446.305A MANUFACTURING PROCESSES

Chapter 7. Sheet-Metal Forming Processes

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Sheet-Metal Characteristics

- **Press working / stamping / shearing**
  - Forming of sheet metals generally is carried out by tensile forces in the plane of the sheet.
  - Application of compressive forces could lead to buckling, folding, and wrinkling of the sheet.
  - Mechanics of all sheet forming basically consists of the processes of stretching and bending.
  - Factors influencing the operation.
    : elongation, yield-point elongation, anisotropy, grain size, residual stresses, springback, and wrinkling.

Elongation (연신율)

- High uniform elongation is desirable for good formability. (large n, m)

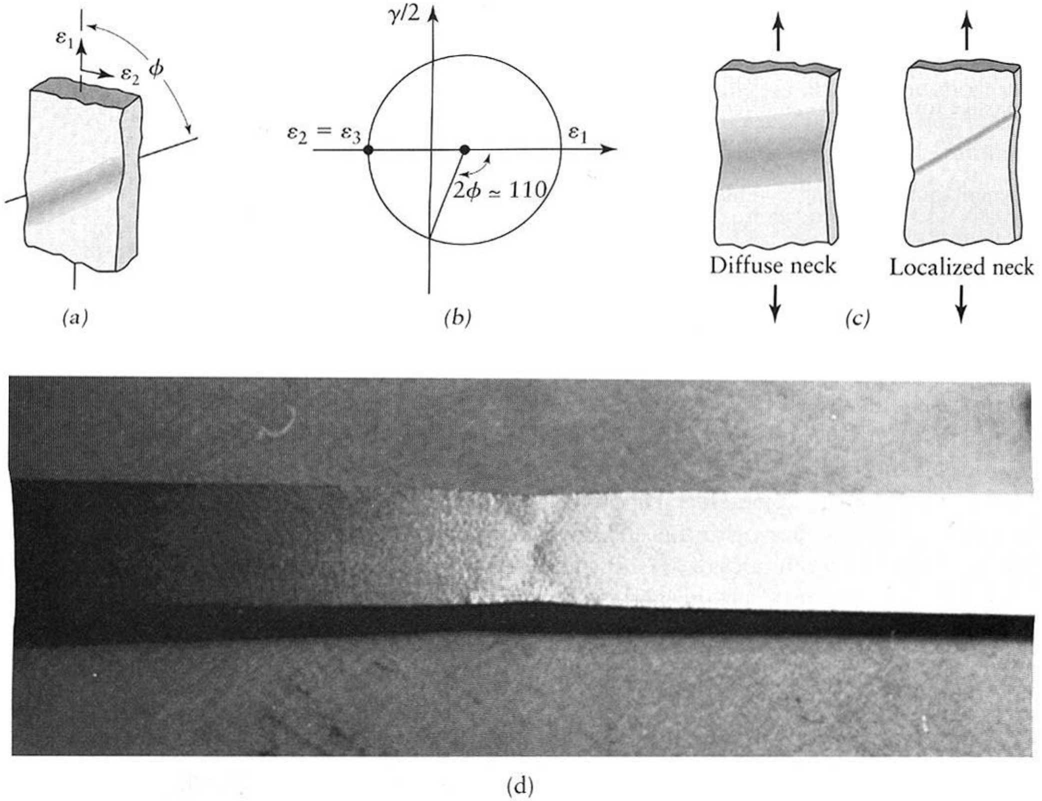


FIGURE 7.1 (a) Localized necking in a sheet specimen under tension. (b) Determination of the angle of neck from the Mohr's circle for strain. (c) Schematic illustrations for diffuse and localized necking. (d) Localized necking in an aluminum strip stretched in tension. Note the double neck.

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

$$\varepsilon = n$$

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

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

Yield Point Elongation (항복점 신장)

- Low-carbon steels exhibit yield-point elongation.
- Lueder's bands(stretcher strain marks, 신장변형마크)

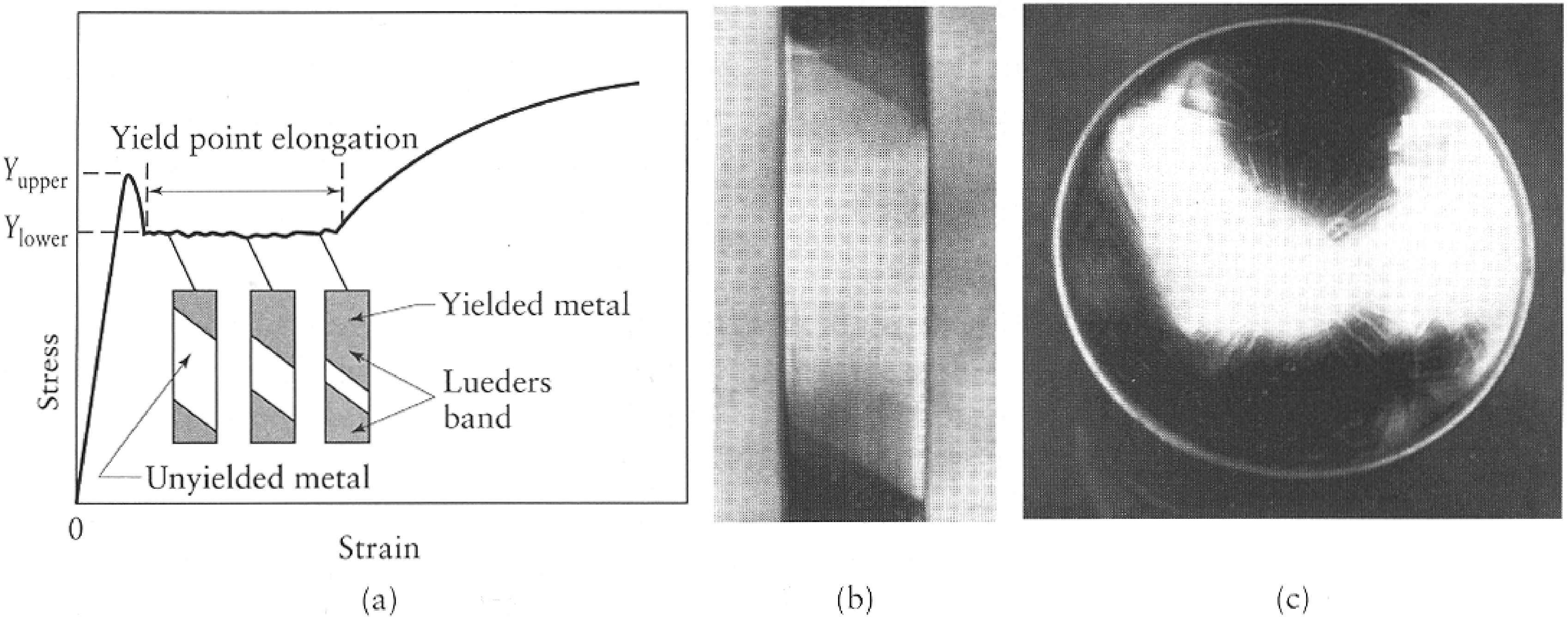


FIGURE 7.2 (a) Yield point elongation and Lueders bands in tension testing. (b) Lueder's bands in annealed low-carbon steel sheet. (c) Stretcher strains at the bottom of a steel can for household products. *Source*: (b) Reprinted Courtesy of Caterpillar Inc.

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

Anisotropy (이방성) / Grain size (결정립 크기) / Residual stresses (잔류응력) / Springback (스프링백) / Wrinkling (주름)

- **Anisotropy**
  - Acquired during thermo mechanical-processing history.
  - Crystallographic anisotropy(결정립의 방향성)
  - Mechanical fibering(기계적 섬유화) : alignment of impurities(불순물), inclusions(개재물) and voids(공극)

- **Coarse grain(조대 결정립) → orange peel**
  - The temperature of residual stresses relieving is lowered to reduce the energy which enlarges the grain.

- **Residual stresses**
  - Tensile residual stresses on surfaces
    → stress-corrosion cracking(응력-부식 균열)

- **Springback : high bend radius-to-thickness ratio.**
- **Wrinkling : occurs where the compressive stresses are developed.**

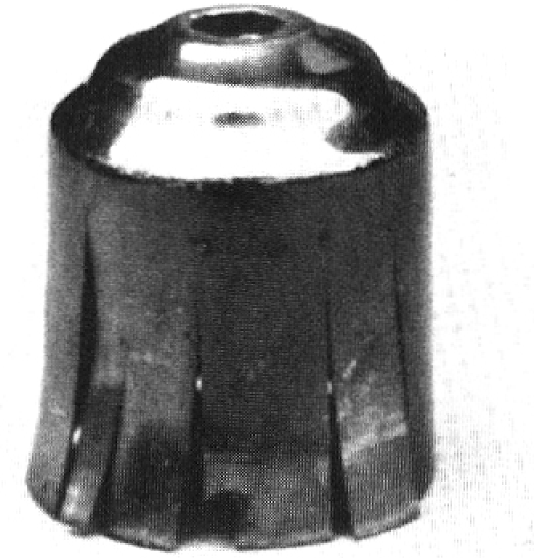


FIGURE 7.3 Stress-corrosion cracking in a deep-drawn brass part for a light fixture. The cracks developed over a period of time. Brass and austenitic (300 series) stainless steels are among metals that are susceptible to stress-corrosion cracking.

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

Shearing Process (전단작업) (1)

- **The shearing process involves cutting sheet metal by subjecting it to shear stresses, usually between a punch and a die.**

- **Shearing process variables**

  : Punch force, punch speed, edge condition of the sheet, lubrication, corner radii of the punch and die, and clearance between the punch and die.

  (6~10% of the sheet thickness : for big sheets)

  (2~8% of the sheet thickness : for general sheets)

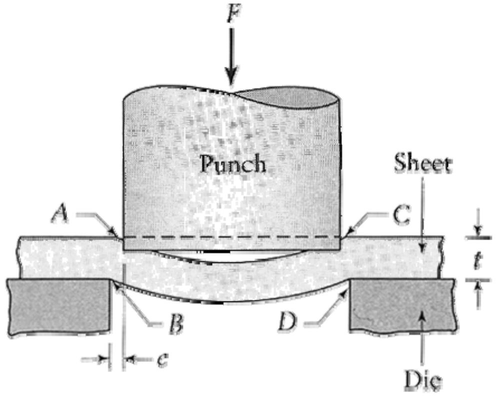


FIGURE 7.4 Schematic illustration of the shearing process with a punch and die. This process is a common method of producing various openings in sheet metals.

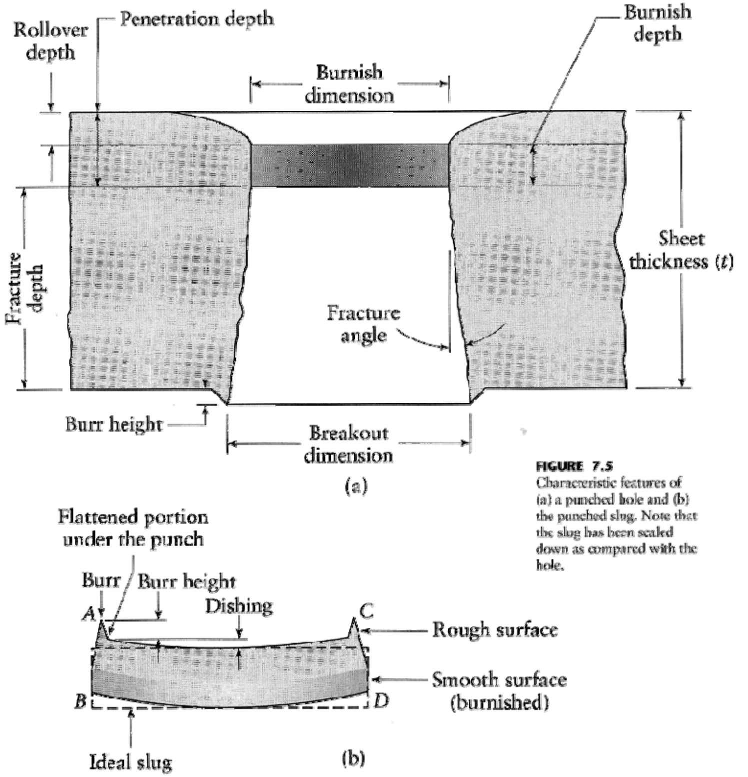
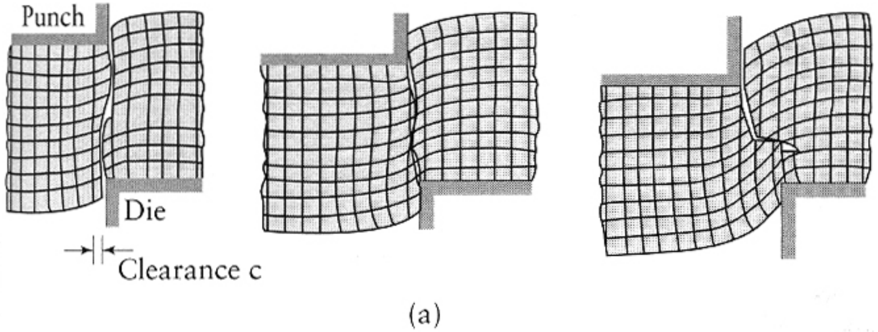


FIGURE 7.5 Characteristic features of (a) a punched hole and (b) the punched slug. Note that the slug has been scaled down as compared with the hole.

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

Shearing Process (전단작업) (2)



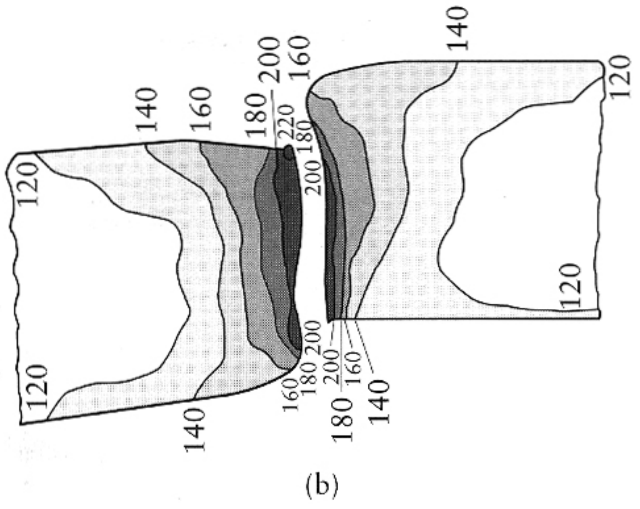


FIGURE 7.6 (a) Effect of clearance *c* between the punch and die on the deformation zone in shearing. As clearance increases, the material tends to be pulled into the die, rather than being sheared. In practice, clearances usually range between 2% and 10% of the thickness of the sheet. (b) Microhardness (HV) contours for a 6.4-mm (0.25-in.) thick AISI 1020 hot-rolled steel in the sheared region. *Source*: After H. P. Weaver and K. J. Weinmann.

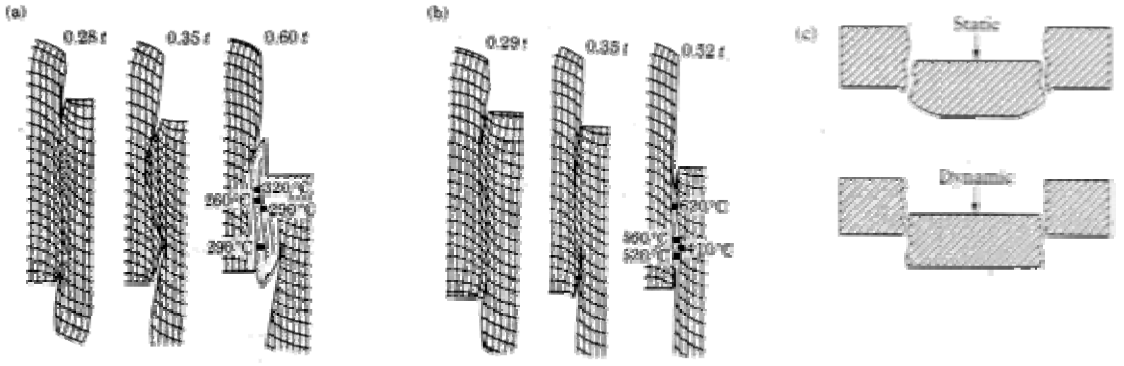


FIGURE 7.7 Deformation and temperature rise in the shearing zone. The temperature was measured by thermocouples. Punching at (a) slow speed and (b) high speed. Note that the deformation is confined to a narrow zone in high-speed shearing and that the temperature is higher than in slow-speed shearing. *Source:* After N. Yanagihara, H. Saito, and T. Nakagawa. Numbers above the figures indicate punch penetration. (c) Fracture zone in shearing with static and dynamic loading.

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

Shearing Process (전단작업) (3)

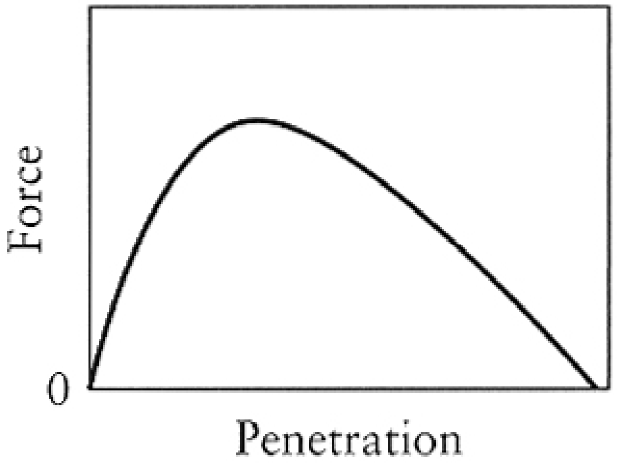
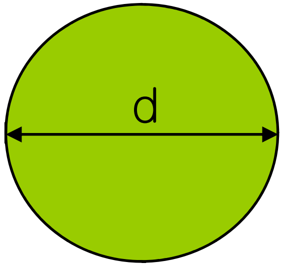


FIGURE 7.7 Typical punch–penetration curve in shearing. The area under the curve is the work done in shearing. The shape of the curve depends on process parameters and material properties.

$$F_{max} = 0.7(UTS)(t)(L)$$

L: total length of the sheared edge(전단면의 총 길이)



- Example – calculation of max. punch force

: d=1in., t=1/8in., annealed titanium-alloy(Ti-6Al-4V)

$$P = 0.7(1/8)(\pi)(140{,}000) = 38{,}500 lb$$

$$= 19.25 tons = 0.17 MN$$

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

Shearing Operations (전단공정)

- **Punching(천공)**
  - sheared slug is discarded.
- **Blanking(블랭킹)**
  - slug is the part itself, and the rest is scrap.
- **Die cutting**
  - Perforation(연속천공)
  - Parting(분리)
  - Notching(노칭)
  - Lancing(랜싱)
- **Fine blanking**
  - Very smooth and square edges can be produced.
  - Clearance on the order of 1% of the sheet thickness.
- **Slitting(분단) : similar to can opener**
- **Steel rules(강척다이)**
- **Nibbling(니블링)**

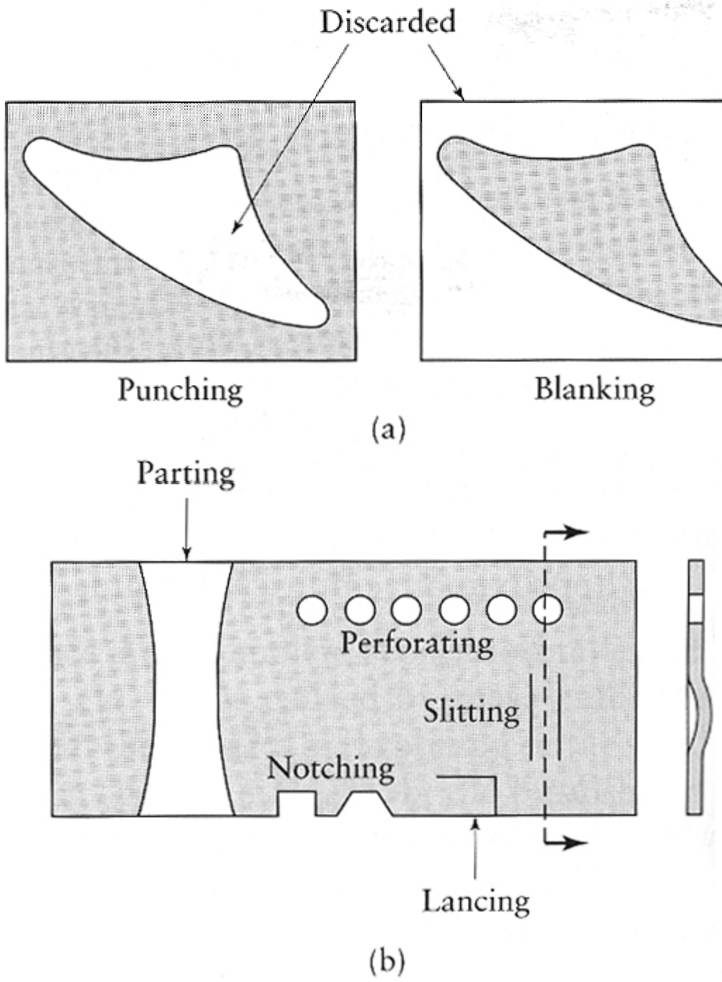
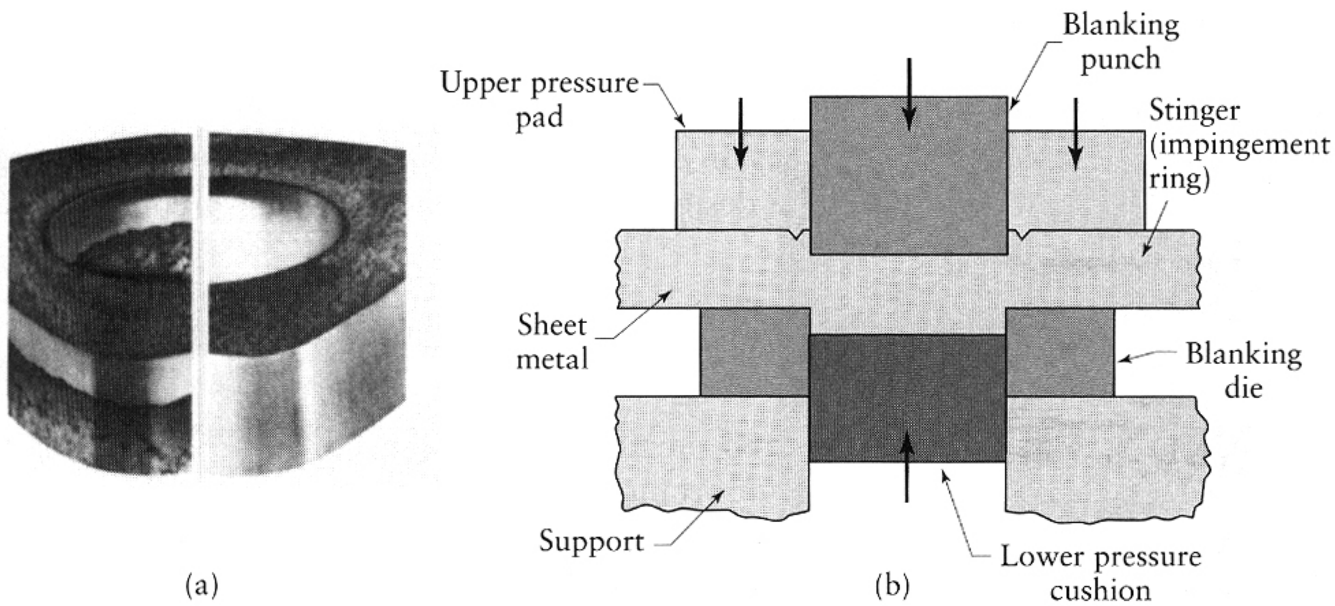


FIGURE 7.8 (a) Punching (piercing) and blanking. (b) Examples of various shearing operations on sheet metal.

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

Blanking (블랭킹) / Slitting (분단)



(a) (b)

FIGURE 7.9 (a) Comparison of sheared edges by conventional (left) and fine-blanking (right) techniques. (b) Schematic illustration of the setup for fine blanking. *Source*: Feintool International Holding.

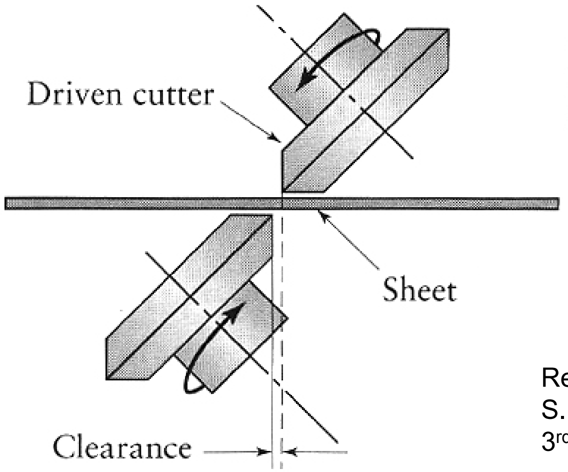


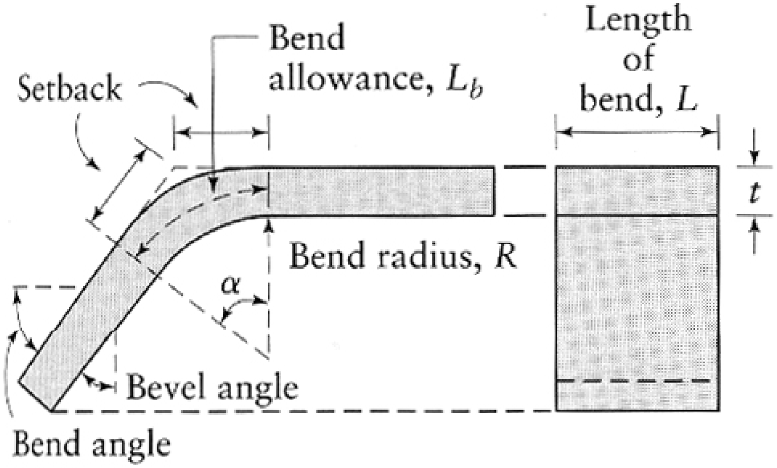
FIGURE 7.10 Slitting with rotary knives. This process is similar to opening cans.

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

Bending (굽힘)

- One of the most common metalworking operations.
- To form parts as certain shapes and impart stiffness to a part by increasing its moment of inertia.
- Outer surface is in tension and inner surface is in compression.
- $e_o > e_i$: shifting of the neutral axis toward the inner surface.

$$e_o = e_i = \frac{1}{\left(\frac{2R}{t}\right)+1}$$



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

Minimum bend radius (최소굽힘반경) (1)

- The radius at which crack appears on the outer surface of the bend.
- Minimum bend radii for various materials – ref. textbook table 7.2
- Such as 2T, 3T, 4T.
- The R/t ratio approaches zero at a tensile reduction of area of 50% - the material can be folded over itself.
- In bending of sheets, appropriate direction of the sheets should be considered due to the anisotropy of the cold rolled sheets.

$$\varepsilon_f = \ln\left(\frac{A_o}{A_f}\right) = \ln\left(\frac{100}{100-r}\right)$$

$$\varepsilon_o = \ln(1+e_o) = \ln\left(1+\frac{1}{(2R/t)+1}\right) = \ln\left(\frac{R+t}{R+(t/2)}\right)$$

$$\min.\ \frac{R}{t} = \frac{50}{r} - 1$$

$$\min.\ \frac{R}{t} = \frac{60}{r} - 1$$: Experimental data

Minimum bend radius (최소굽힘반경) (2)

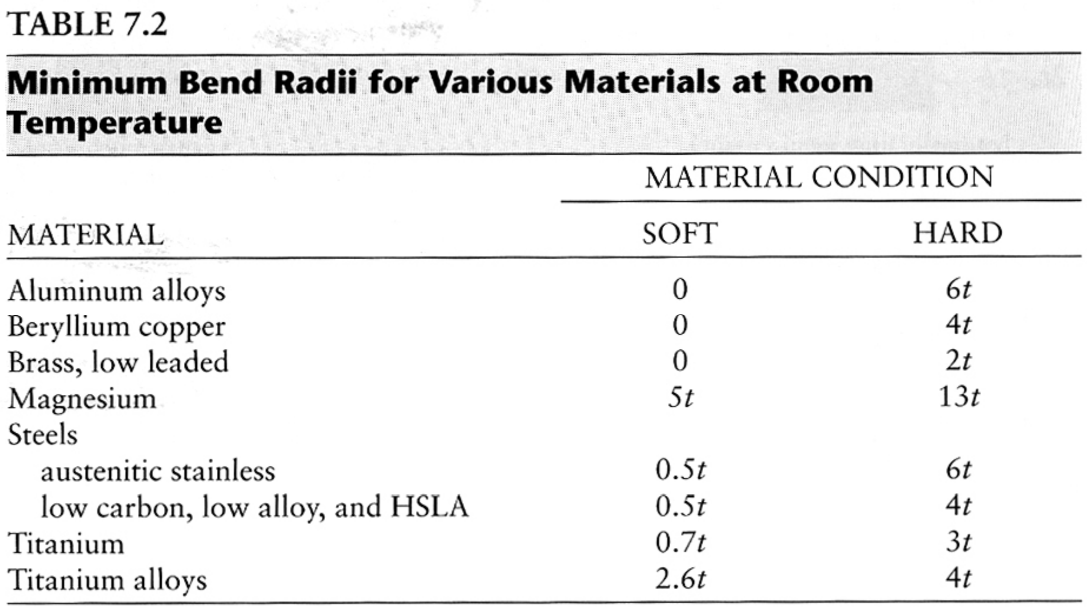
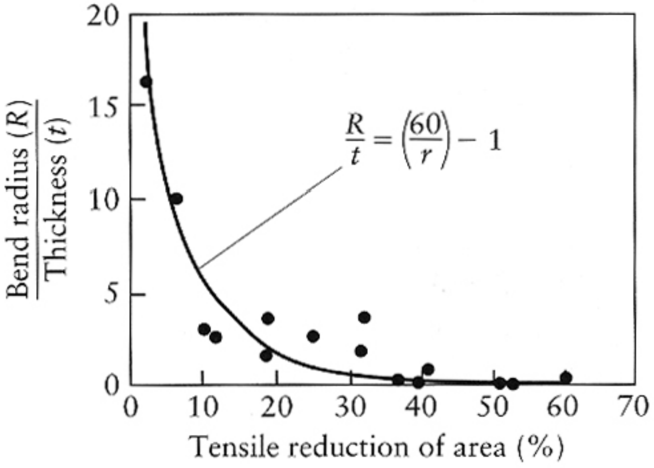


TABLE 7.2

Minimum Bend Radii for Various Materials at Room Temperature

	MATERIAL CONDITION	
MATERIAL	SOFT	HARD
Aluminum alloys	0	6t
Beryllium copper	0	4t
Brass, low leaded	0	2t
Magnesium	5t	13t
Steels		
austenitic stainless	0.5t	6t
low carbon, low alloy, and HSLA	0.5t	4t
Titanium	0.7t	3t
Titanium alloys	2.6t	4t



(b)

FIGURE 7.15 (a) Bending terminology. The bend radius is measured to the inner surface of the bend. Note that the length of the bend is the width of the sheet. Also note that the bend angle and the bend radius (sharpness of the bend) are two different variables. (b) Relationship between the ratio of bend radius to sheet thickness and tensile reduction of area for various materials. Note that sheet metal with a reduction of area of about 50% can be bent and flattened over itself without cracking. *Source:* After J. Datsko and C. T. Yang.

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

Minimum bend radius (최소굽힘반경) (3)

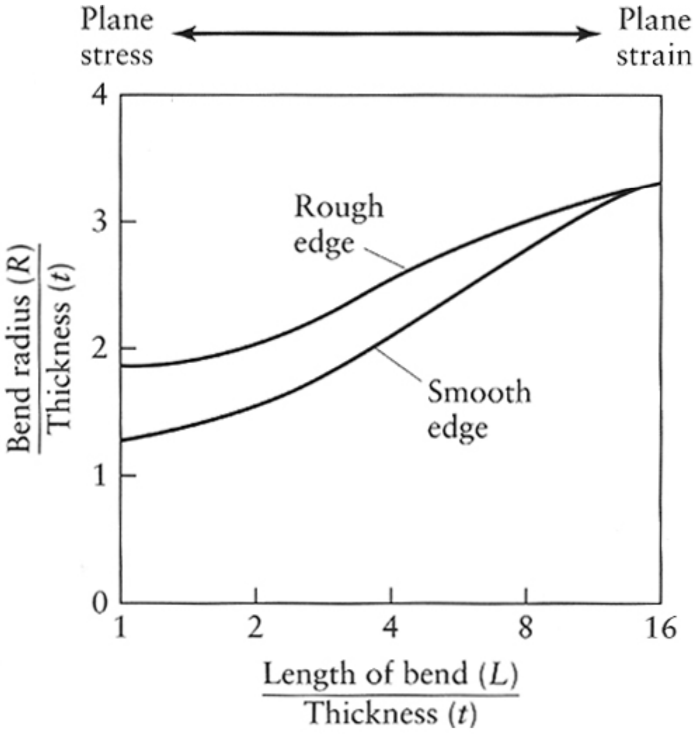
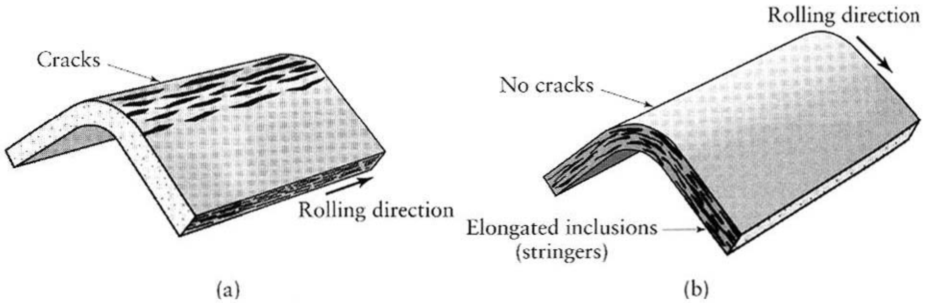
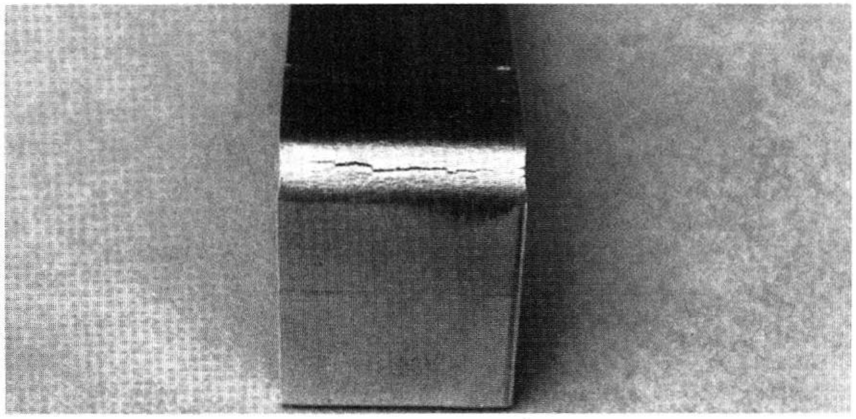


FIGURE 7.16 The effect of length of bend and edge condition on the ratio of bend radius to thickness for 7075-T aluminum. *Source:* After G. Sachs and G. Espey.



(a)

(b)



(c)

FIGURE 7.17 (a) and (b) The effect of elongated inclusions (stringers) on cracking as a function of the direction of bending with respect to the original rolling direction of the sheet. This example shows the importance of the direction of cutting from large sheets in workpieces that are subsequently bent to make a product. (c) Cracks on the outer radius of an aluminum strip bent to an angle of 90°.

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

Springback (스프링백) (1)

- **Because all materials have a finite modulus of elasticity, plastic deformation is followed by elastic recovery upon removal of the load; in bending this recovery is known as springback.**

- **Elastic recovery increases with the stress level and with decreasing elastic modulus.**

- **Negative springback(역 스프링 백)**

- **Compensation of springback**

  : In practice, springback is usually compensated for by using overbending(과도굽힘).

Springback (스프링백) (2)

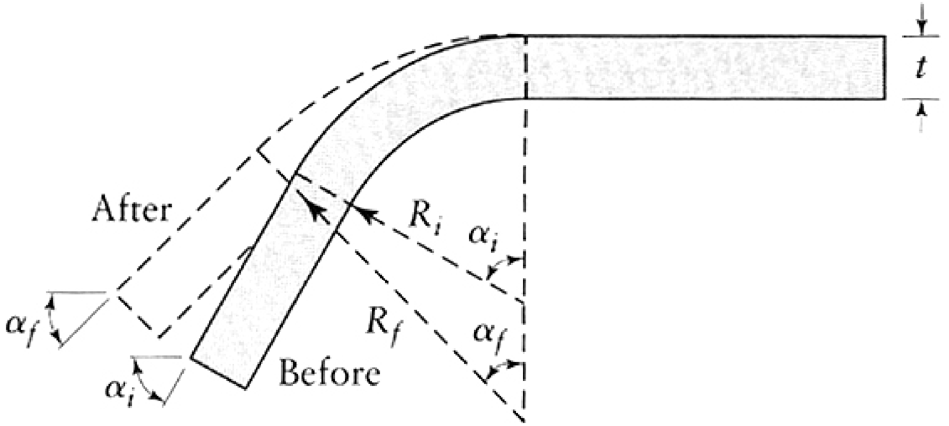


FIGURE 7.18 Terminology for springback in bending. Springback is caused by the elastic recovery of the material upon unloading. In this example, the material tends to recover toward its originally flat shape. However, there are situations where the material bends farther upon unloading (negative springback), as shown in Fig. 7.20.

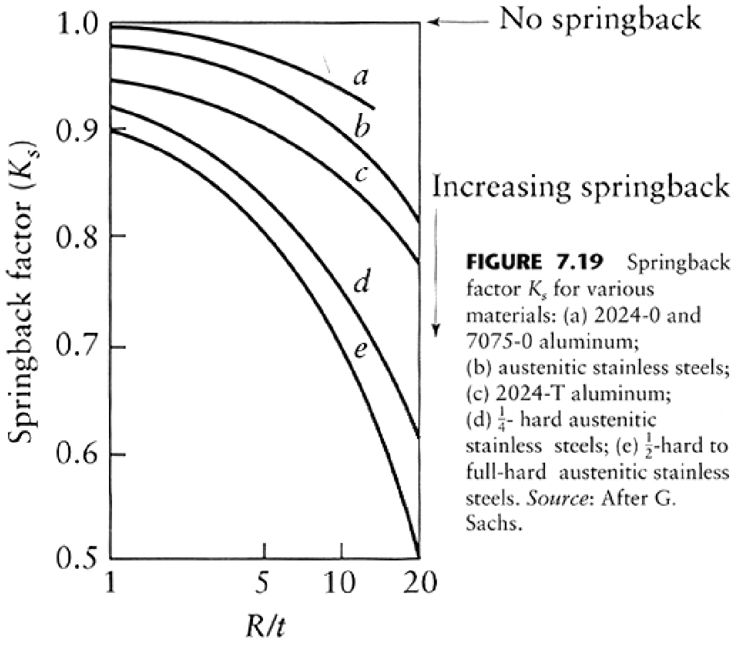


FIGURE 7.19 Springback factor K_s for various materials: (a) 2024-0 and 7075-0 aluminum; (b) austenitic stainless steels; (c) 2024-T aluminum; (d) $\frac{1}{4}$- hard austenitic stainless steels; (e) $\frac{1}{2}$-hard to full-hard austenitic stainless steels. *Source*: After G. Sachs.

$$\text{Bend allowance} = \left(R_i + \frac{t}{2}\right)\alpha_i = \left(R_f + \frac{t}{2}\right)\alpha_f$$

$$K_s = \frac{\alpha_f}{\alpha_i} = \frac{(2R_i/t)+1}{(2R_f/t)+1}$$

$$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{Et}\right)^3 - 3\left(\frac{R_i Y}{Et}\right) + 1$$

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

Springback (스프링백) (3)

- **Negative springback(역스프링백)**

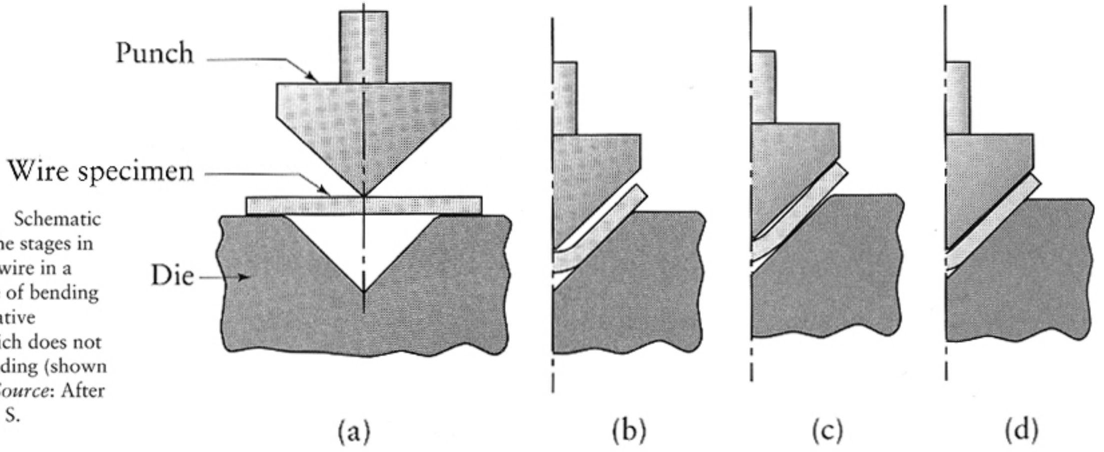


FIGURE 7.20 Schematic illustration of the stages in bending round wire in a V-die. This type of bending can lead to negative springback, which does not occur in air bending (shown in Fig. 7.24a). *Source*: After K. S. Turke and S. Kalpakjian.

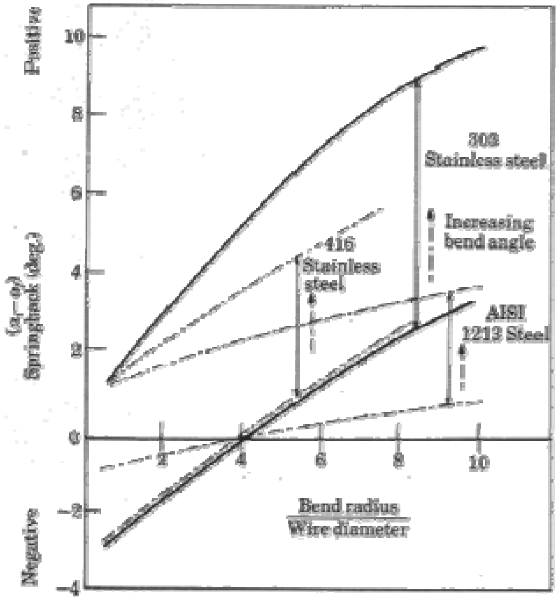


FIGURE 7.22 Range of positive and negative springback for various materials (with the same modulus of elasticity) as a function of the ratio of bend radius to wire diameter. *Source*: After K. S. Turke and S. Kalpakjian, *Proc. NAMRC III*, 1975, pp. 246–262.

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

Springback (스프링백) (4)

- **Compensation of springback**
  - Overbending the part in the die.
  - High localized compressive stresses between the tip of the punch and the die surface.
  - Subjected to tension while being bent; stretch bending.
  - Bending may be carried out at elevated temperature.

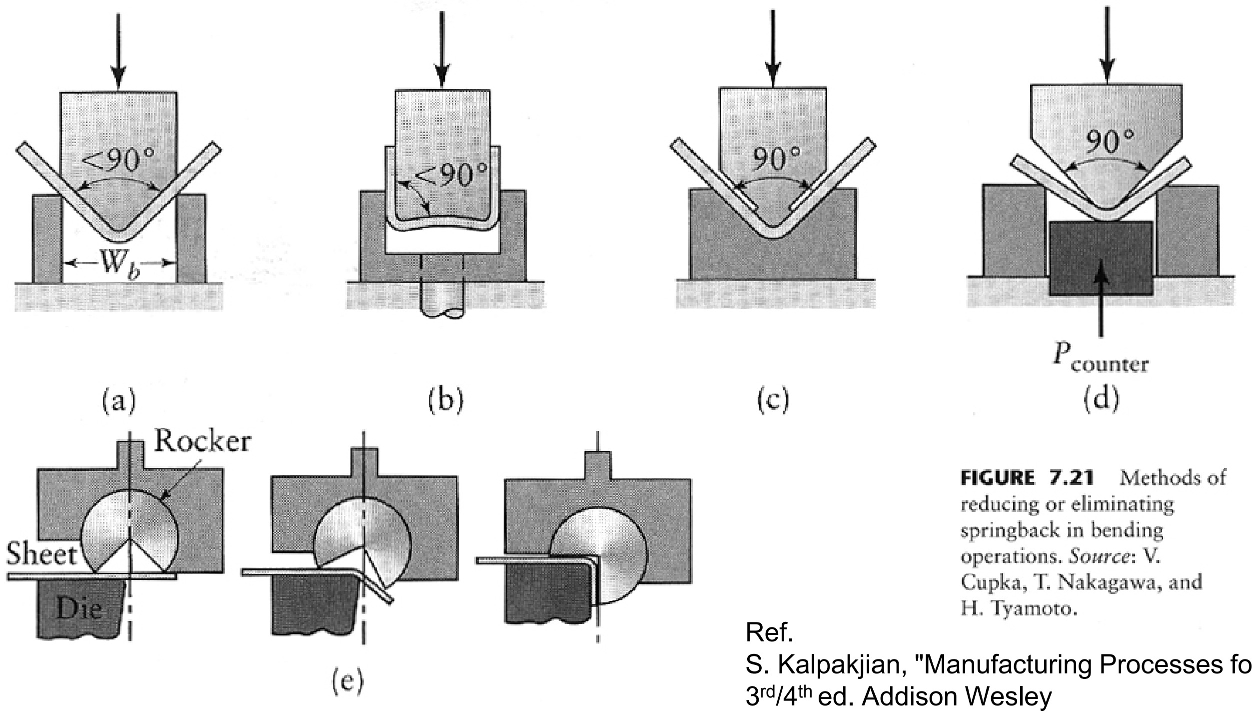
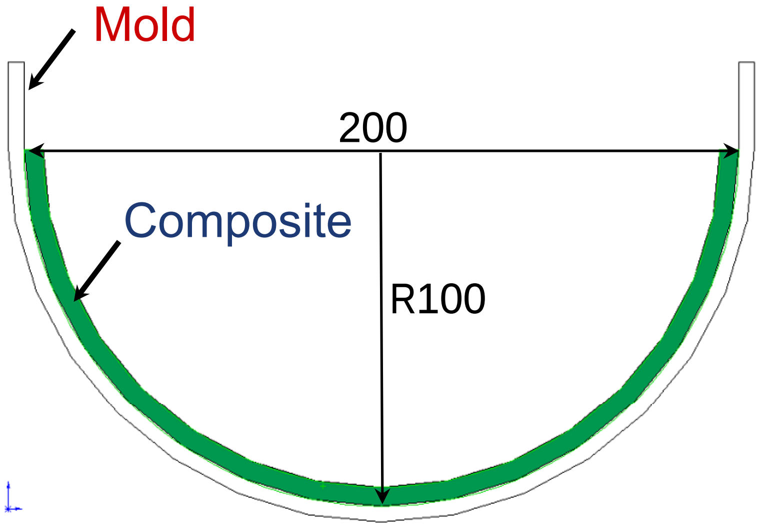


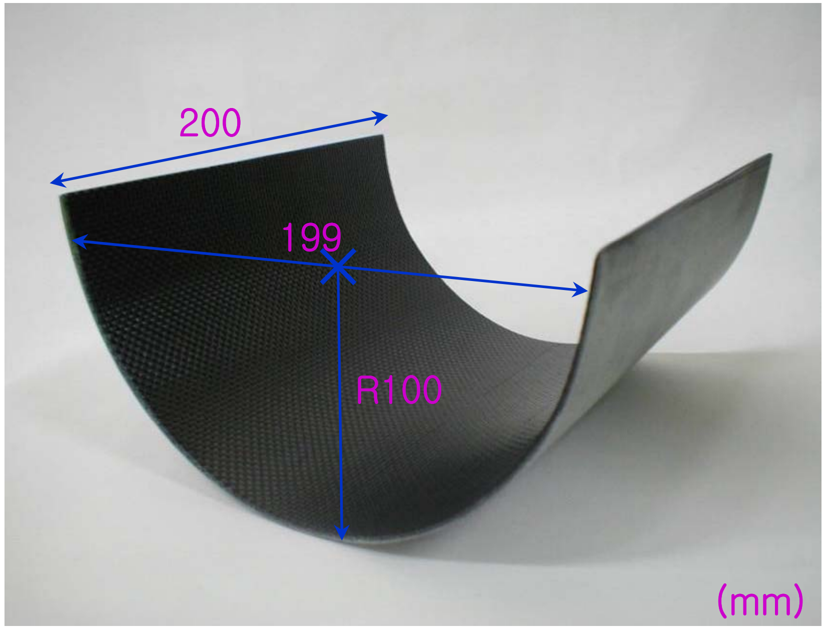
FIGURE 7.21 Methods of reducing or eliminating springback in bending operations. *Source*: V. Cupka, T. Nakagawa, and H. Tyamoto.

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

3-D shape Laminate Composite Fabrication (1)

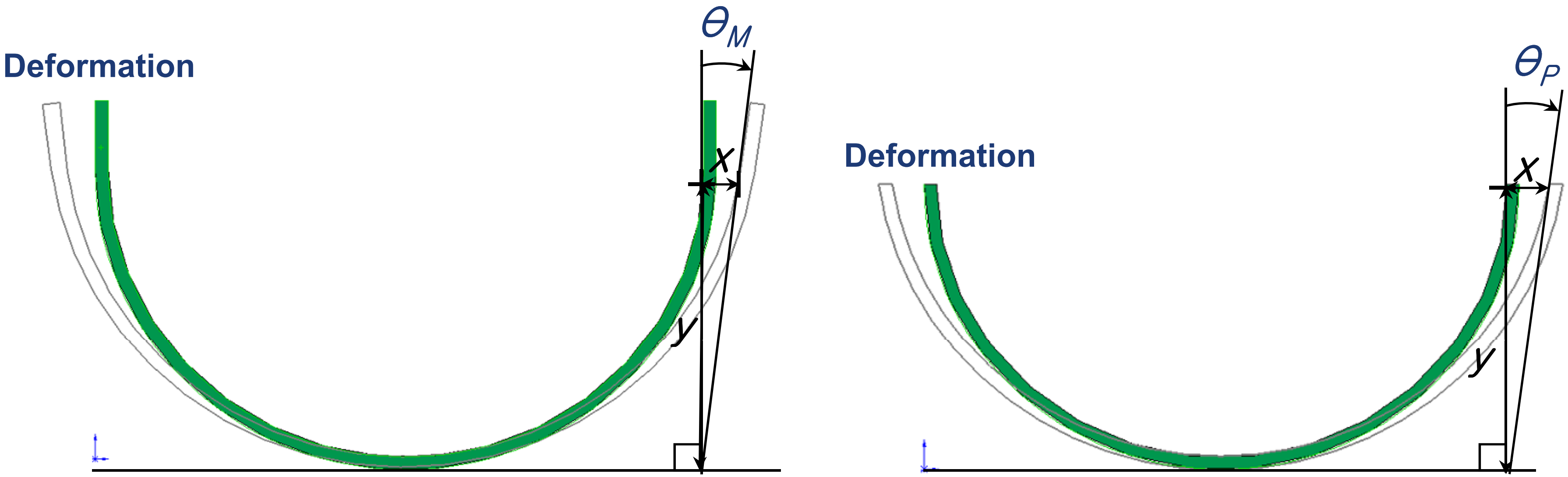
- Bending mold and laminate composite
- Hybrid 3-D shape laminate composite (glass 8 piles + carbon 8 plies)





3-D shape Laminate Composite Fabrication (2)

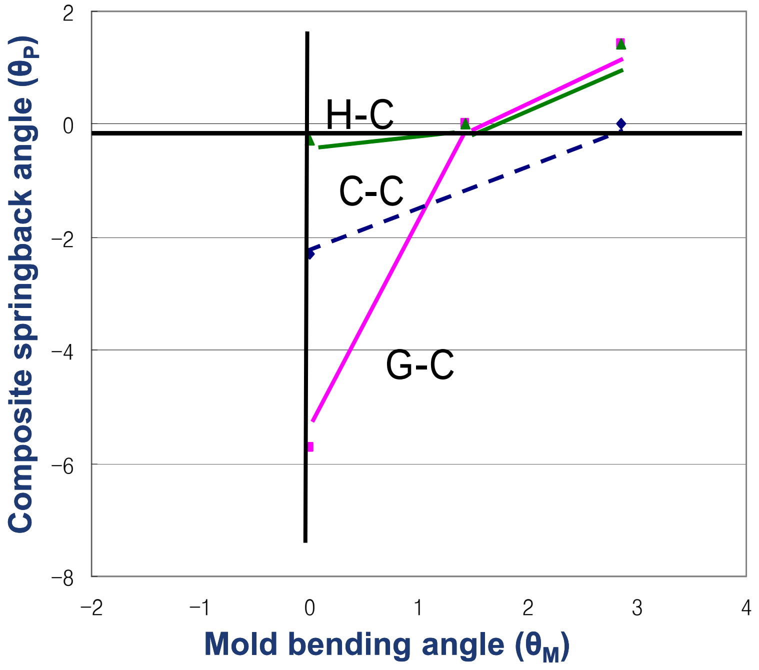
- The angle of ‘C’ shape mold and composite springback
- ● θ_M : angle of mold bending ● θ_P : angle of composite springback



$$\theta = \tan^{-1}(x / y)$$

3-D shape Laminate Composite Fabrication (3)

- Springback compensation by changing bending angle of the mold : ‘C’ shape



G−C shape		C−C shape		H−C shape	
θ_M (°)	θ_P (°)	θ_M (°)	θ_P (°)	θ_M (°)	θ_P (°)
0°	−5.71°	0°	−2.29°	0°	−0.29°
2.86°	1.43°	2.86°	0°	−1.43°	0°
1.43°	0°	2.86°	0°	−2.86°	1.43°

➢ G : Glass, C : Carbon, H : Hybrid

Springback (스프링백) (5)

- Example – estimating springback

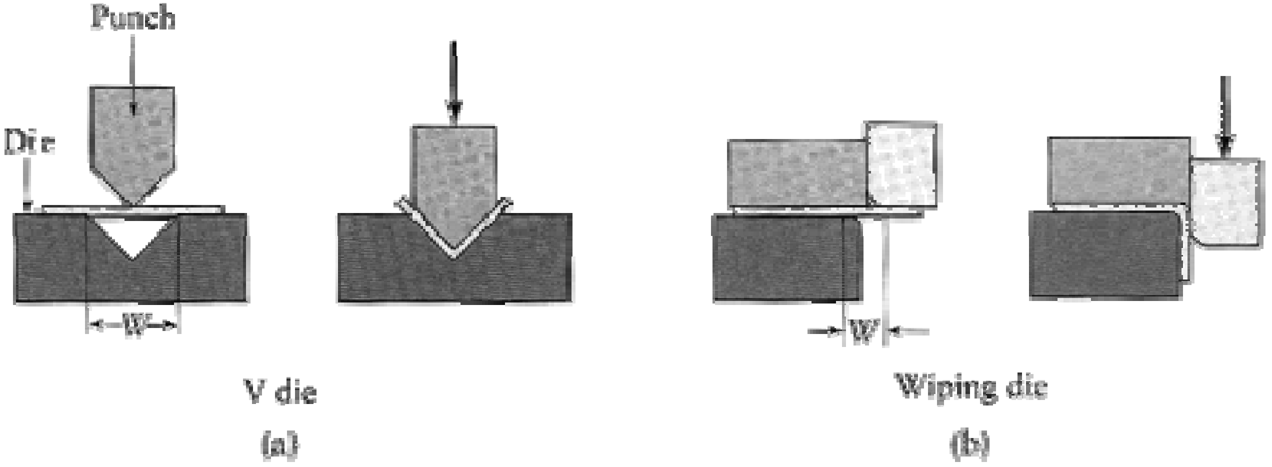
$$R_i = 0.5in.,\ Y = 40{,}000\,psi,\ E = 29\times10^6\,psi,\ t = 0.0359in.$$

$$\frac{R_i Y}{Et} = \frac{(0.5)(40{,}000)}{(29\times10^6)(0.0359)} = 0.0192$$

$$\frac{R_i}{R_f} = 4(0.0192)^3 - 3(0.0192) + 1 = 0.942$$

$$R_f = \frac{0.5}{0.942} = 0.531in.$$

$$\boxed{F_{\max} = k\frac{(UTS)Lt^2}{W}}$$



V die
(a)

Wiping die
(b)

FIGURE 7.22 Common die-bending operations, showing the die-opening dimension W used in calculating bending forces. [See Eq. (7.11).]

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

Bending Operations (굽힘가공) (1)

- Press-brake forming(프레스-브레이크 성형)

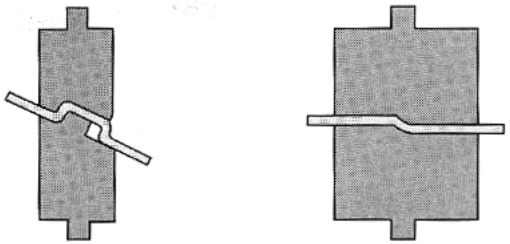
  : sheet metal or plate can be bent easily with simple fixtures, using press.
- Beading(비딩)

  : edge of the sheet metal is bent into the cavity of a die.
- Flanging(플랜징)

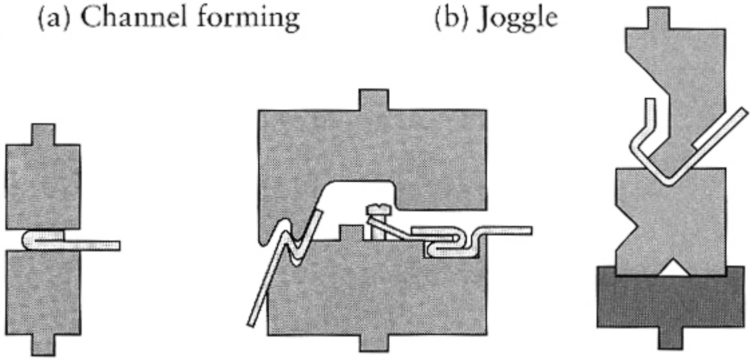
  : process of bending the edges of sheet metals, usually in 90°.
  - Shrink flanging : compressive hoop stresses.
  - Stretch flanging : tensile hoop stresses.
- Hemming(헤밍)

  : edge of the sheet is folded over itself.
- Roll forming(롤성형)
- Tube bending(관재굽힘작업)

  : bending and forming tubes and other hollow sections requires special tooling to avoid buckling and folding.



(a) Channel forming (b) Joggle

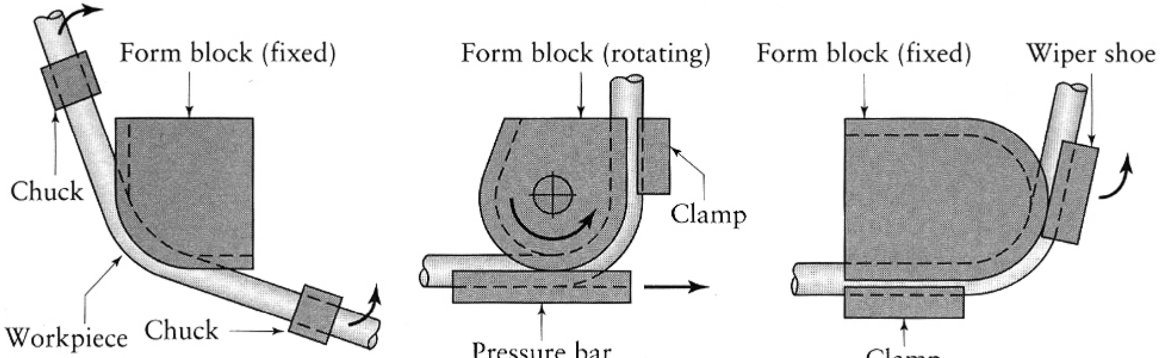


(c) Hemming (flattening) (d) Two-stage lock seam (e) Offset forming

FIGURE 7.23 Schematic illustrations of various bending operations in a press brake.

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

Bending Operations (굽힘가공) (2)



(a) Stretch bending (b) Draw bending (c) Compression bending

(d) Mandrels for tube bending

FIGURE 7.29 Methods of bending tubes. Using internal mandrels, or filling tubes with particulate materials such as sand, is often necessary to prevent collapsing of the tubes during bending. Solid rods and structural shapes are also bent by these techniques.

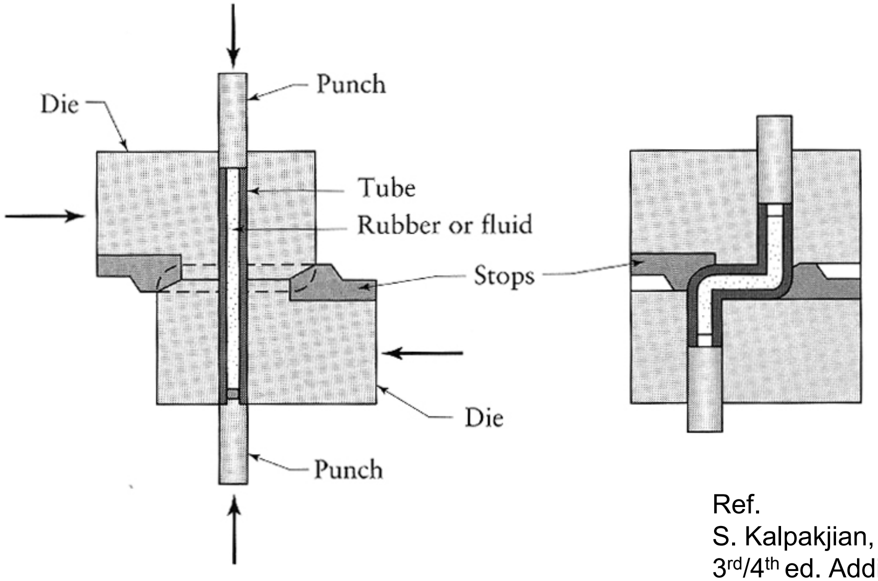


FIGURE 7.30 A method of forming a tube with sharp angles, using axial compressive forces. Compressive stresses are beneficial in forming operations because they delay fracture. Note that the tube is supported internally with rubber or fluid to avoid collapsing during forming. *Source*: After J. L. Remmerswaal and A. Verkaik.

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

Stretch forming (신장성형)

- The sheet metal is clamped around its edges and stretched over a die or form block, which moves upward, downward, or sideways, depending on the particular machine. (for low-volume production)

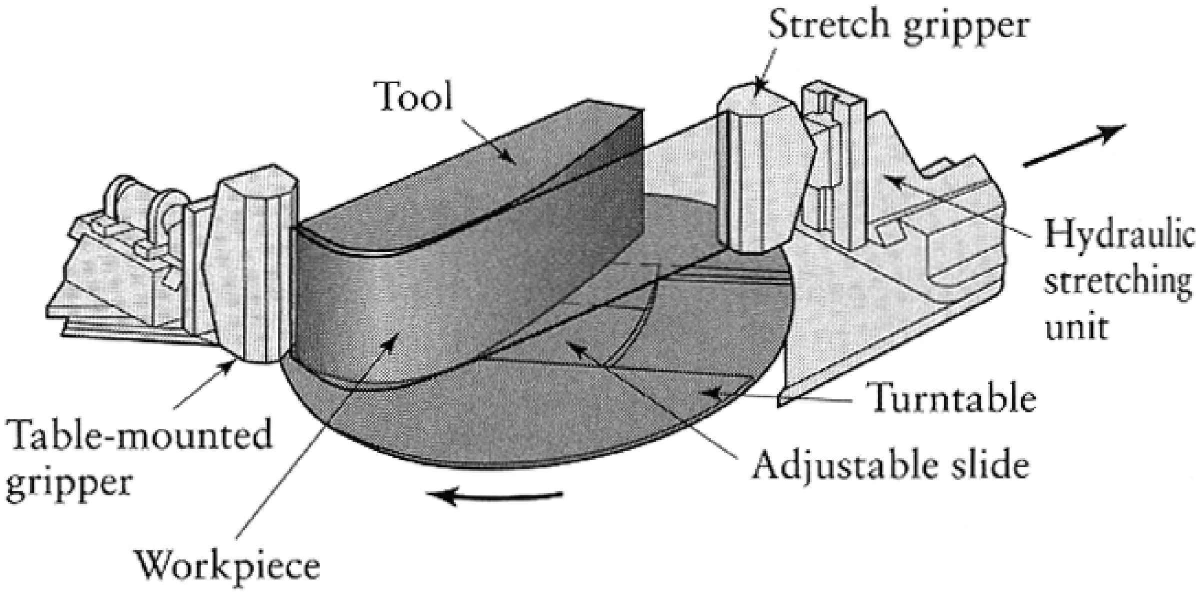


FIGURE 7.31 Schematic illustration of a stretch-forming process. Aluminum skins for aircraft can be made by this process. *Source:* Cyril Bath Co.

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

Bulging

- **Bulging involves placing a tubular, conical, or curvilinear hollow part in a split female die and expanding it with a rubber or polyurethane plug.**
  - Example – water pitchers(주전자), beads on drums(드럼통)

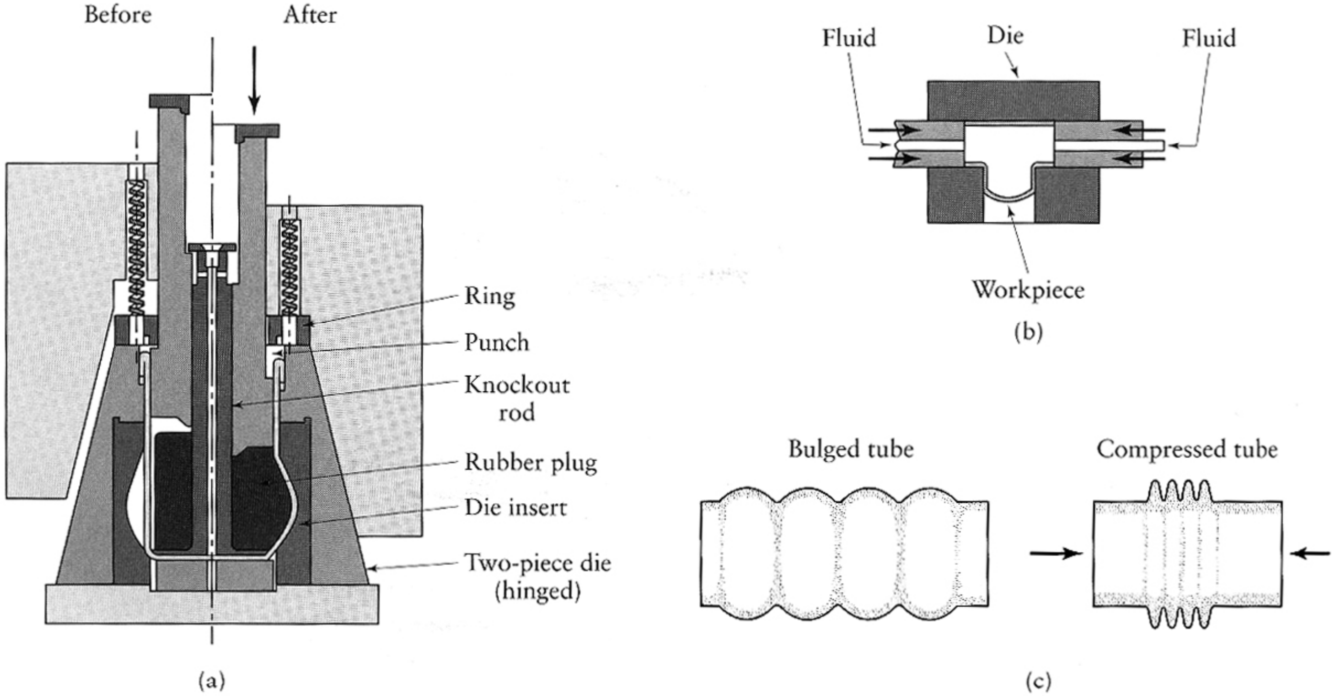


FIGURE 7.32 (a) Bulging of a tubular part with a flexible plug. Water pitchers can be made by this method. (b) Production of fittings for plumbing by expanding tubular blanks with internal pressure. The bottom of the piece is then punched out to produce a "T." *Source:* Schey J. A., *Introduction to Manufacturing Processes*, 2d ed., New York: McGraw-Hill, 1987. (c) Manufacturing of bellows.

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

Rubber forming (고무성형)

- One of the dies in a set is made of flexible material, such as a rubber or polyurethane membrane.
- Hydroforming(하이드로폼 가공) or fluid-forming(유체성형가공법)

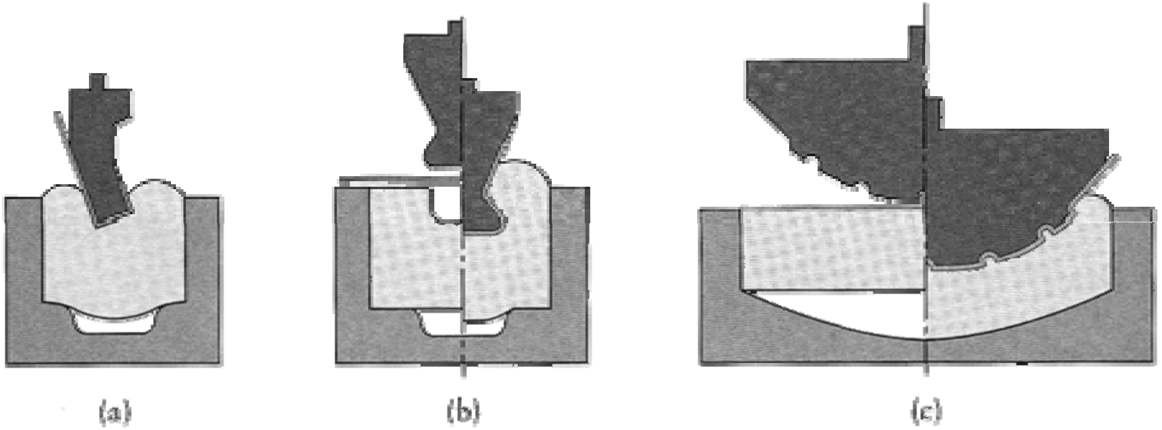


FIGURE 7.33 Examples of bending and embossing sheet metal with a metal punch and a flexible pad serving as the female die. *Source:* Polyurethane Products Corporation.

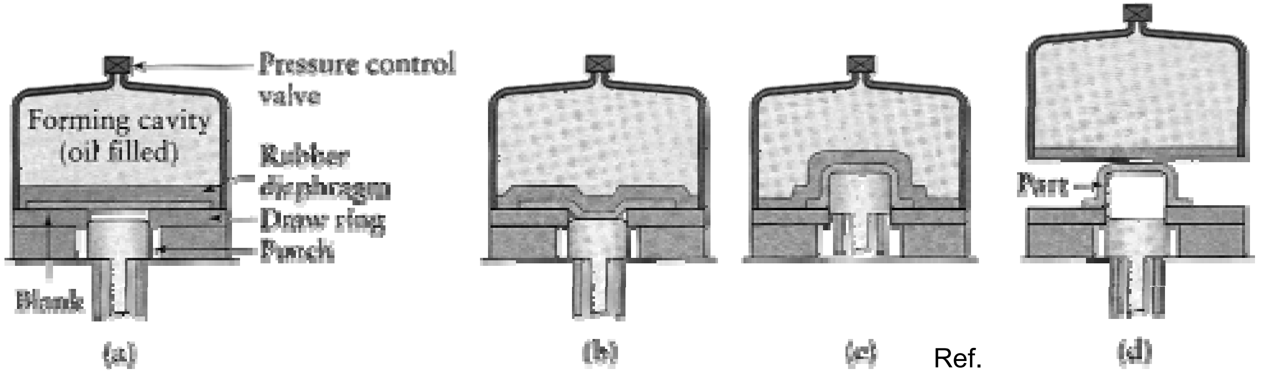
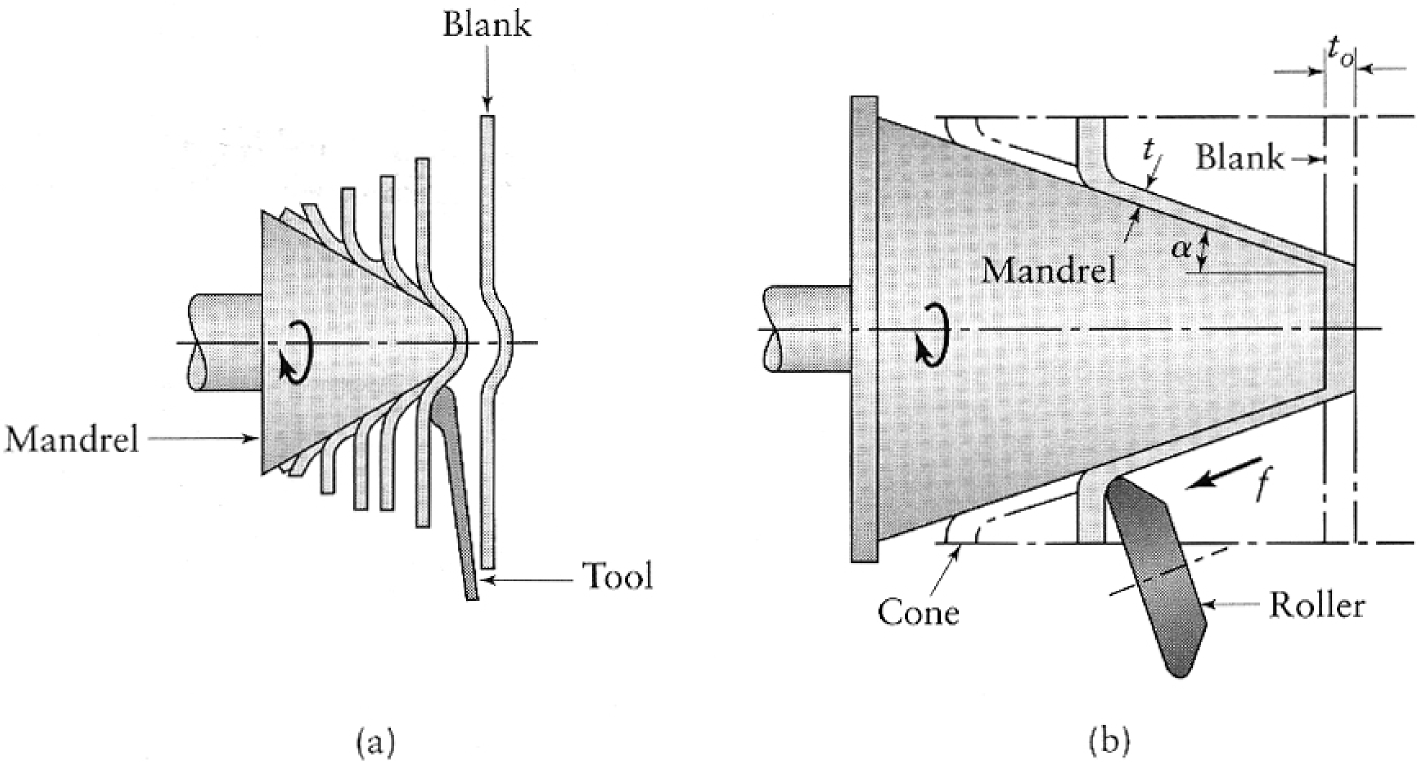


FIGURE 7.34 The hydroform, or fluid-forming, process. Note that, unlike in the ordinary deep-drawing process, the dome pressure forces the cup walls against the punch. The cup travels with the punch, and thus deep drawability is improved.

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

Spinning

- **Spinning involves the forming of axisymmetric parts over a rotating mandrel, using rigid tools or rollers.**



(a) (b)

FIGURE 7.36 Schematic illustration of spinning processes: (a) conventional spinning and (b) shear spinning. Note that in shear spinning, the diameter of the spun part, unlike in conventional spinning, is the same as that of the blank. The quantity *f* is the feed (in mm/rev or in./rev).

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

Various Forming Methods (1)

- **Peen forming : used to produce curvatures on thin sheet metals by shot peening one surface of the sheet.**

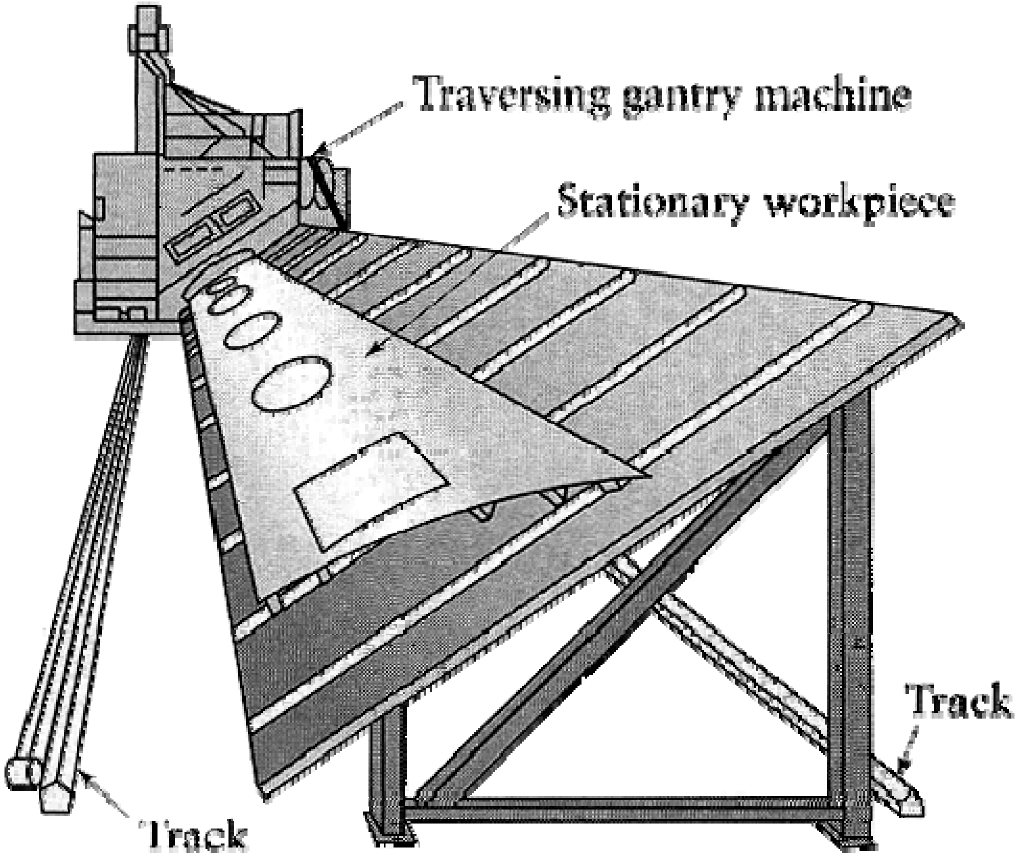

FIGURE 7.48 Peen-forming machine to form a large sheet-metal part, such as an aircraft-skin panel. The sheet is stationary, and the machine traverses it. *Source:* Metal Improvement Company.

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S. Kalpakjian, "Manufacturing Processes for Engineering Materials",
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Various Forming Methods (2)

- **Honeycomb structures**

  (a) Adhesive(접착제) → curing(경화) → stretching(확장)

  (b) Designed rolls(롤) → corrugated sheets(골판재) → adhisive(접착제) → curing(경화)

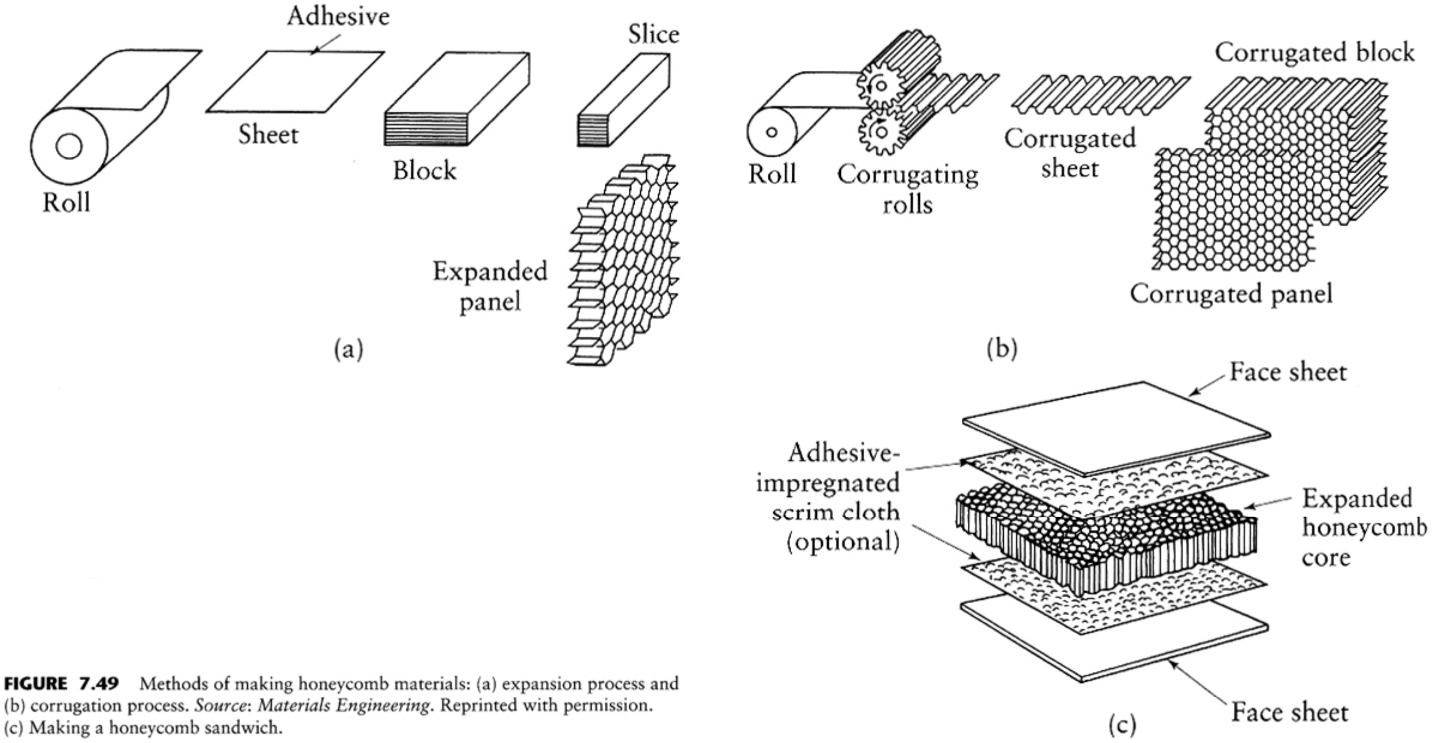

FIGURE 7.49 Methods of making honeycomb materials: (a) expansion process and (b) corrugation process. *Source: Materials Engineering*. Reprinted with permission. (c) Making a honeycomb sandwich.

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

Deep drawing (1)

- **A flat sheet-metal blank is formed into a cylindrical or box-shaped part by means of a punch that passes the blank into the die cavity.**
  - Example – cans(캔), kitchen sinks(싱크대), automobile panels(자동차 판)
- **Pure drawing(순수 드로잉) : the amount of drawn sheet metal**
- **Pure stretching(순수 신장) : the amount of stretched sheet metal**
  - Draw beads(드로우 비드) : the blank can be prevented from flowing freely into the die cavity.
- **Deformation of the sheet metal takes place mainly under the punch and the sheet begins to stretch, eventually resulting in necking and tearing.**
- **Ironing(아이어닝)**
  - If the thickness of the sheet as it enters the die cavity is greater than the clearance between the punch and the die, the thickness will be reduced.
- **Limiting Drawing Ratio(LDR, 한계 드로잉비)**
  - The maximum ratio of blank diameter to punch diameter that can be drawn without failure, or D_o/D_p.
- **Earing(귀생김)**
  - Planar anisotropy causes ears to form in drawn cups, producing a wavy edge.

Deep drawing (2)

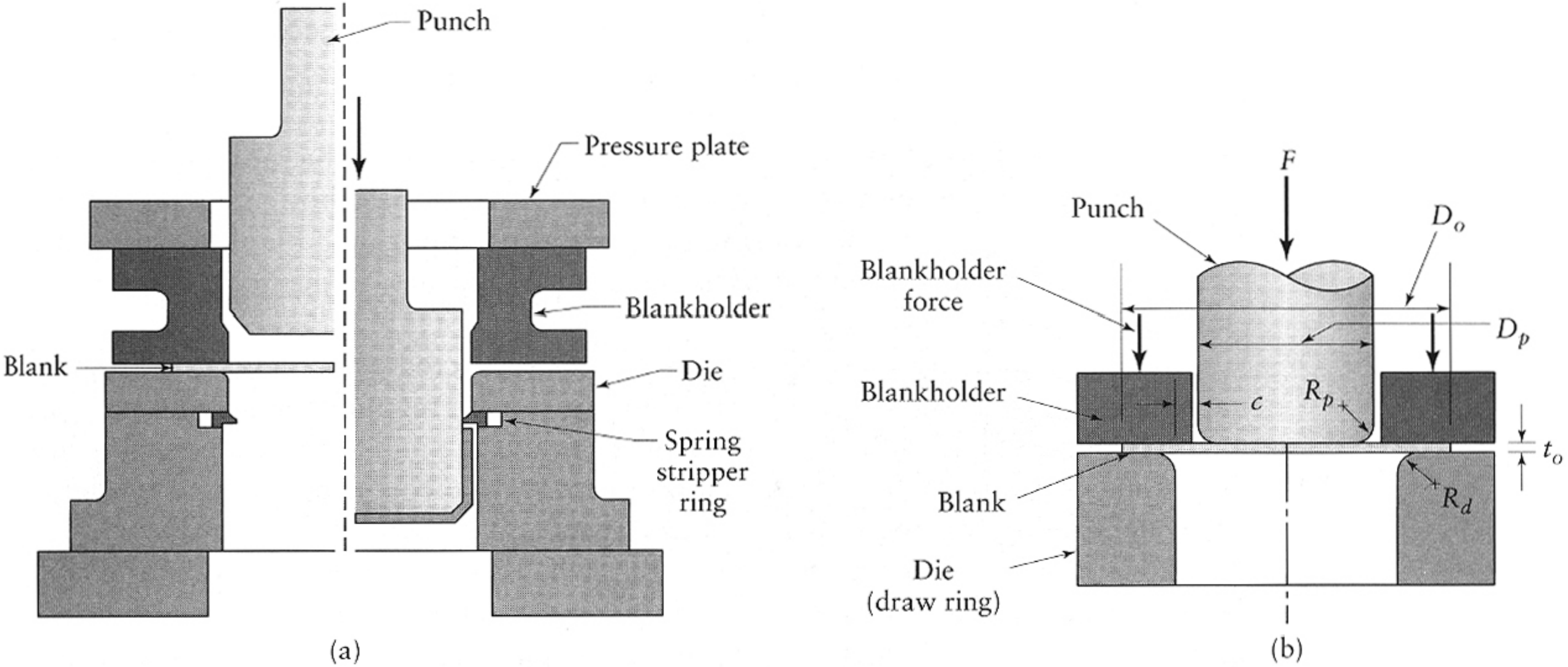

FIGURE 7.50 (a) Schematic illustration of the deep-drawing process. This procedure is the first step in the basic process by which aluminum beverage cans are produced today. The stripper ring facilitates the removal of the formed cup from the punch. (b) Variables in deep drawing of a cylindrical cup. Only the punch force in this illustration is a dependent variable; all others are independent variables, including the blankholder force.

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

Deep drawing (3)

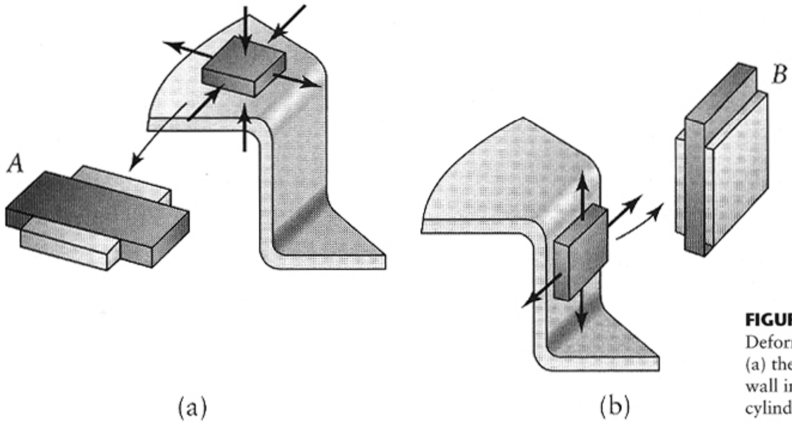

FIGURE 7.51 Deformation of elements in (a) the flange and (b) the cup wall in deep drawing of a cylindrical cup.

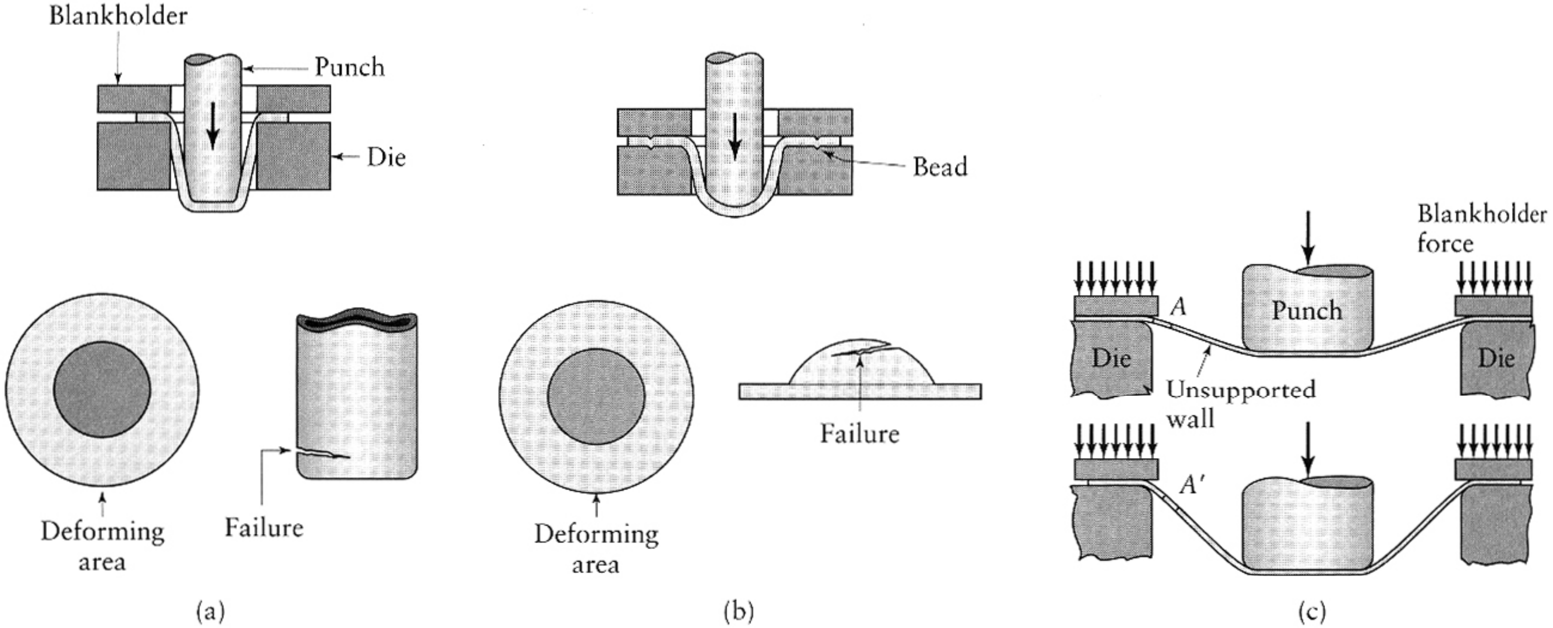

FIGURE 7.52 Examples of drawing operations: (a) pure drawing and (b) pure stretching. The bead prevents the sheet metal from flowing freely into the die cavity. (c) Possibility of wrinkling in the unsupported region of a sheet in drawing. *Source*: After W. F. Hosford and R. M. Caddell.

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

Deep drawing (4)

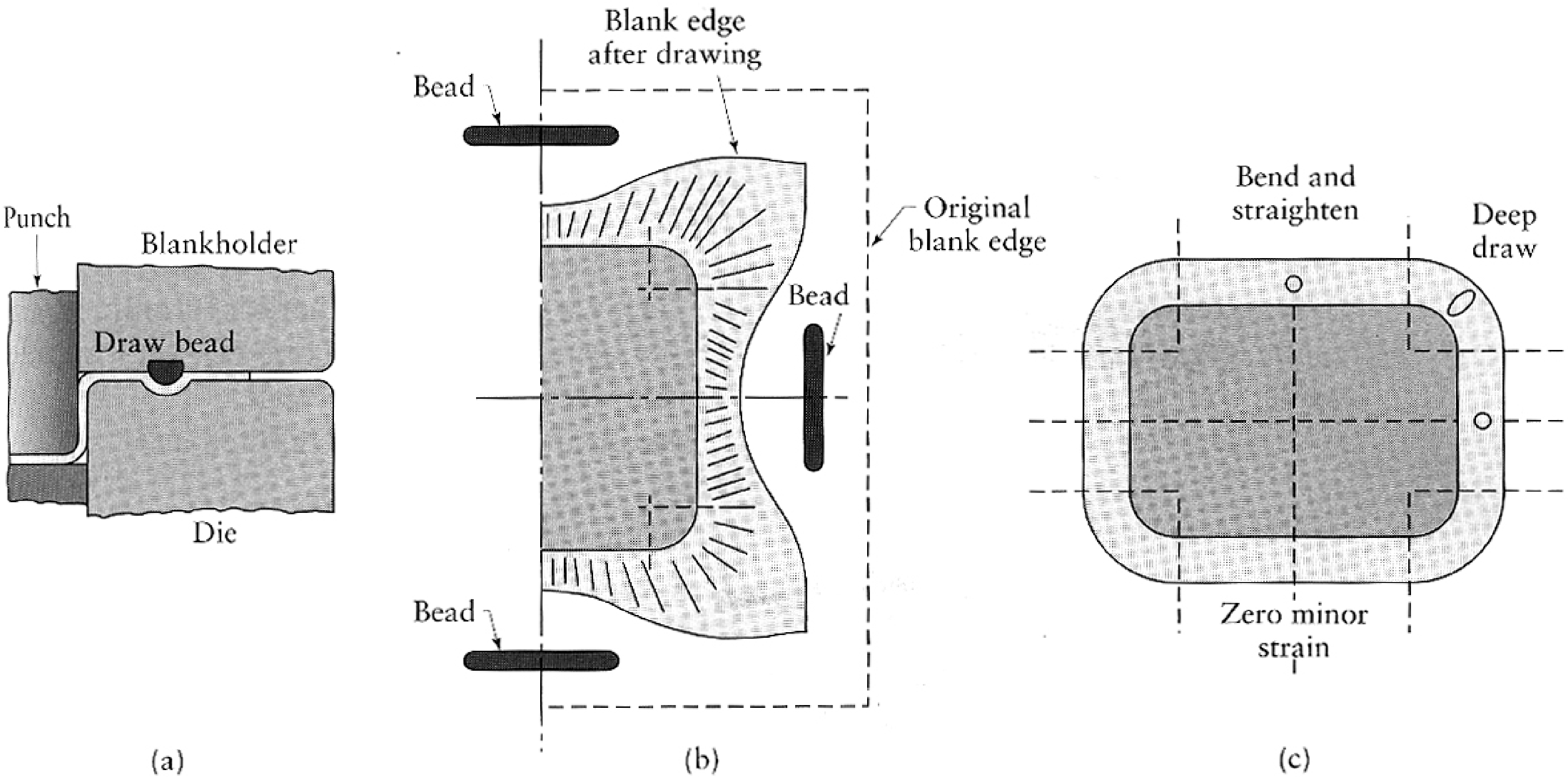

FIGURE 7.53 (a) Schematic illustration of a draw bead. (b) Metal flow during drawing of a box-shaped part, using beads to control the movement of the material. (c) Deformation of circular grids in drawing. (See Section 7.13.) *Source*: After S. Keeler.

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

Deep drawing (5)

Limiting drawing ratio

$$R = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\ln\left(\frac{w_o}{w_f}\right)}{\ln\left(\frac{t_o}{t_f}\right)}$$

$$R = \frac{\ln\left(\frac{w_o}{w_f}\right)}{\ln\left(\frac{w_f l_f}{w_o l_o}\right)}$$

$$\overline{R} = \frac{R_0 + 2R_{45} + R_{90}}{4}$$

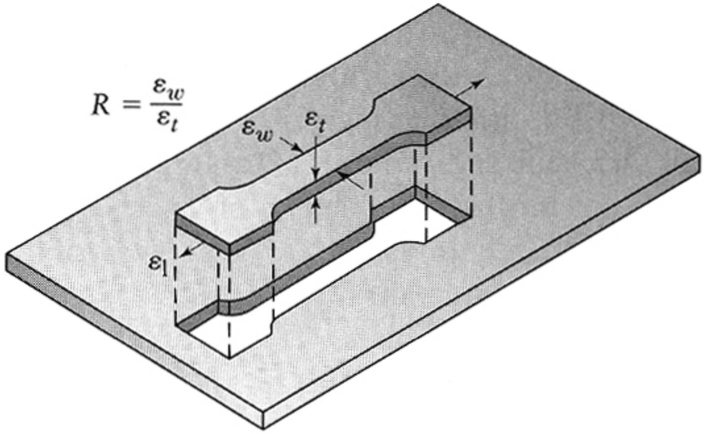

FIGURE 7.55 Definition of the normal anisotropy, *R*, in terms of width and thickness strains in a tensile-test specimen cut from a rolled sheet. Note that the specimen can be cut in different directions with respect to the length, or rolling direction, of the sheet.

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

LDR (1)

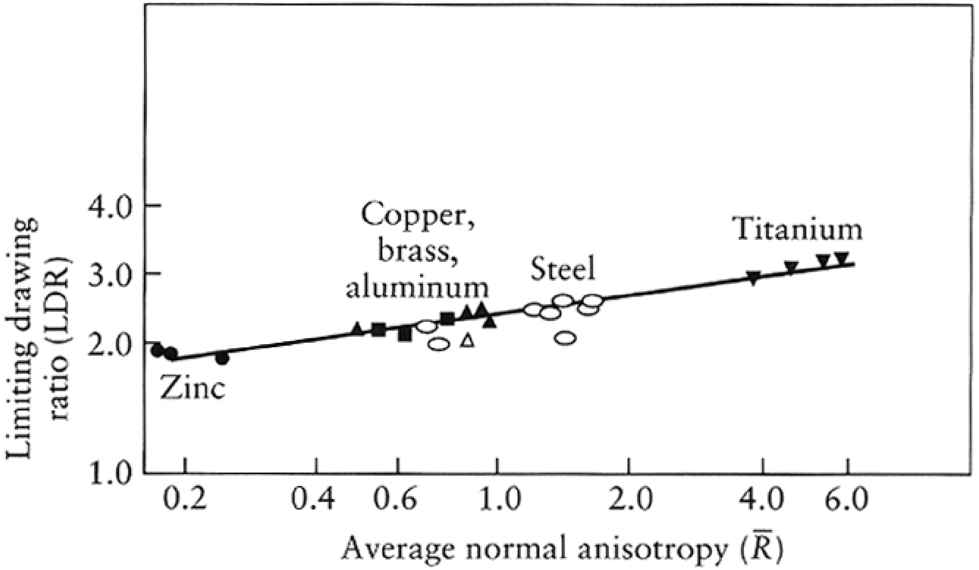


FIGURE 7.58 Effect of average normal anisotropy, $\bar{R}$, on limiting drawing ratio (LDR) for a variety of sheet metals. Zinc has a high *c*/*a* ratio (see Figure 3.2c), whereas titanium has a low ratio. *Source*: After M. Atkinson.

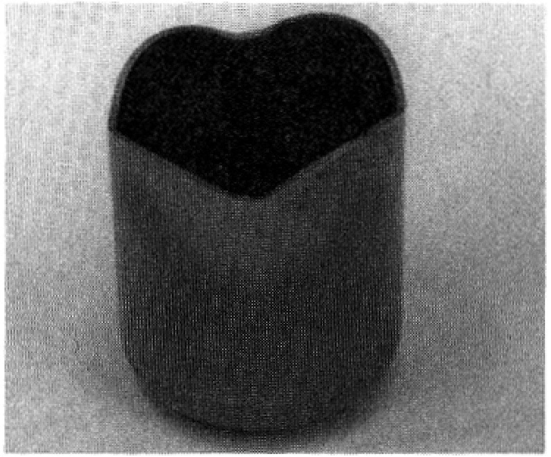


FIGURE 7.59 Earing in a drawn steel cup, caused by the planar anisotropy of the sheet metal.

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

LDR (2)

Example – estimating the limiting drawing ratio : stretched by 23% in length, decreased in thickness by 10%

$$w_o t_o l_o = w_f t_f l_f \quad \text{or} \quad \frac{w_f t_f l_f}{w_o t_o l_o} = 1$$

$$\frac{l_f - l_o}{l_o} = 0.23 \quad \text{or} \quad \frac{l_f}{l_o} = 1.23$$

$$\frac{t_f - t_o}{t_o} = -0.10 \quad \text{or} \quad \frac{t_f}{t_o} = 0.90.$$

$$\text{Hence} \quad \frac{w_f}{w_o} = 0.903$$

$$R = \frac{\ln\left(\dfrac{w_o}{w_f}\right)}{\ln\left(\dfrac{t_o}{t_f}\right)} = \frac{\ln 1.107}{\ln 1.111} = 0.965$$

$R = \overline{R}$ if the sheet has planar isotropy.

Then, $LDR = 2.4$

Maximum punch force

$$F_{\max} = \pi D_p t_o (UTS)\left(\frac{D_o}{D_p} - 0.7\right)$$

Forming-limit Diagram

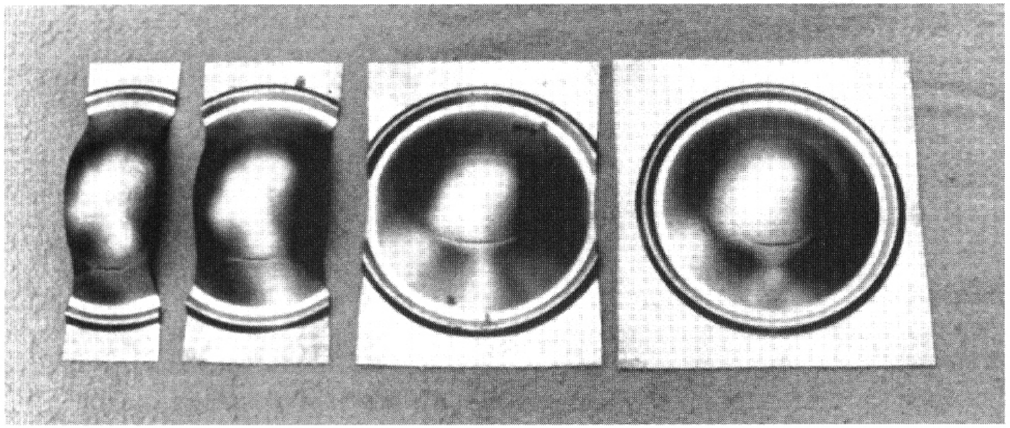
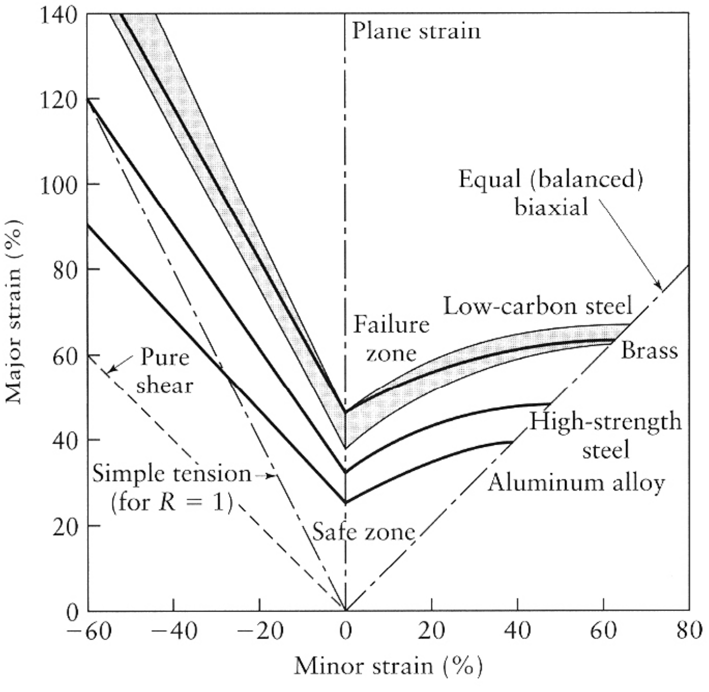
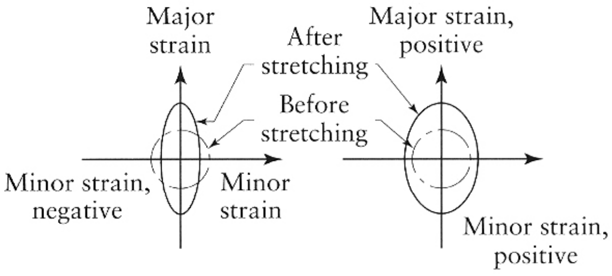


FIGURE 7.65 Bulge-test results on steel sheets of various widths. The first specimen (farthest left) stretched farther before cracking than the last specimen. From left to right, the state of stress changes from almost uniaxial to biaxial stretching. *Source*: Courtesy of Ispat Inland Inc.



(a)



(b)

FIGURE 7.66 (a) Forming-limit diagram (FLD) for various sheet metals. The major strain is always positive. The region above the curves is the failure zone; hence, the state of strain in forming must be such that it falls below the curve for a particular material; *R* is the normal anisotropy. (b) Note the definition of positive and negative minor strains. If the area of the deformed circle is larger than the area of the original circle, the sheet is thinner than the original, because the volume remains constant during plastic deformation. *Source*: After S. S. Hecker and A. K. Ghosh.

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

Design Considerations

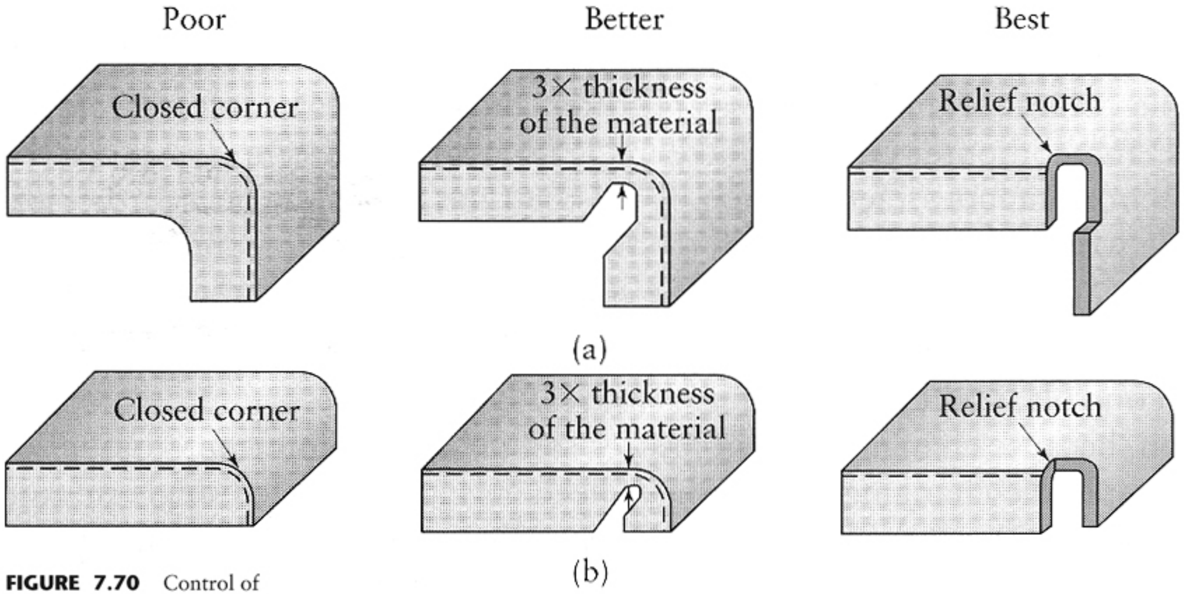


FIGURE 7.70 Control of tearing and buckling of a flange in a right-angle bend. *Source*: Society of Manufacturing Engineers.

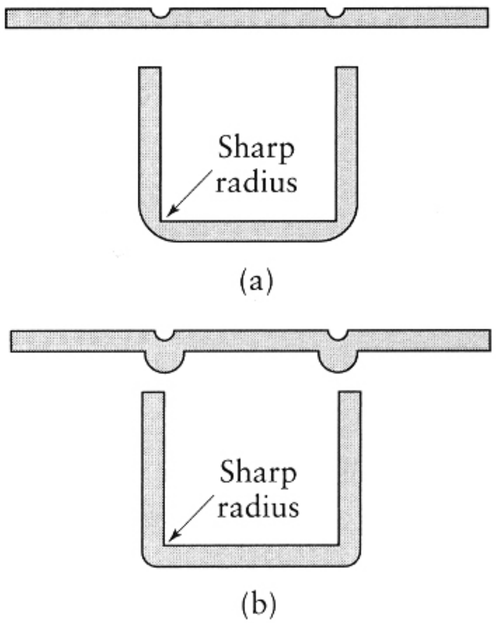


FIGURE 7.73 Application of (a) scoring or (b) embossing to obtain a sharp inner radius in bending. However, unless properly designed, these features can lead to fracture. *Source*: Society of Manufacturing Engineers.

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

Case study

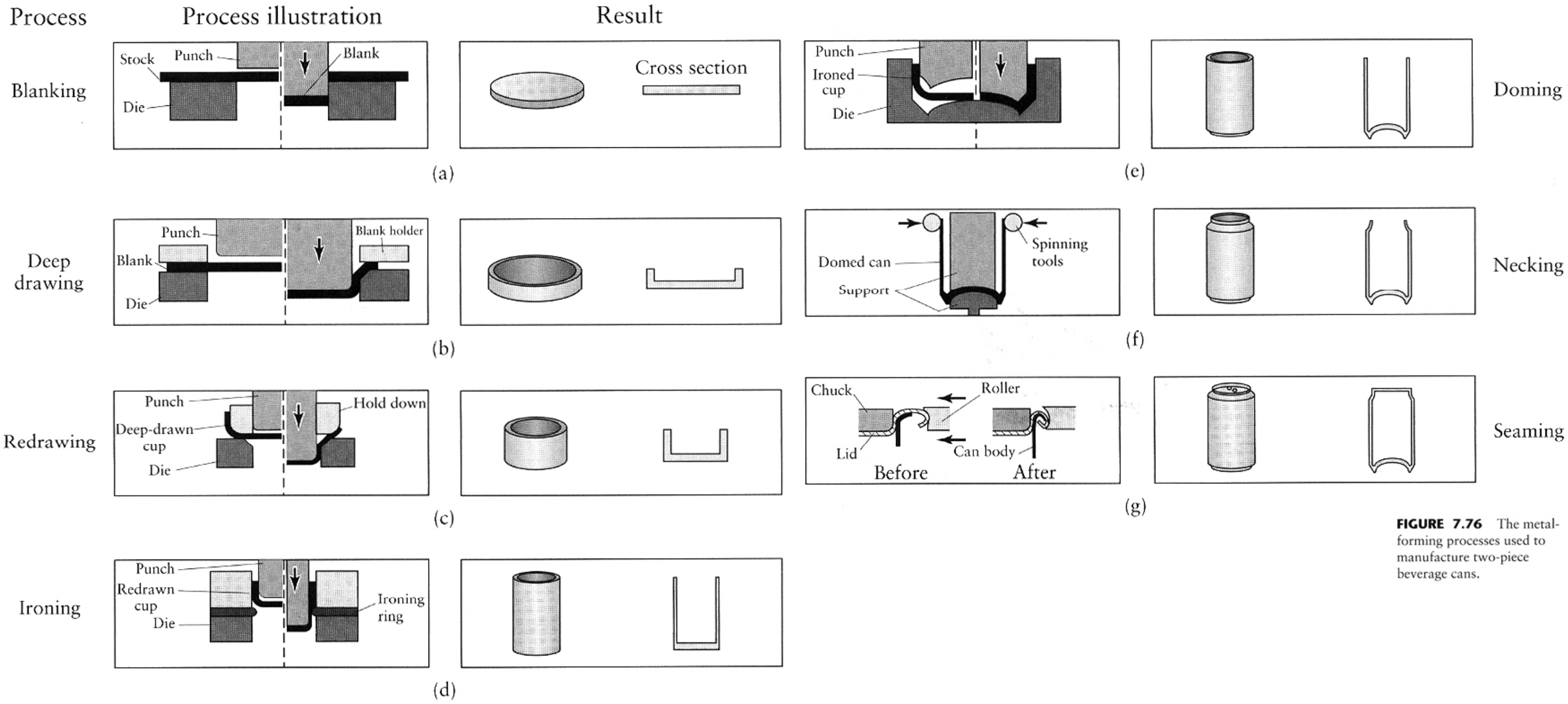


FIGURE 7.76 The metal-forming processes used to manufacture two-piece beverage cans.

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