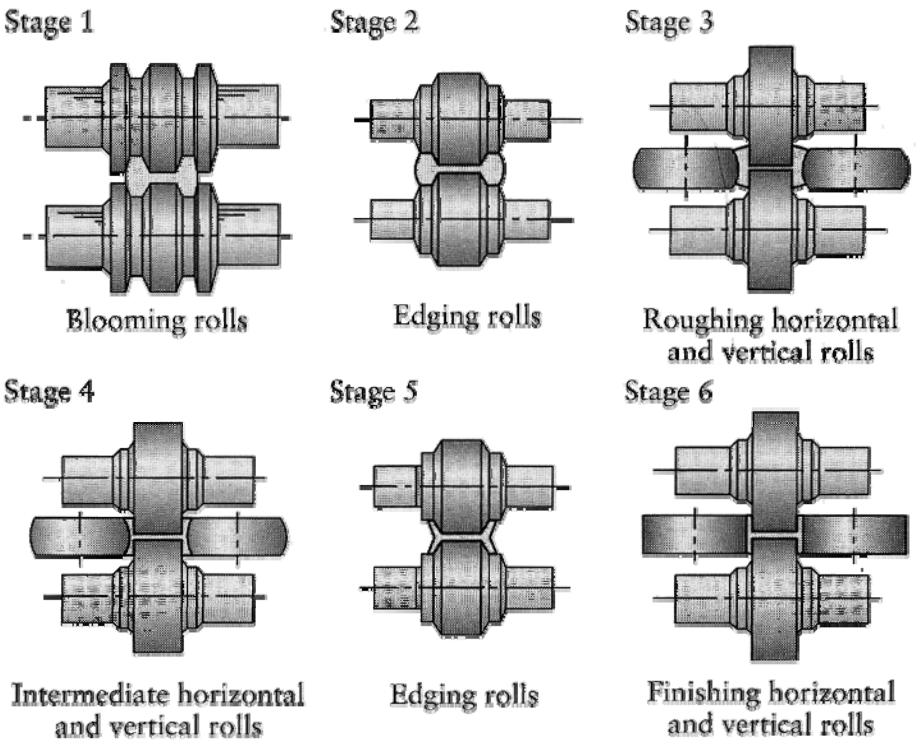
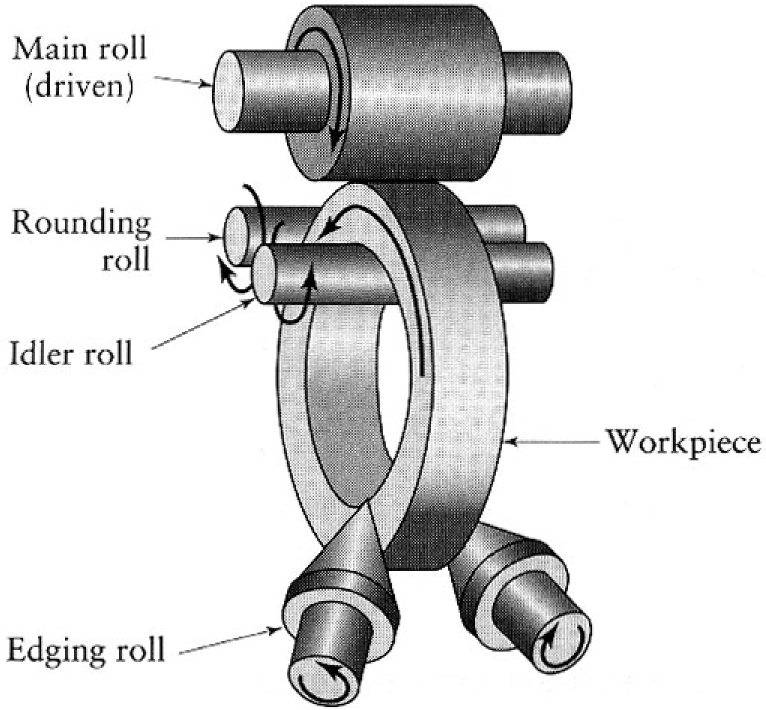


FIGURE 6.44 Stages in shape rolling of an H-section part. Various other structural sections, such as channels and I-beams, are also rolled by this process.

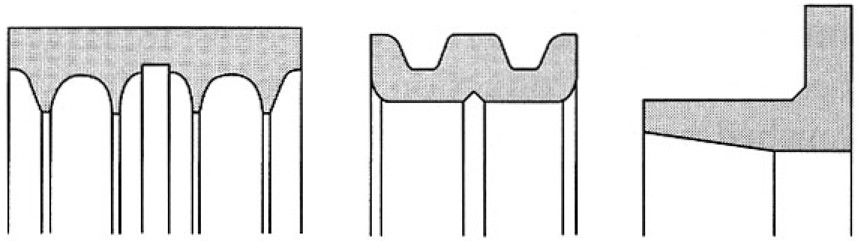
Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Miscellaneous rolling operations (2)

- **Ring rolling**



(a)



(b)

FIGURE 6.45 (a) Schematic illustration of a ring-rolling operation. Reducing the thickness results in an increase in the part's diameter. (b) Examples of cross-sections that can be formed by ring rolling.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Miscellaneous rolling operations (3)

- **Thread and gear rolling**

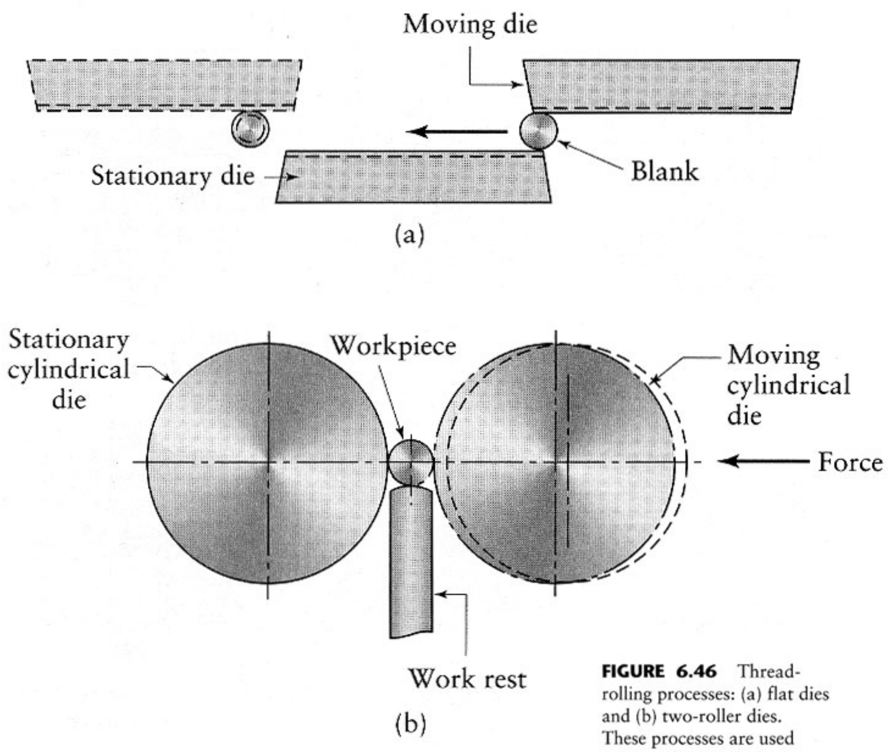


FIGURE 6.46 Thread-rolling processes: (a) flat dies and (b) two-roller dies. These processes are used extensively in making threaded fasteners at high rates of production.

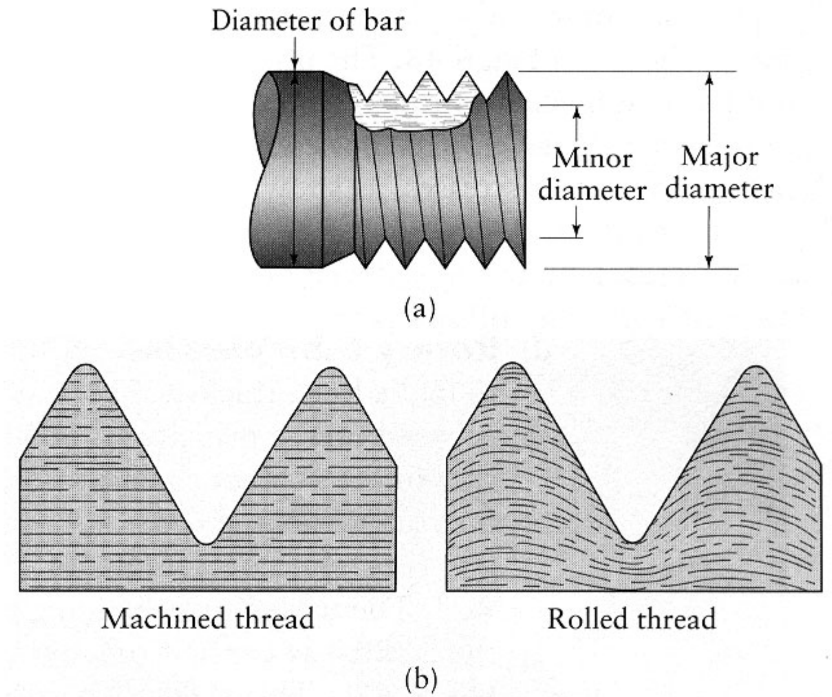


FIGURE 6.47 (a) Schematic illustration of threads. (b) Grain-flow lines in machined and rolled threads. Unlike machined threads, which are cut through the grains of the metal, rolled threads follow the grains and are stronger, because of the cold working involved.

Grain flow lines (단류선)

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Miscellaneous rolling operations (4)

- **Rotary tube piercing**
  - Thick-walled seamless tube.

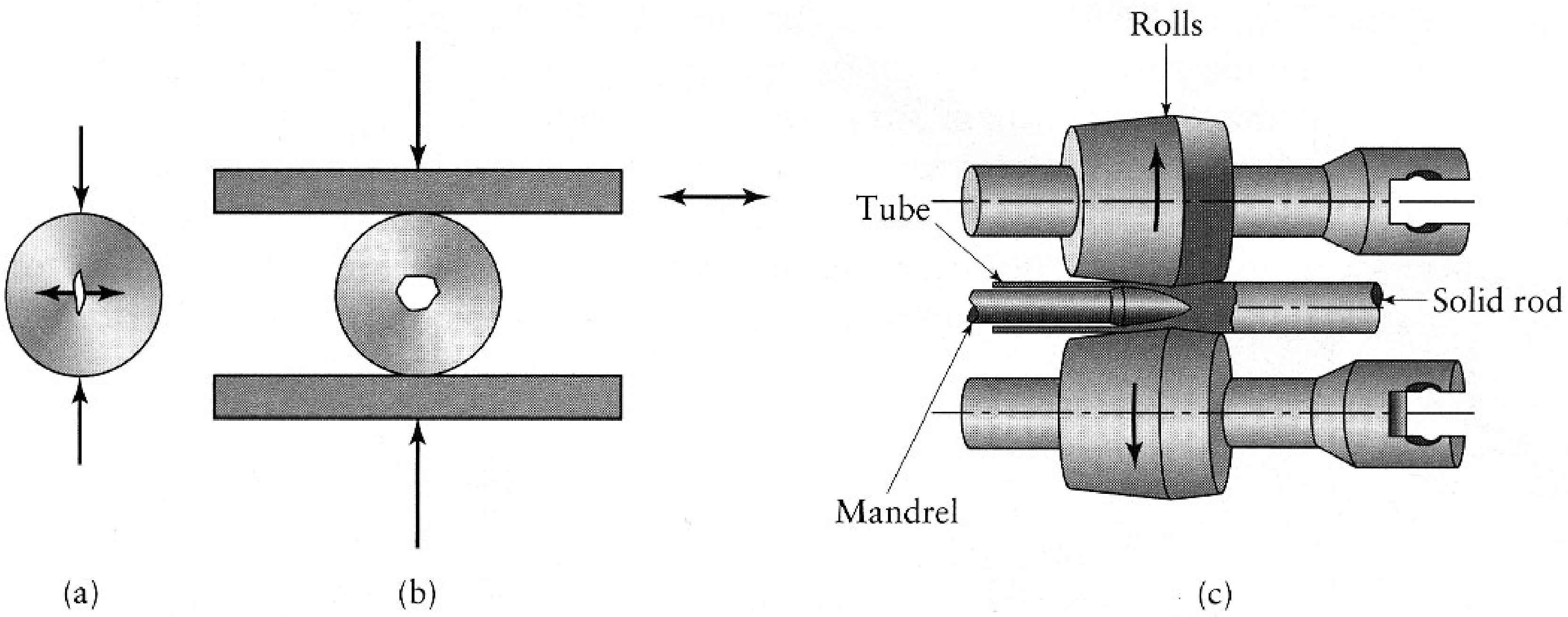
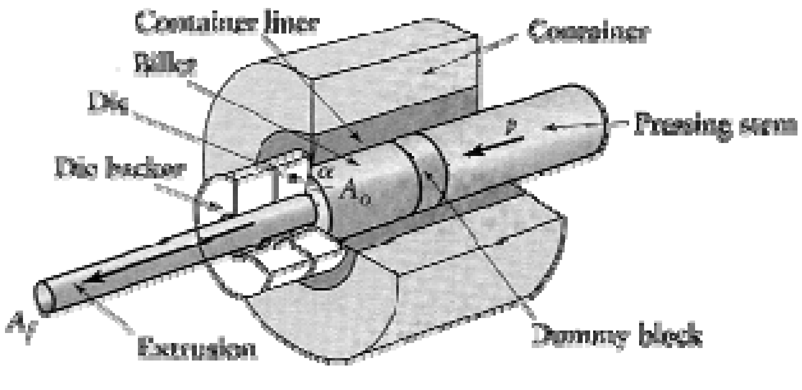


FIGURE 6.48 Cavity formation by secondary tensile stresses in a solid round bar and its use in the rotary-tube-piercing process. This is the principle of the Mannesmann mill for seamless tube making. The mandrel is held in place by the long rod, although techniques have been developed in which the mandrel remains in place without the rod.

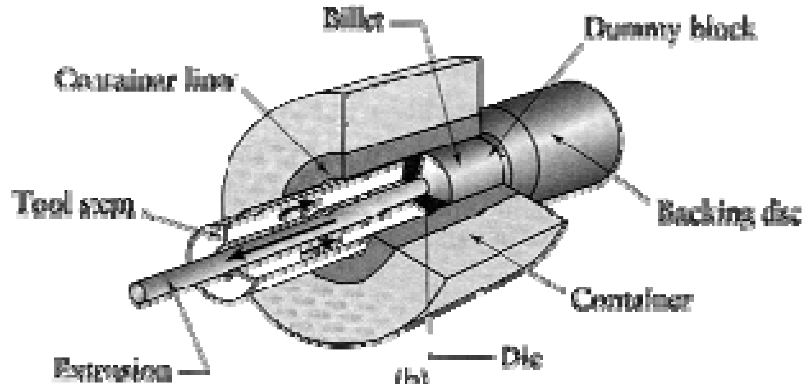
Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Extrusion (압출)



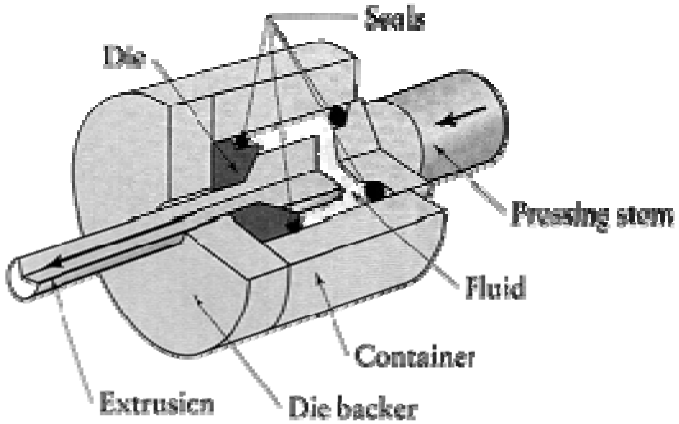
(a)

Direct extrusion(직접압출) : high friction between billet and wall



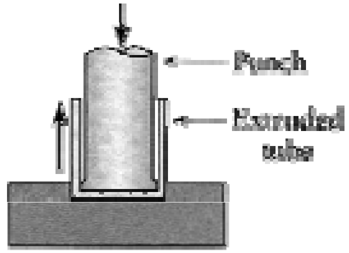
(b)

Indirect extrusion(간접압출) : no friction between billet and wall, die moves to the billet.



(c)

Hydrostatic extrusion(정수압압출) : no friction along the container walls.



(d)

Impact extrusion(충격압출) : form of indirect extrusion, suitable for hollow shapes.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", $3^{rd}/4^{th}$ ed. Addison Wesley

Mechanics of extrusion (1)

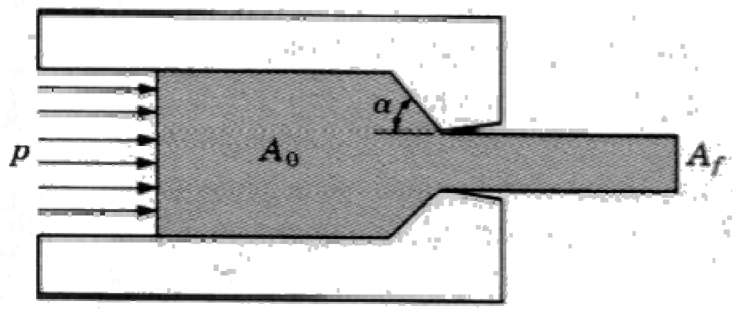


FIGURE 6.54 Variables in the direct-extrusion process.

$$\text{Extrusion ratio, } R = \frac{A_o}{A_f}$$

$$\varepsilon_1 = \ln\left(\frac{A_o}{A_f}\right) = \ln\left(\frac{L_f}{L_o}\right) = \ln R$$

Energy dissipated in plastic deformation per unit volume $\longrightarrow u = Y\varepsilon_1$

$$\text{Work} = (A_o)(L_o)(u)$$

$$\text{Work} = FL_o = pA_oL_o$$

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

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Mechanics of extrusion (2)

When friction is included

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

$$P_{total} = P_{plastic} + P_{friction}$$

$$P_{total} = pV_o(\pi D_0^2 / 4)$$

$$P_{plastic} = V_o(\pi D_0^2/4)(Y)[\ln(D_o/D_f)^2]$$

$$P_{friction} = (V_o)(\pi D_0^2/\sqrt{2})(Y/2)\ln(D_o/D_f)$$

$$p/Y = 3.41\ln(D_o/D_f) = 1.7[\ln(D_o/D_f)^2]$$

$$p = 1.7Y\ln R$$

$$(p_{friction})\left(\frac{\pi D_0^2}{4}\right) = \pi D_o k L$$

$$p_{friction} = k\frac{4L}{D_o} = Y\frac{2L}{D_o}$$

$$p = Y\left(1.7\ln R + \frac{2L}{D_o}\right)$$

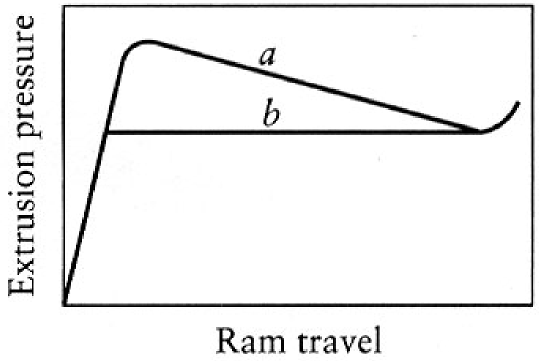


FIGURE 6.52 Schematic illustration of typical extrusion pressure as a function of ram travel: (a) direct extrusion and (b) indirect extrusion. The pressure in direct extrusion is higher because of frictional resistance in the chamber as the billet moves toward the die.

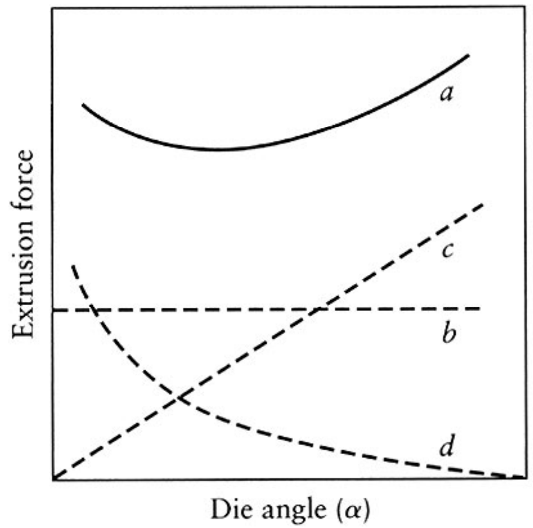


FIGURE 6.53 Schematic illustration of extrusion force as a function of die angle: (a) total force; (b) ideal force; (c) force required for redundant deformation; (d) force required to overcome friction. Note that there is an optimum die angle where the total extrusion force is a minimum.

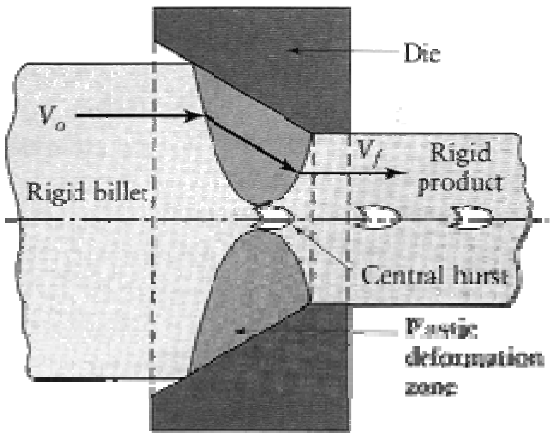
$$\text{Actual forces}: \; p = Y(a + b\ln R)$$

$(Emperical\;\; formula)$

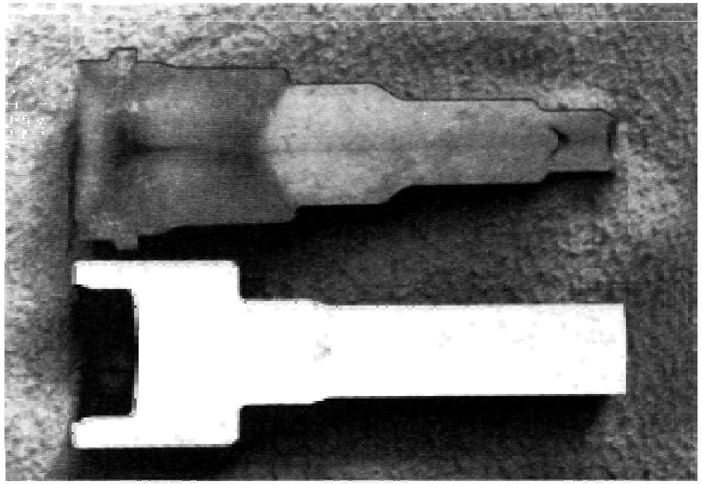
Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Defects in extrusion

- Surface cracking(표면균열)
  - **Too high extrusion temperature, friction, or extrusion speed.**
  - **Periodic sticking of the extruded product along the die land.**
- Extrusion defect(파이프결함)
  - **Surface oxides and impurities drawn toward the center of the billet.**
  - **Reduced by modifying the flow pattern, machining the surface of the billet or using a dummy block.**
- Internal cracking(내부균열) : due to hydrostatic tensile stress at the center line.



(a)



(b) Chevron cracking

FIGURE 6.59 (a) Deformation zone in extrusion, showing rigid and plastic zones. Note that the plastic zones do not meet, leading to chevron cracking. The same observations are also made in drawing round bars through conical dies and drawing flat sheet or plate through wedge-shaped dies. Source: After B. Avitzur. (b) Chevron cracking in round steel bars during extrusion. Unless the part is inspected properly, such internal defects may remain undetected and possibly cause failure of the part in service.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Drawing (인발)

- The cross-sectional area of a bar or tube is reduced by pulling it through a converging die.
- Rod and wire drawing are usually finishing process.

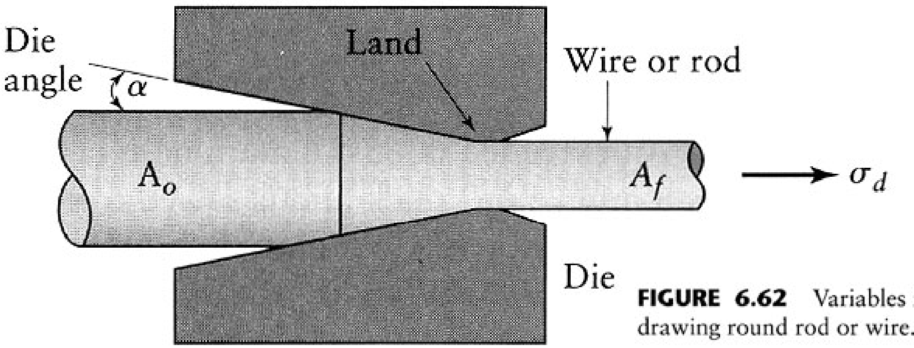


FIGURE 6.62 Variables in drawing round rod or wire.

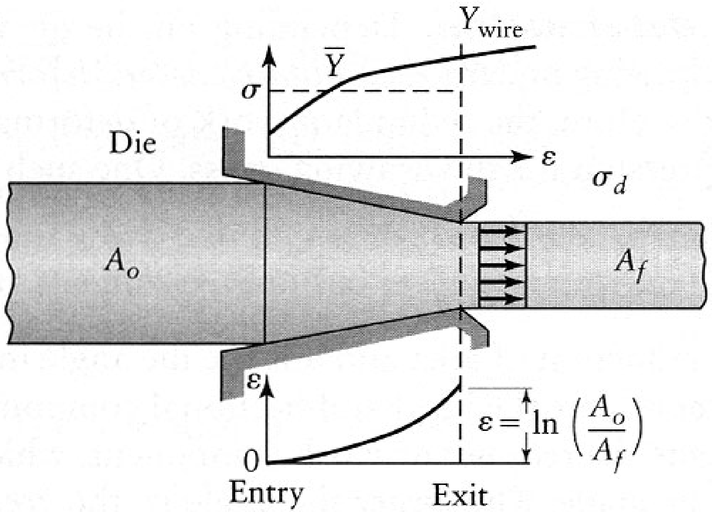


FIGURE 6.63 Variation in strain and flow stress in the deformation zone in drawing. Note that the strain increases rapidly toward the exit. The reason is that when the exit diameter is zero, the true strain reaches infinity. The point Y_{wire} represents the yield stress of the drawn wire.

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

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

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

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

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Defects in drawing

- Similar to defects in extrusion.
- Seams(솔기결함) : longitudinal scratches or folds in the material.

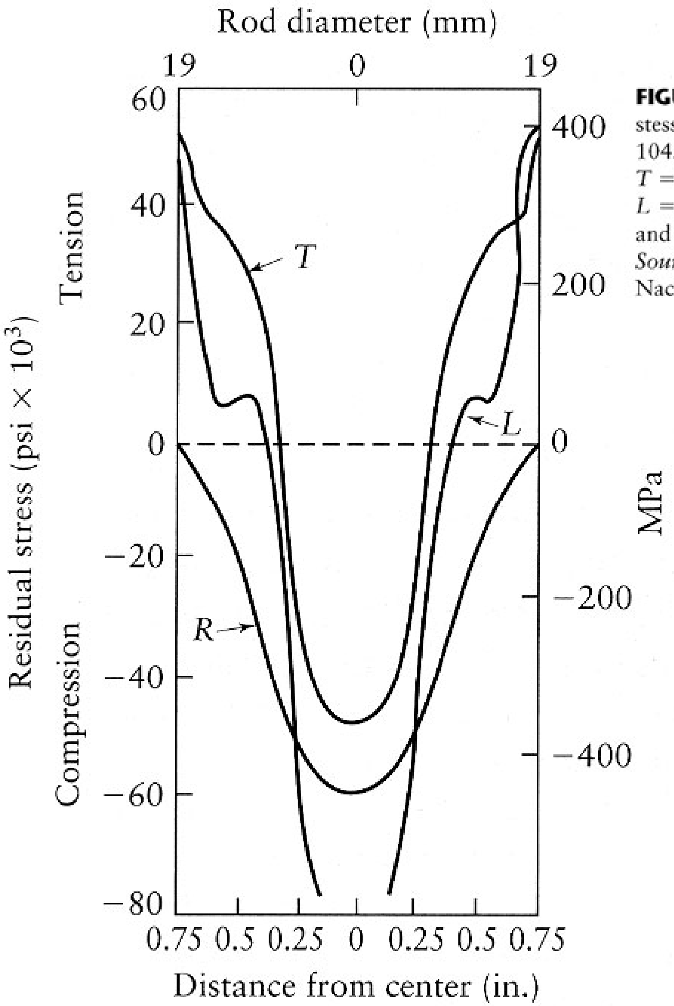


FIGURE 6.68 Residual stesses in cold-drawn AISI 1045 carbon steel round rod: T = transverse direction, L = longitudinal direction, and R = radial direction. *Source*: After E. S. Nachtman.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Swaging (스웨이징) (1)

- The metal flows in to the dies which apply compressive force or impact to the metal at room temperature.
- Rotary swaging(회전 스웨이징) : a solid rod or a tube is reduced in diameter by reciprocating radial movement of dies.
- The Internal diameter and thickness or shape of the tube can be controlled with or without mandrels(맨드릴).

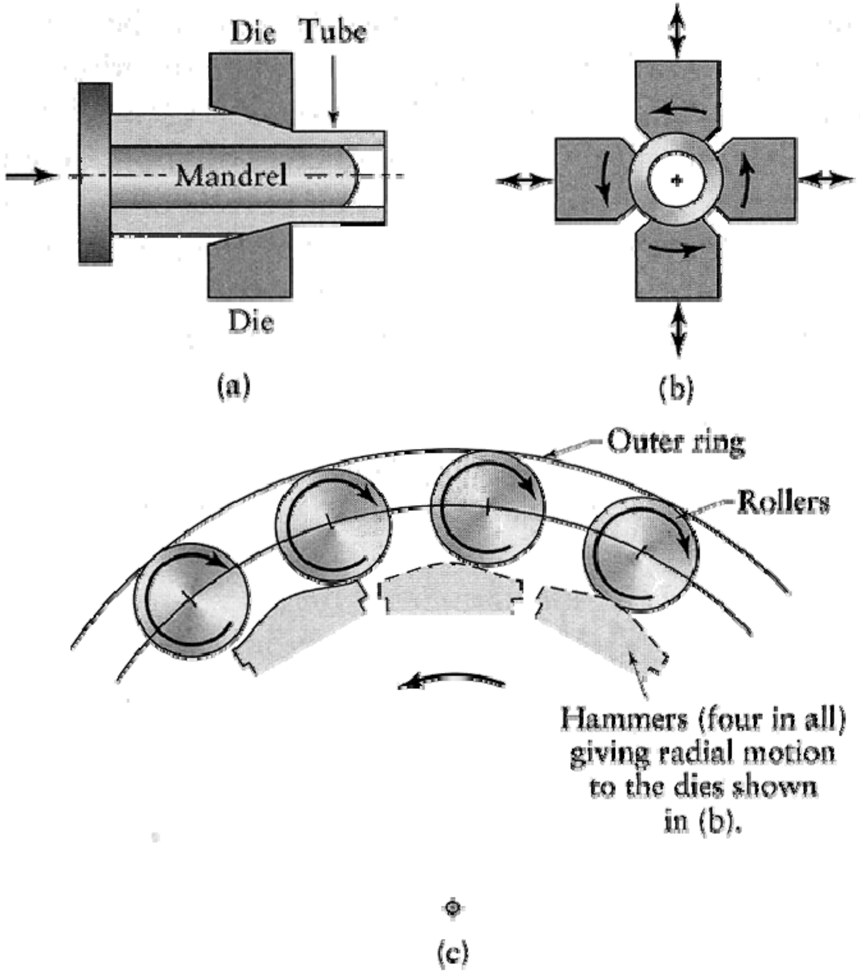


FIGURE 6.71 Schematic illustration of the swaging process: (a) side view and (b) front view. (c) Schematic illustration of roller arrangement, curvature on the four radial hammers (that give motion to the dies), and the radial movement of a hammer as it rotates over the rolls.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Swaging (스웨이징) (2)

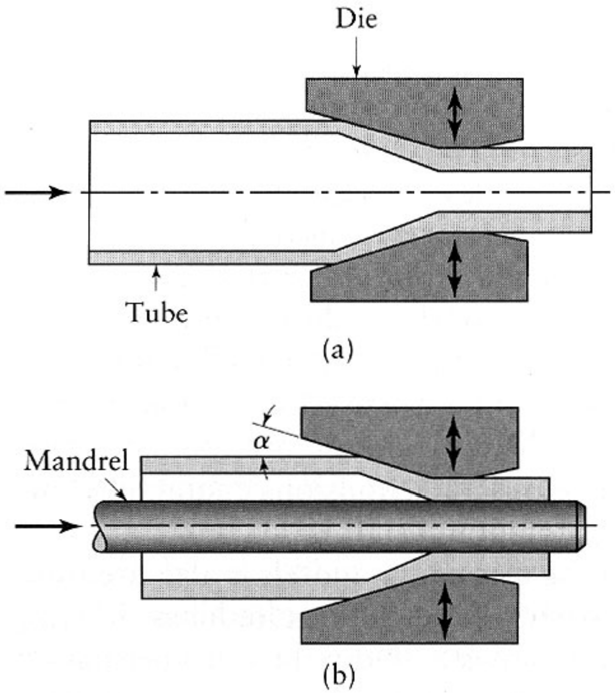


FIGURE 6.72 Reduction of outer and inner diameters of tubes by swaging. (a) Free sinking without a mandrel. The ends of solid bars and wire are tapered (pointing) by this process in order to feed the material into the conical die. (b) Sinking on a mandrel. Coaxial tubes of different materials can also be swaged in one operation.

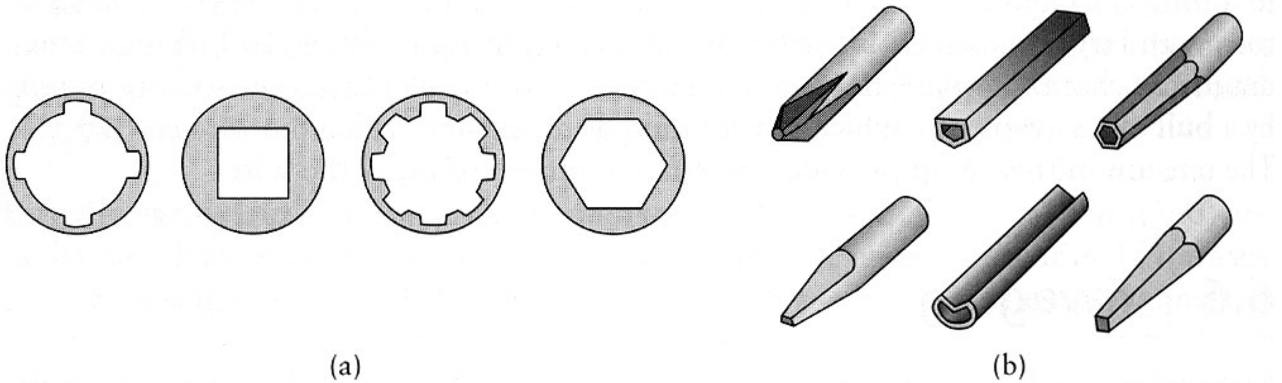


FIGURE 6.73 (a) Typical cross-sections produced by swaging tube blanks with a constant wall thickness on shaped mandrels. Rifling of small gun barrels can also be made by swaging, using a specially shaped mandrel. The formed tube is then removed by slipping it out of the mandrel. (b) These parts can also be made by swaging.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Case study (Space shuttle)

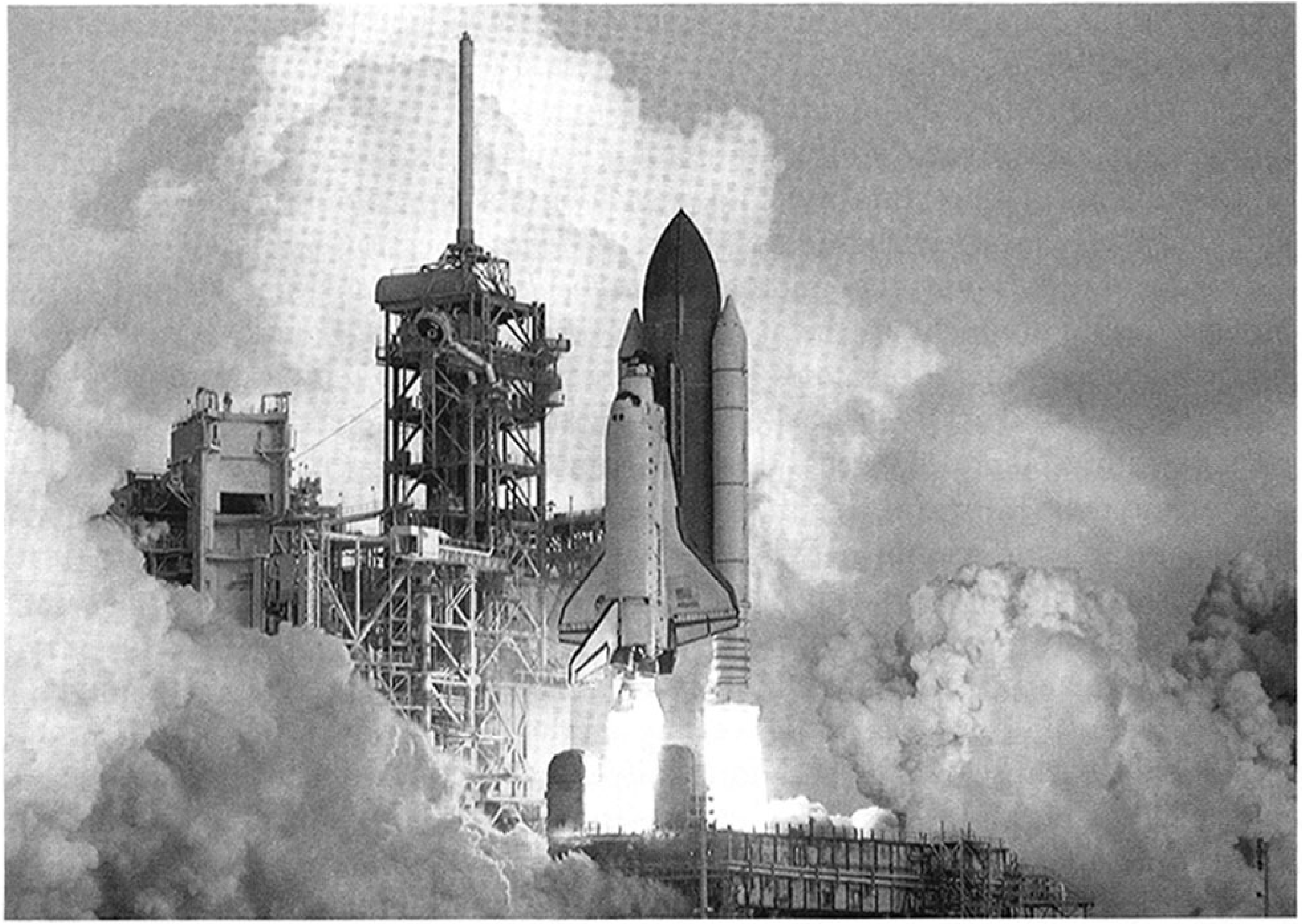


FIGURE 6.74 The Space Shuttle *Atlantis* is launched by two strap-on solid rocket boosters. *Source*: NASA.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Solid rocket casing

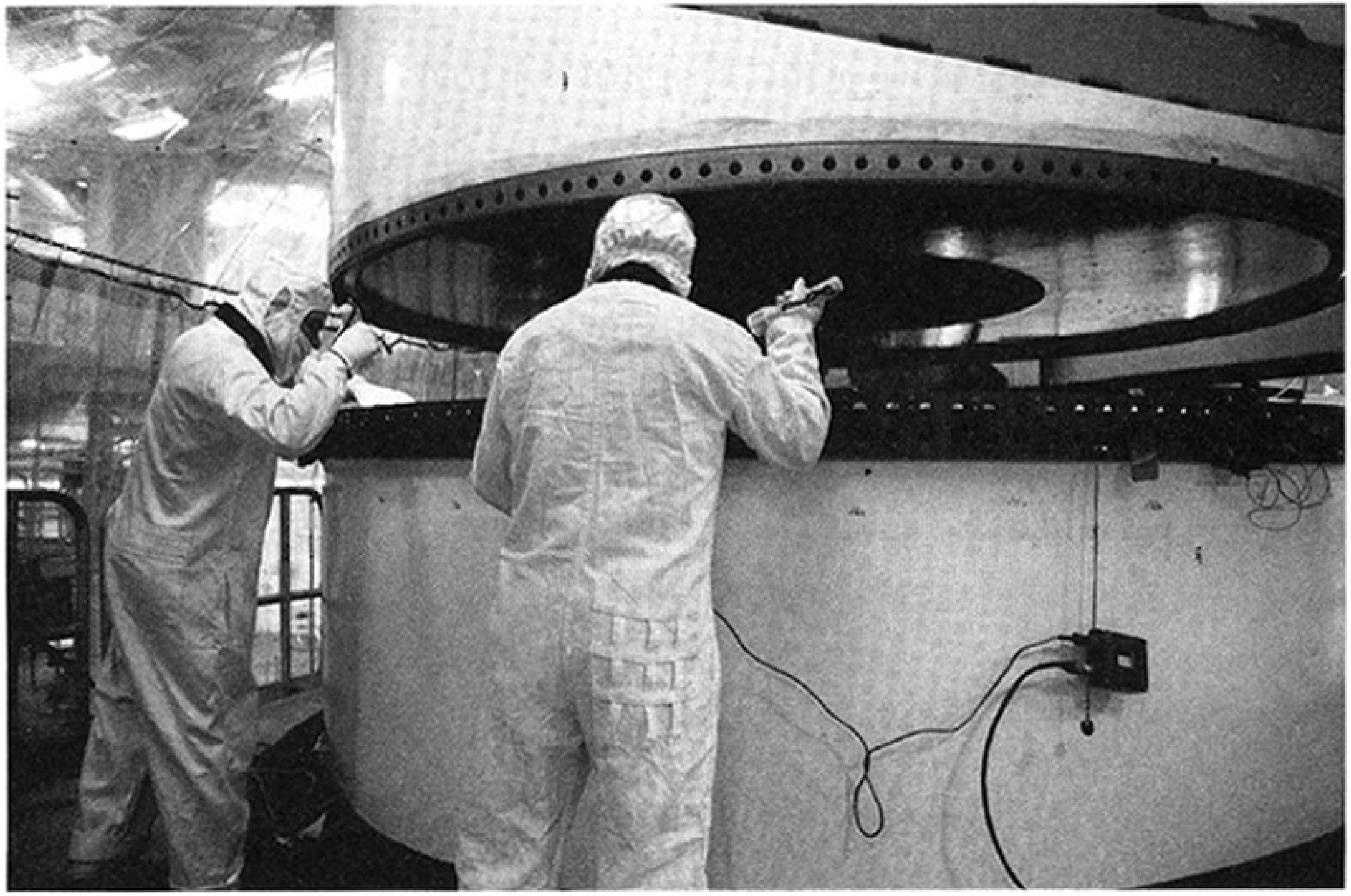


FIGURE 6.75 Assembly of steel case segments to form a solid rocket booster. Note that most of the rocket casing is below the platform level. *Source*: NASA.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley

Forging processes for solid rocket casing

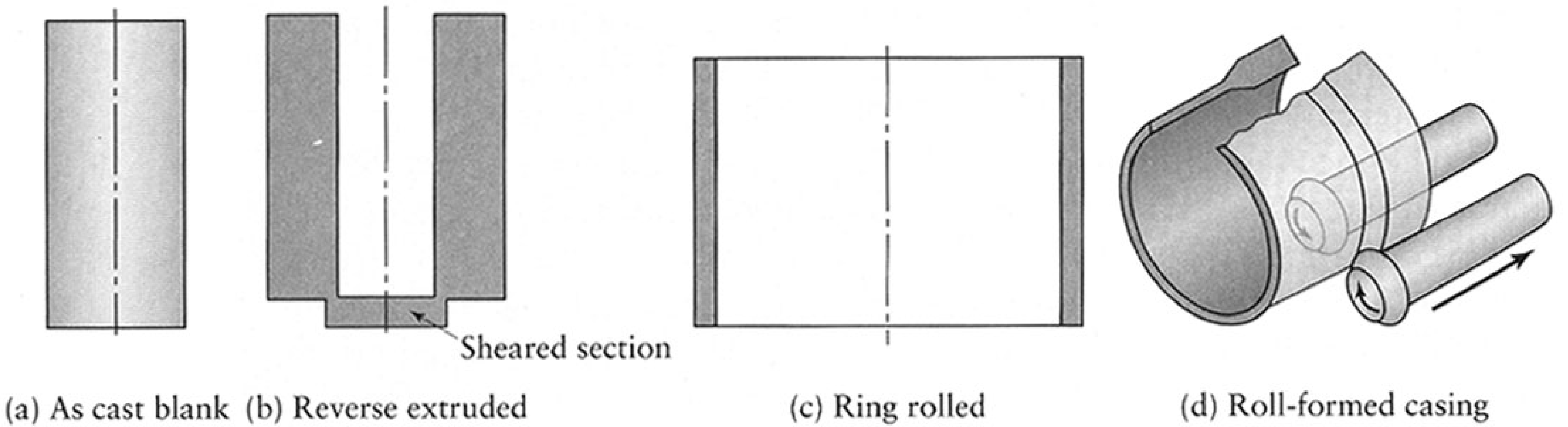


FIGURE 6.76 The forming processes involved in the manufacture of solid rocket casings for the U.S. Space Shuttle.

Ref.
S. Kalpakjian, "Manufacturing Processes for Engineering Materials", 3rd/4th ed. Addison Wesley