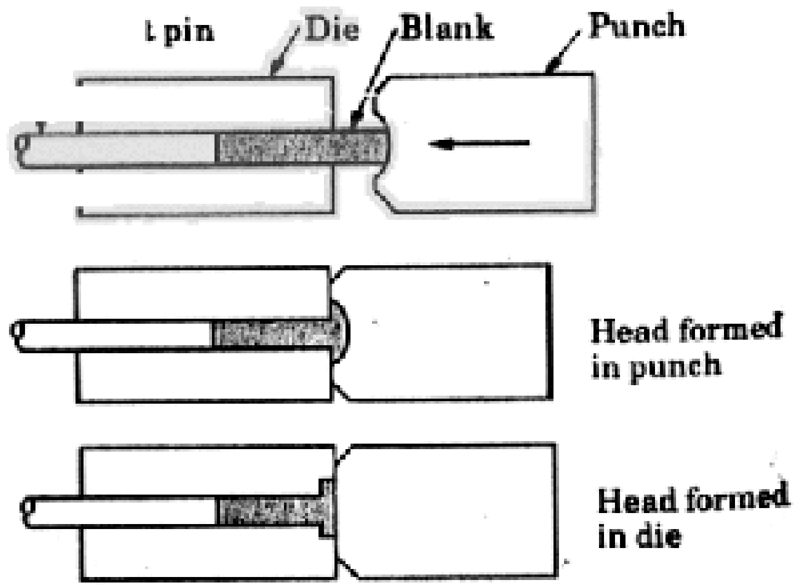
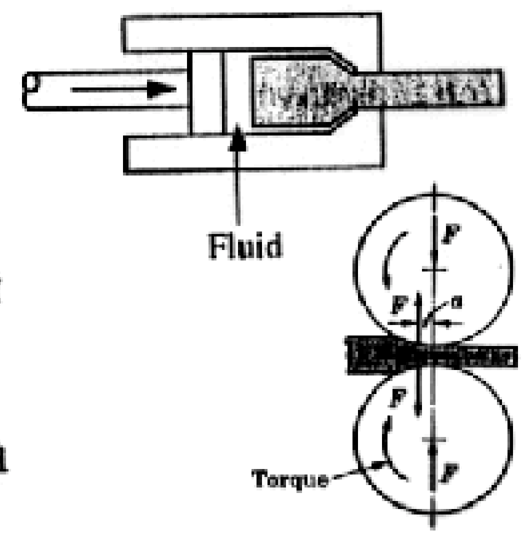
Metal Squeezing:





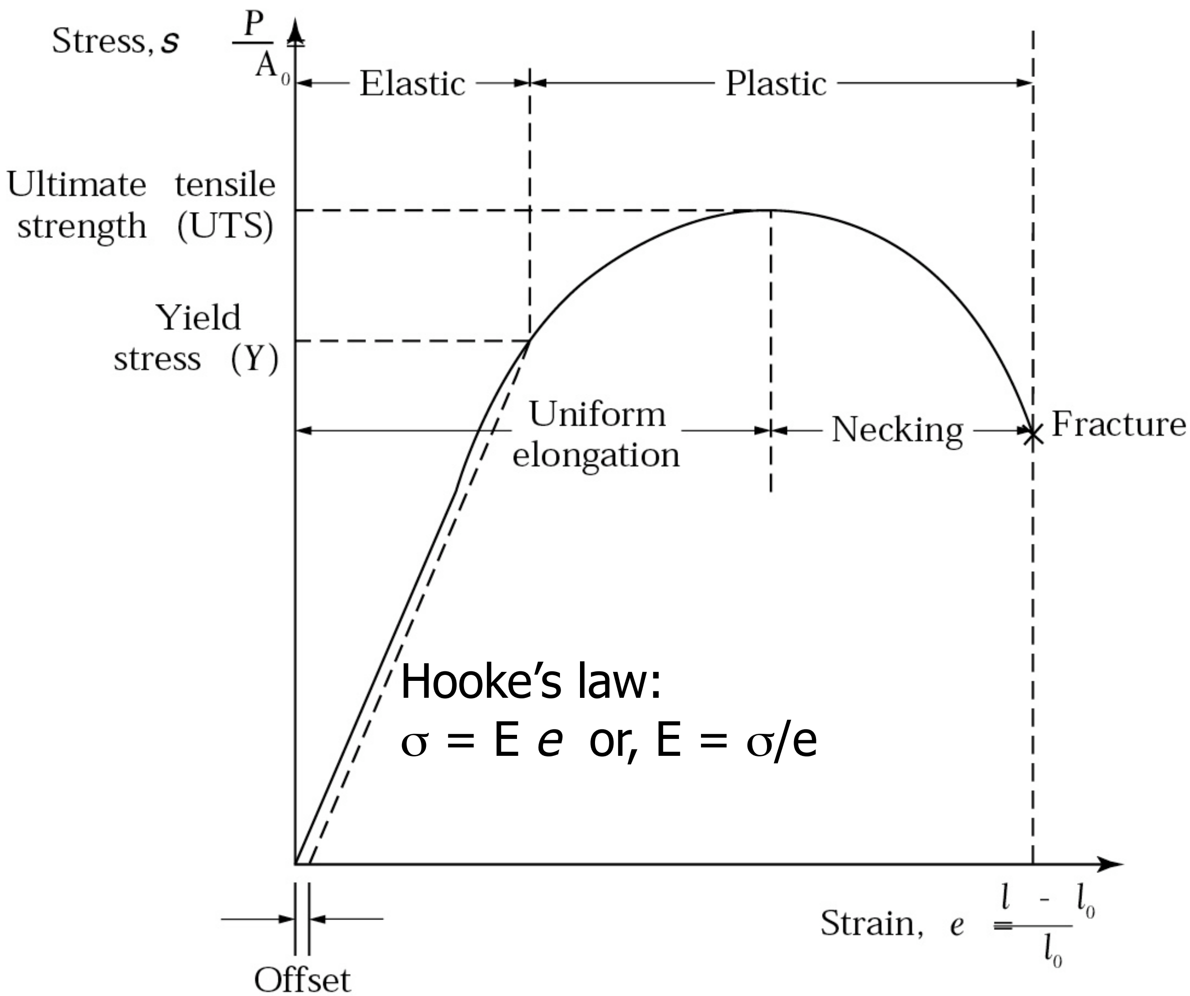
Cost: 👍
Cheap: $0.1 - $100.00

Flexibility: 👎
Fixed by die shape. Dies take days to manufacture. Shapes limited.

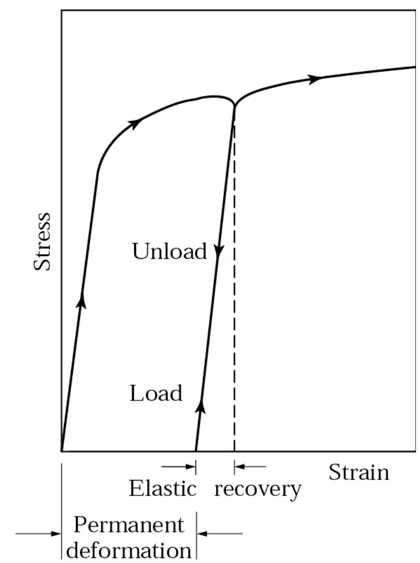
Quality: ~
Reasonable quality.

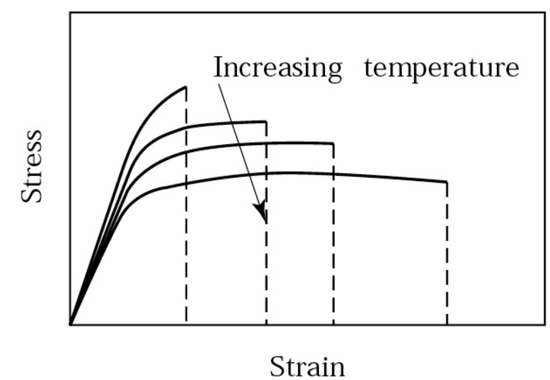
Rate: 👍
Fast, high volume.
Cycle time ~ seconds

Stress-Strain Curve

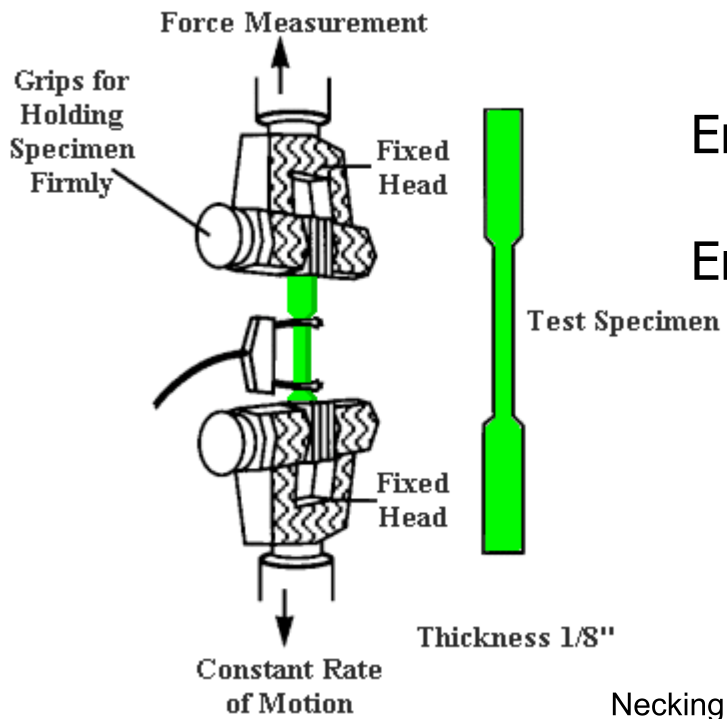


Hooke's law:
$\sigma = E\, e$ or, $E = \sigma / e$



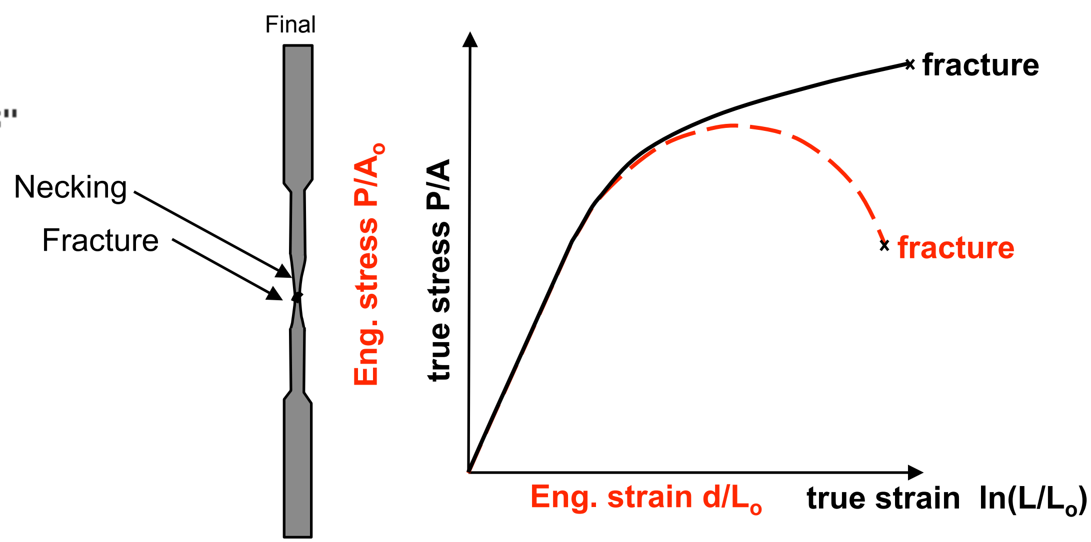


Tensile test



Engineering stress: $\sigma = P/A_o$

Engineering strain: $e = (L - L_o)/L_o = d/L_o$



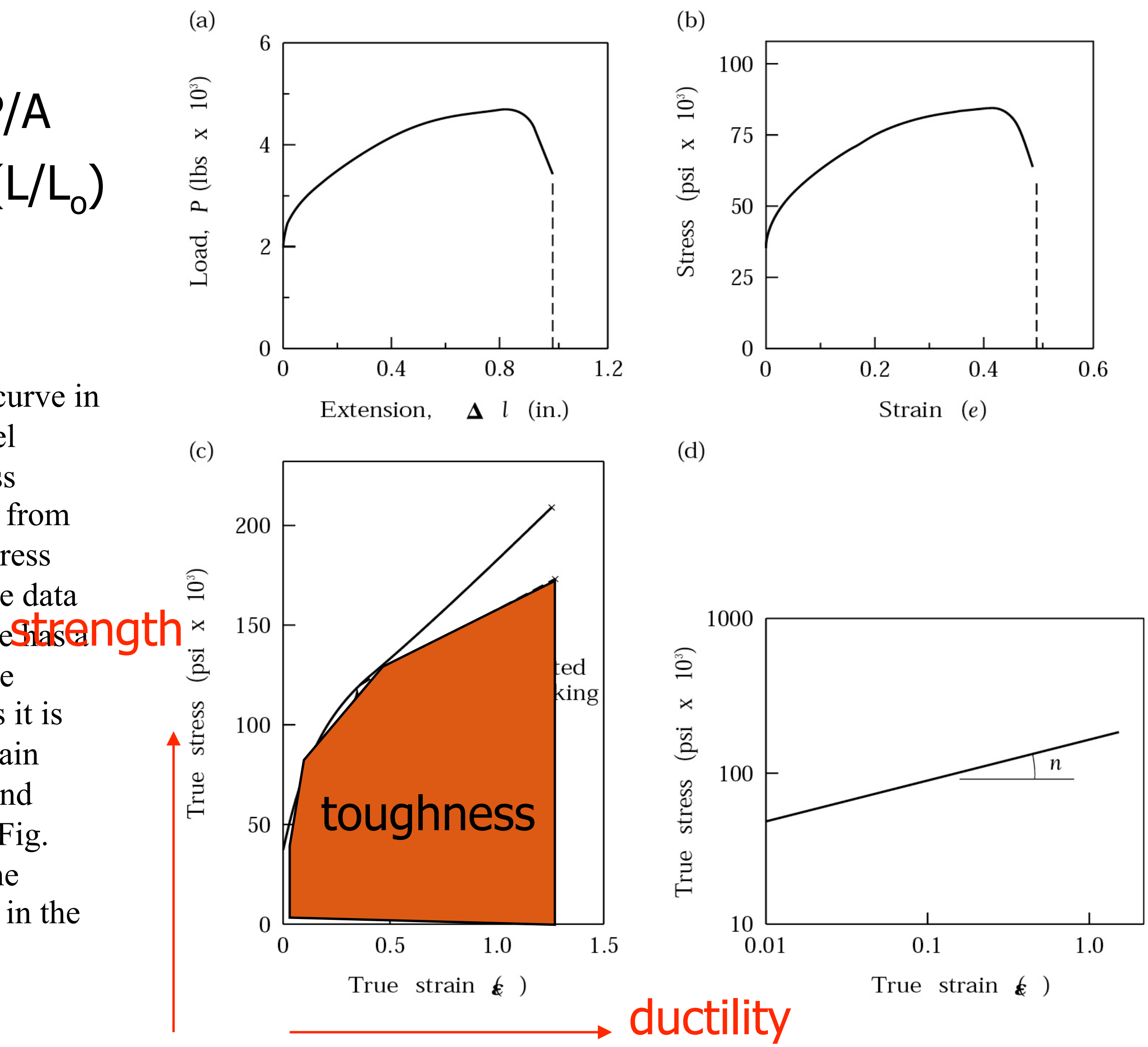
True Stress, Strain

True stress: $\sigma = P/A$

True strain: $\varepsilon = \ln(L/L_o)$

$\sigma = K\varepsilon^n$

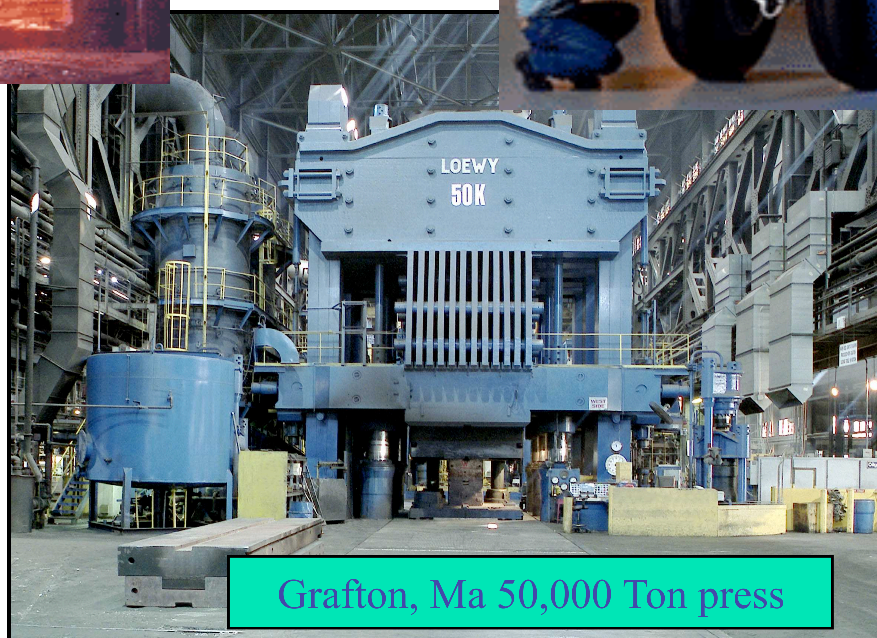
Figure 2.5 (a) Load-elongation curve in tension testing of a stainless steel specimen. (b) Engineering stress -engineering strain curve, drawn from the data in Fig. 2.5a. (c) True stress -true strain curve, drawn from the data in Fig. 2.5b. Note that this curve has a positive slope, indicating that the material is becoming stronger as it is strained. (d) True stress-true strain curve plotted on log-log paper and based on the corrected curve in Fig. 2.5c. The correction is due to the triaxial state of stress that exists in the necked region of a specimen.



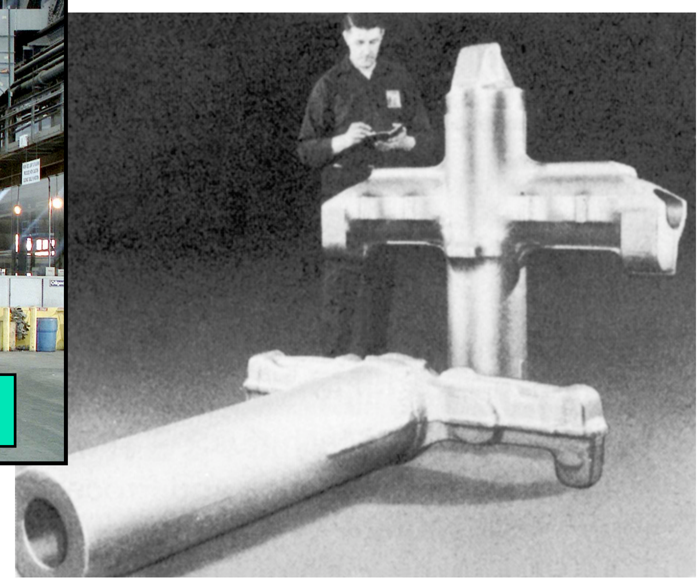
Forming Processes

- Forging
- Extrusion
- Rolling
- Sheet metal

Forged Landing Gear



Grafton, Ma 50,000 Ton press



Outline of Forging and Related Operations

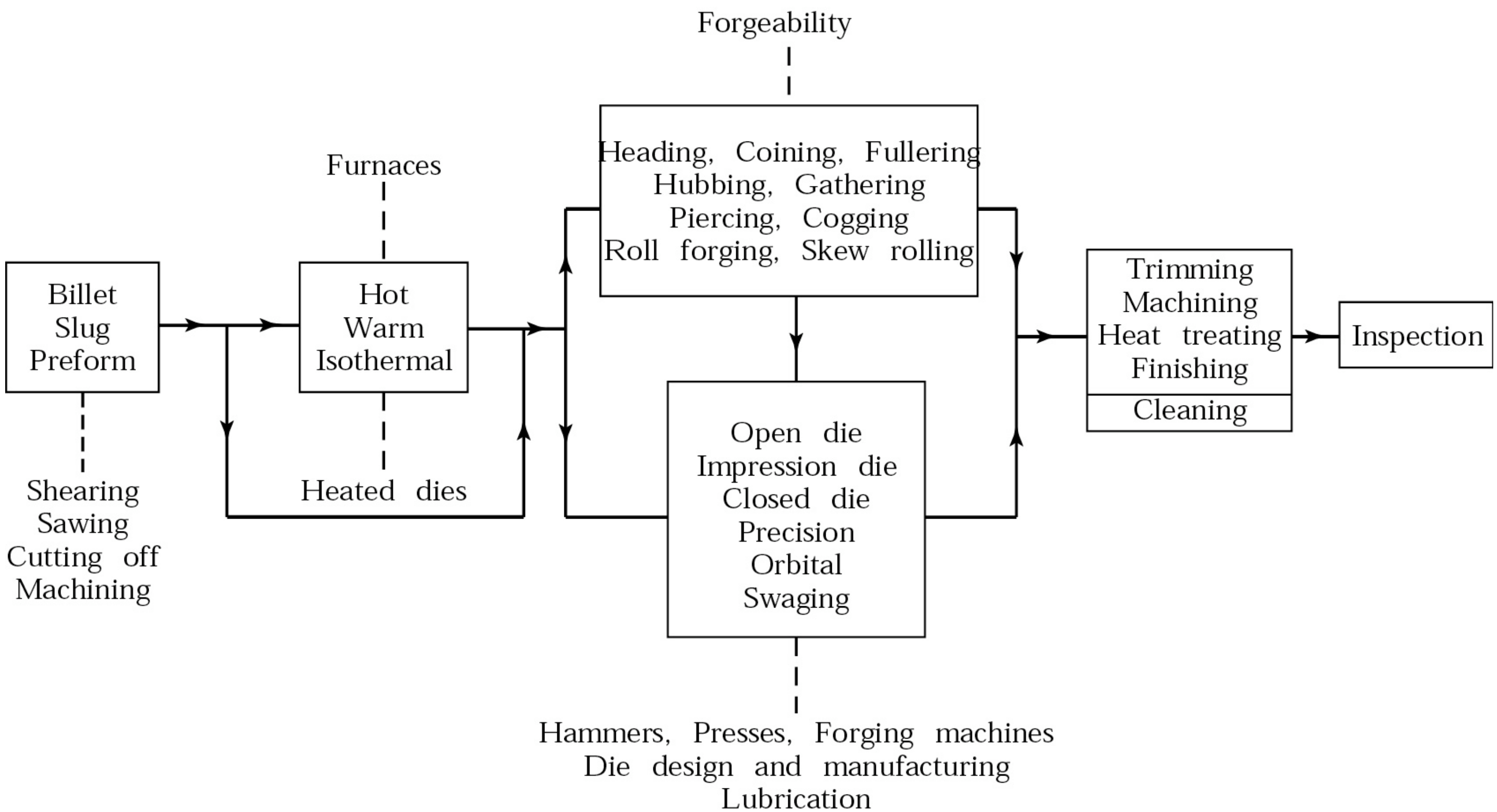


Figure 14.2

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Upsetting

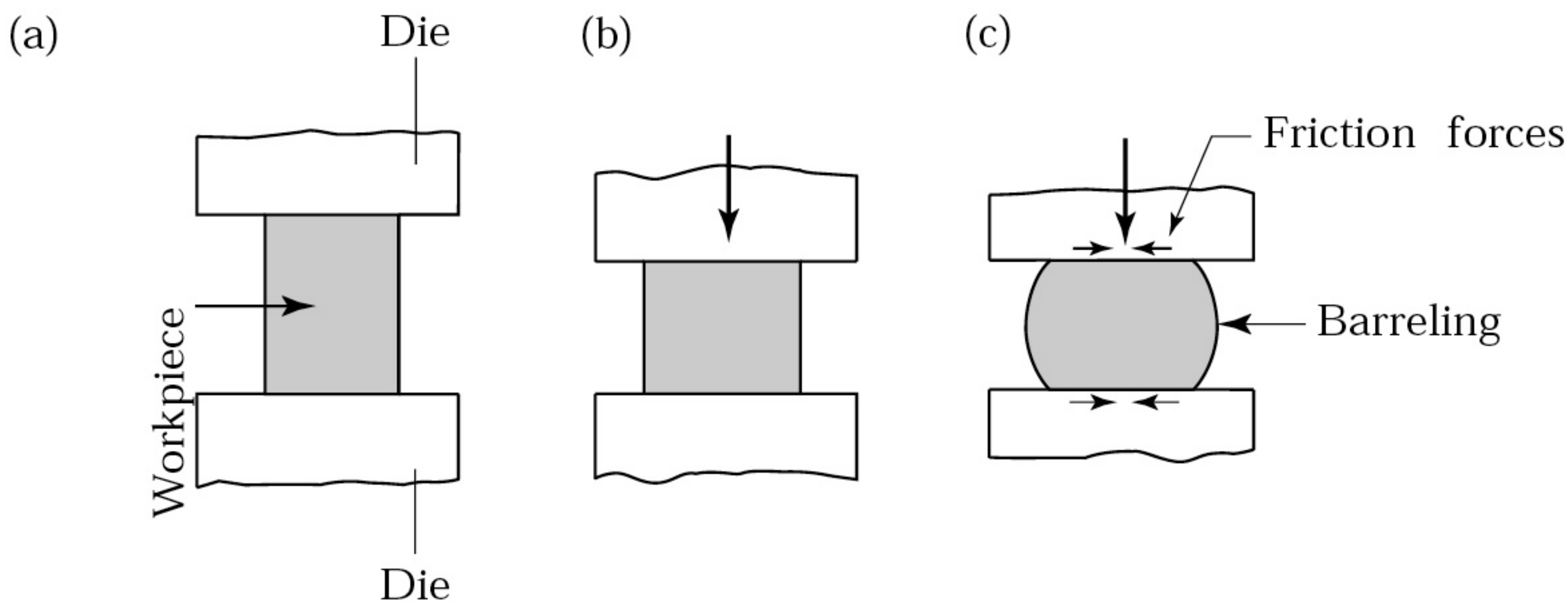

Figure 14.4 (a) Solid cylindrical billet upset between two flat dies. (b) Uniform deformation of the billet without friction. (c) Deformation with friction. Note barreling of the billet caused by friction forces at the billet-die interfaces.

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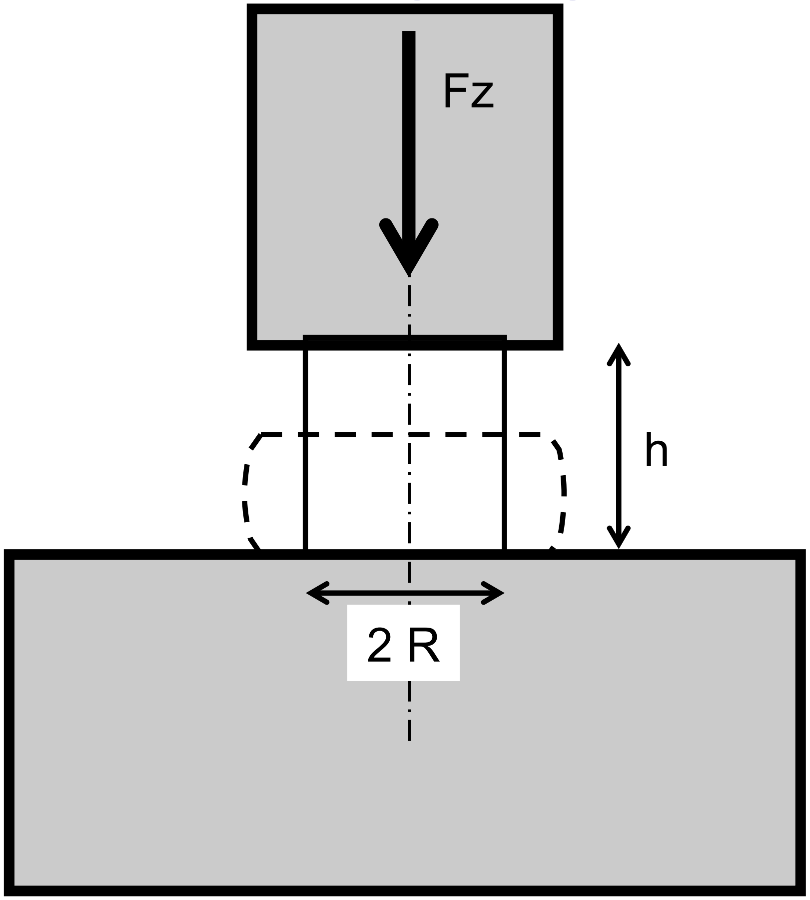
Forging force and friction



- Axisymmetric upsetting
- Purpose
  - Find $F_z(\mu)$
  - Sensitivity
- Assumptions:
  - Tresca flow
  - Constant friction coefficient
  - Plastic deformation

$$|F_z| = (\pi \cdot R^2) \cdot Y \cdot \left[1 + \left(\frac{2}{3} \cdot \frac{\mu \cdot R}{h}\right)\right]$$

Cogging

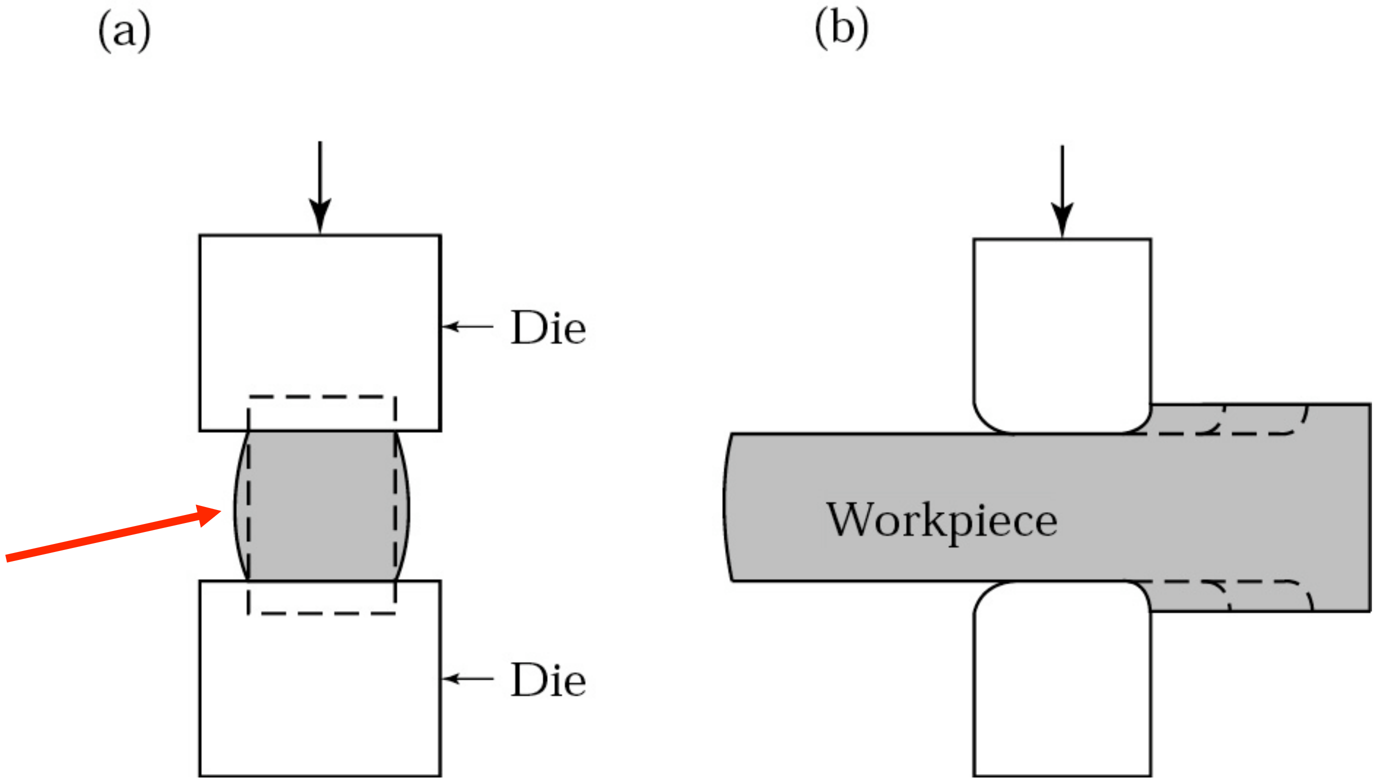


Figure 14.5 Two views of a cogging operation on a rectangular bar. Blacksmiths use this process to reduce the thickness of bars by hammering the part on an anvil. Note the barreling of the workpiece.

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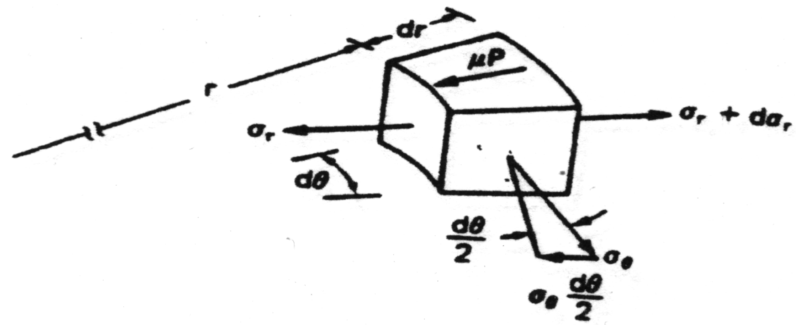
Forging force and friction



Eq. A – Equilibrium in r direction

$$\underbrace{}_{}\quad dF_{\text{inner arc}} \quad dF_{\text{friction top \& bottom}} \quad dF_{\text{hoop}} \quad dF_{\text{outer arc}}$$

$$\Sigma dF_r = 0 = \overbrace{-\sigma_r \cdot h \cdot r \cdot d\theta}^{dF_{\text{inner arc}}} \overbrace{- 2 \cdot \mu \cdot p \cdot r \cdot d\theta \cdot dr}^{dF_{\text{friction top \& bottom}}} \overbrace{- 2 \cdot \sigma_\theta \cdot h \cdot dr \cdot \frac{d\theta}{2}}^{dF_{\text{hoop}}} \overbrace{+ (\sigma_r + d\sigma_r) \cdot (r + dr) \cdot h \cdot d\theta}^{dF_{\text{outer arc}}}$$

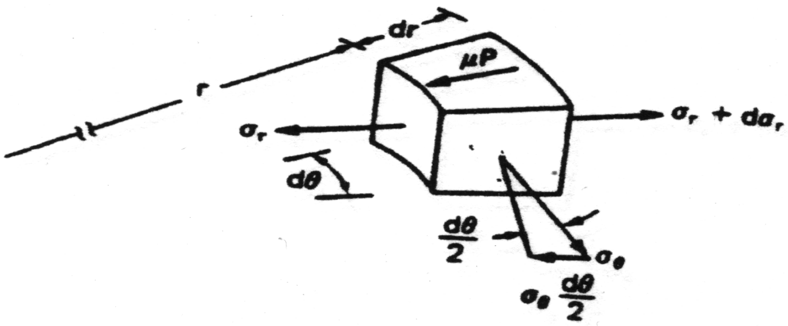
$$\frac{d\sigma_r}{dr} = \frac{2 \cdot \mu \cdot p}{h} = -\frac{2 \cdot \mu \cdot \sigma_z}{h}$$

Eq. B - Tresca Yield Criterion

$$\sigma_r - \sigma_z = Y$$

$$\sigma_z = -Y \cdot \exp\left[\frac{2\mu}{h}(R - r)\right]$$

Forging force and friction cont.



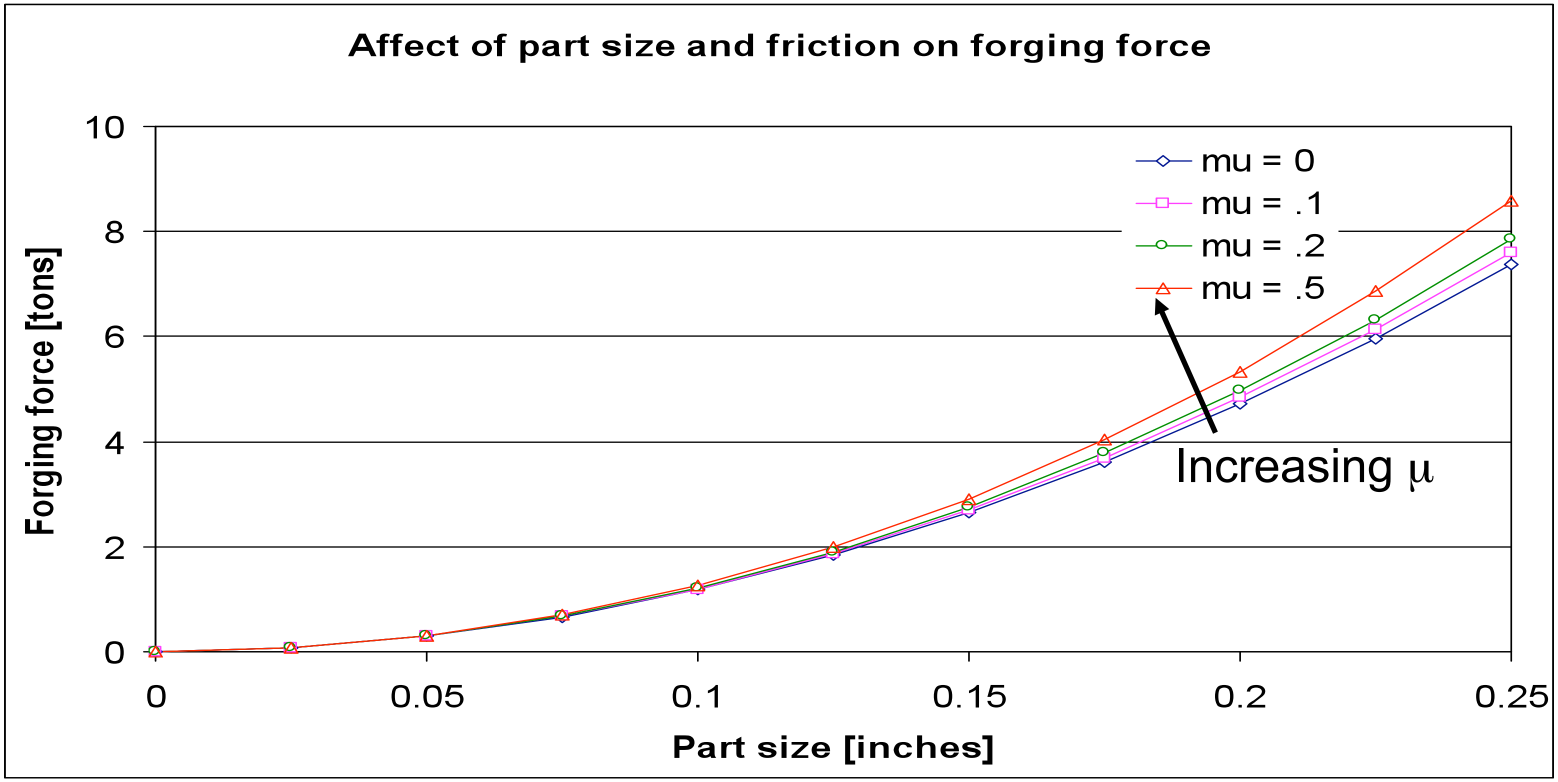
$$F_z = \int_0^R \sigma_z \cdot 2 \cdot \pi \cdot r \cdot dr = \left(\pi \cdot R^2\right) \cdot \frac{1}{2} \cdot \left(\frac{h}{\mu \cdot R}\right)^2 \cdot Y \cdot \left[\exp\left(\frac{2 \cdot \mu \cdot R}{h}\right) - \left(\frac{2 \cdot \mu \cdot R}{h}\right) - 1\right]$$

Now use Taylor's series expansion (3 terms) to approximate the exponential function

Expand about 0, makes this approximation valid for small values of $2\mu R/h$

$$\left|F_z\right| = \left(\pi \cdot R^2\right) \cdot Y \cdot \left[1 + \left(\frac{2}{3} \cdot \frac{\mu \cdot R}{h}\right)\right]$$

Forging force and friction



σθ

Y=75000 psi
h = ½ inch

Impression-Die Forging

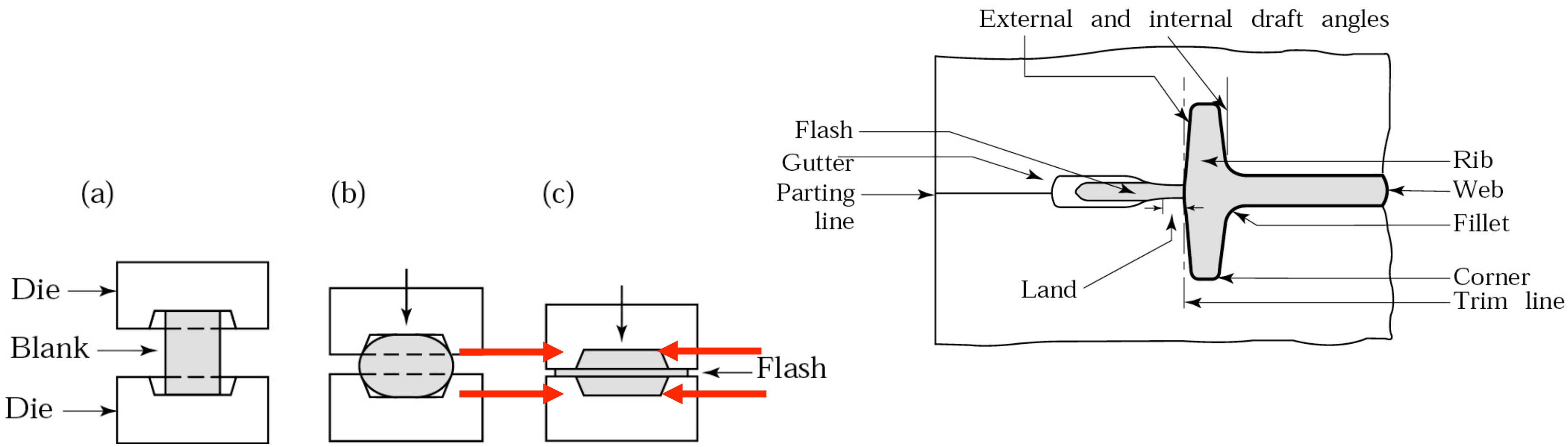


Figure 14.6 Stages in impression-die forging of a solid round billet. Note the formation of flash, which is excess metal that is subsequently trimmed off (see Fig. 14.8).

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Forging a Connecting Rod

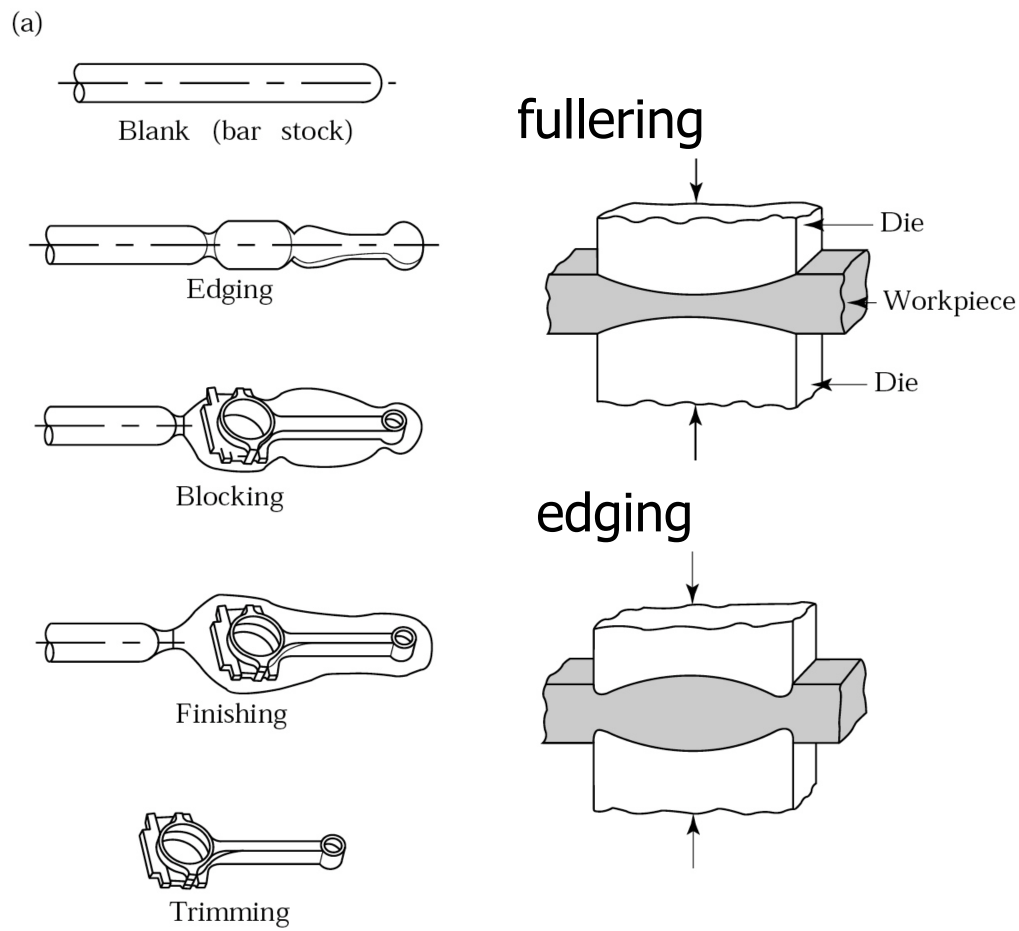

Figure 14.7 (a) Stages in forging a connecting rod for an internal combustion engine. Note the amount of flash required to ensure proper filling of the die cavities. (b) Fullering, and (c) edging operations to distribute the material when preshaping the blank for forging.

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Heading/Upset Forging/Coining

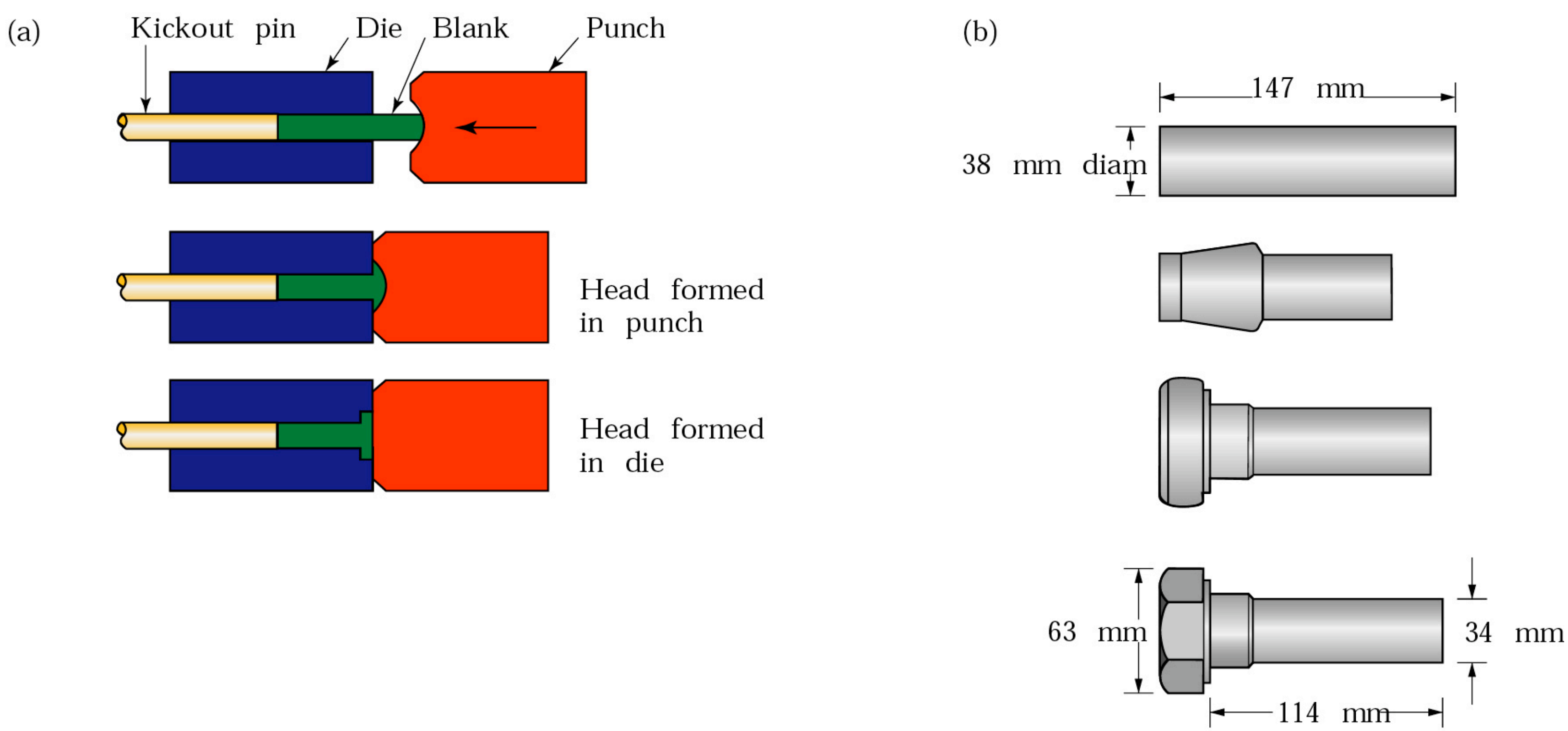

Figure 14.11 (a) Heading operation, to form heads on fasteners such as nails and rivets. (b) Sequence of operations to produce a bolt head by heading.

Pierced Round Billet

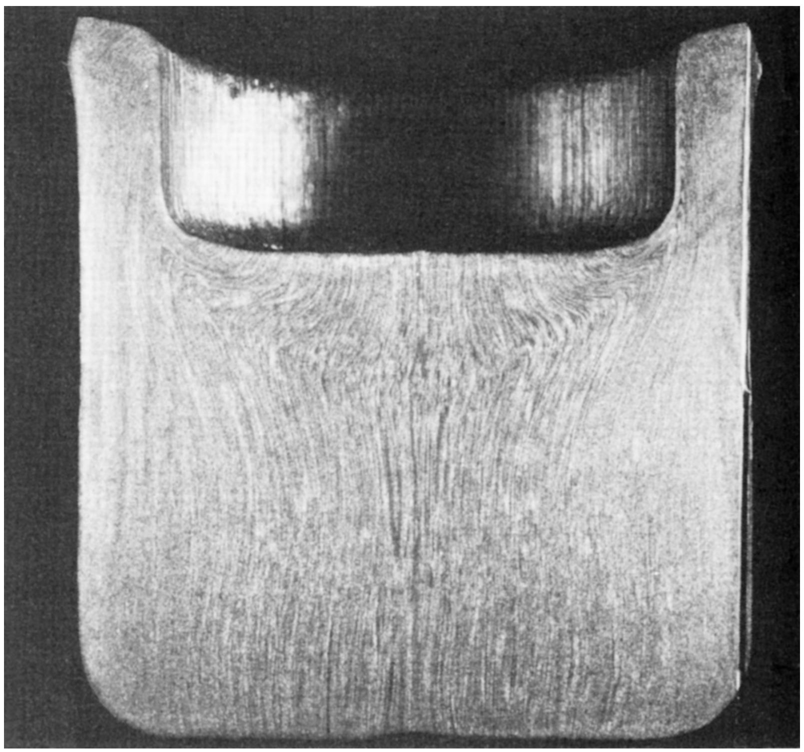

Figure 14.12 A pierced round billet, showing grain flow pattern. *Source*: Courtesy of Ladish Co., Inc.

Defects in Forged Parts

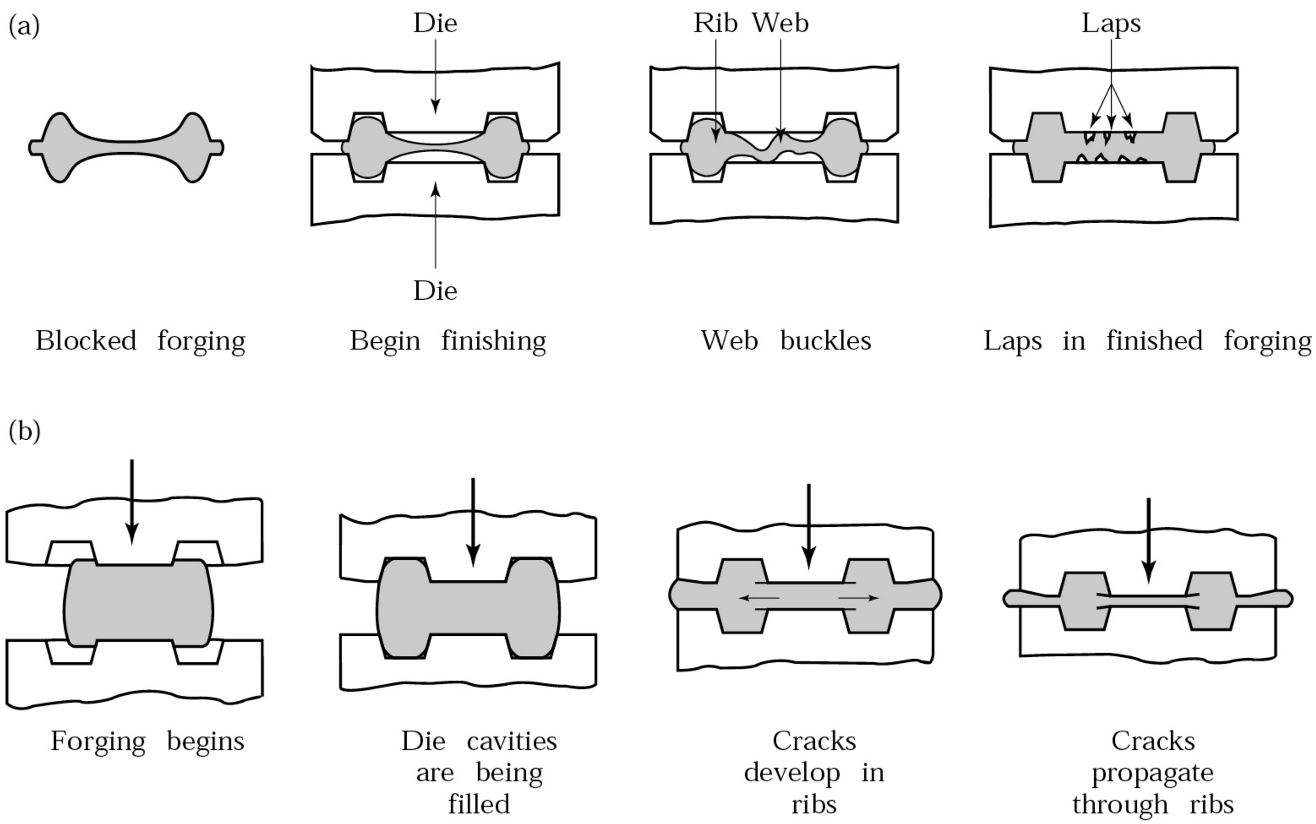

Figure 14.20 Examples of defects in forged parts. (a) Labs formed by web buckling during forging; web thickness should be increased to avoid this problem. (b) Internal defects caused by oversized billet; die cavities are filled prematurely, and the material at the center flows past the filled regions as the dies close.

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Order of Forgeablilty

Metal or alloy	Approximate range of hot forging temperature (°C)
Aluminum alloys	400–550
Magnesium alloys	250–350
Copper alloys	600–900
Carbon and low–alloy steels	850–1150
Martensitic stainless steels	1100–1250
Austenitic stainless steels	1100–1250
Titanium alloys	700–950
Iron-base superalloys	1050–1180
Cobalt-base superalloys	1180–1250
Tantalum alloys	1050–1350
Molybdenum alloys	1150–1350
Nickel-base superalloys	1050–1200
Tungsten alloys	1200–1300

Process characteristics

- Material/continuum changes during processing
  - Machining = Local, concentrated
  - Deforming = Over large volume
- Force
  - Machining: ~10s - 100s of lbs
  - Stamping: ~10s - 100s of tons
  - Forging: ~100s – 10000s tons
- Materials - Virtually all ductile materials
- Shapes - Limited by strain/flow
- Size - Limited by force/equipment

Forming Processes

- Forging
- Extrusion
- Rolling
- Sheet metal

Rolling Processes

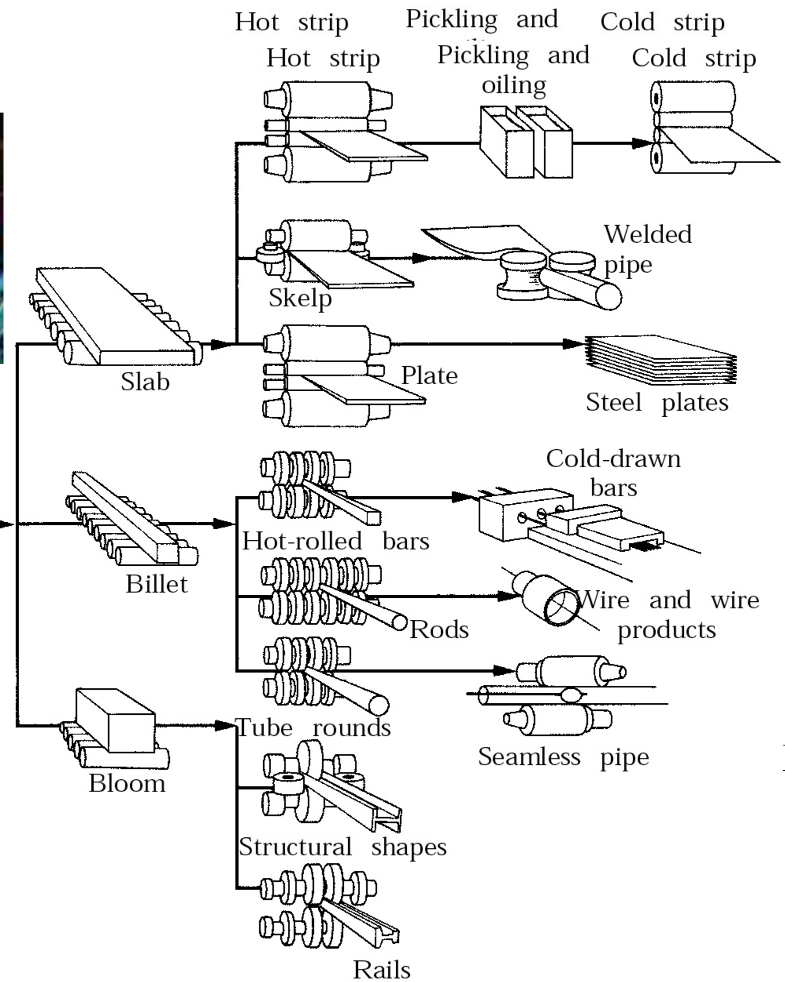


Figure 13.1 Schematic outline of various flat- and shape-rolling processes. *Source*: American Iron and Steel Institute.

Rolling Mill

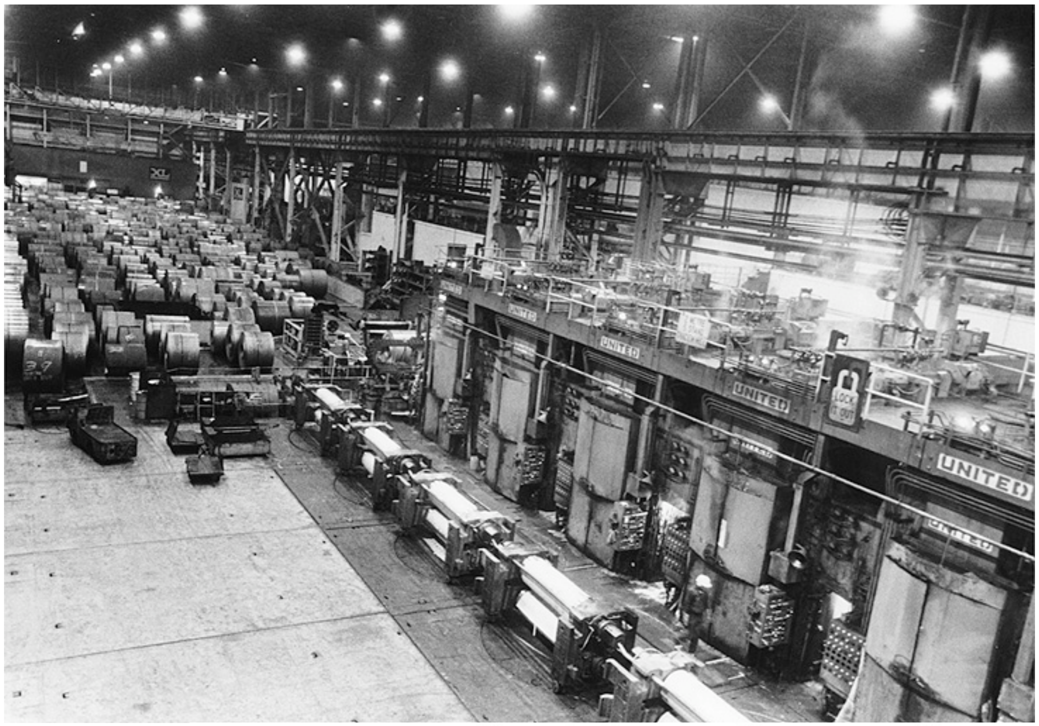
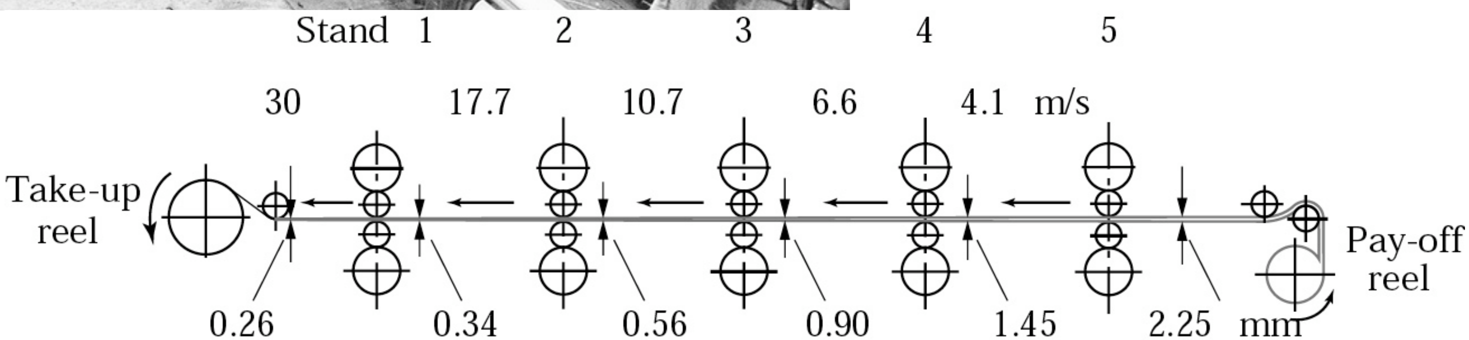
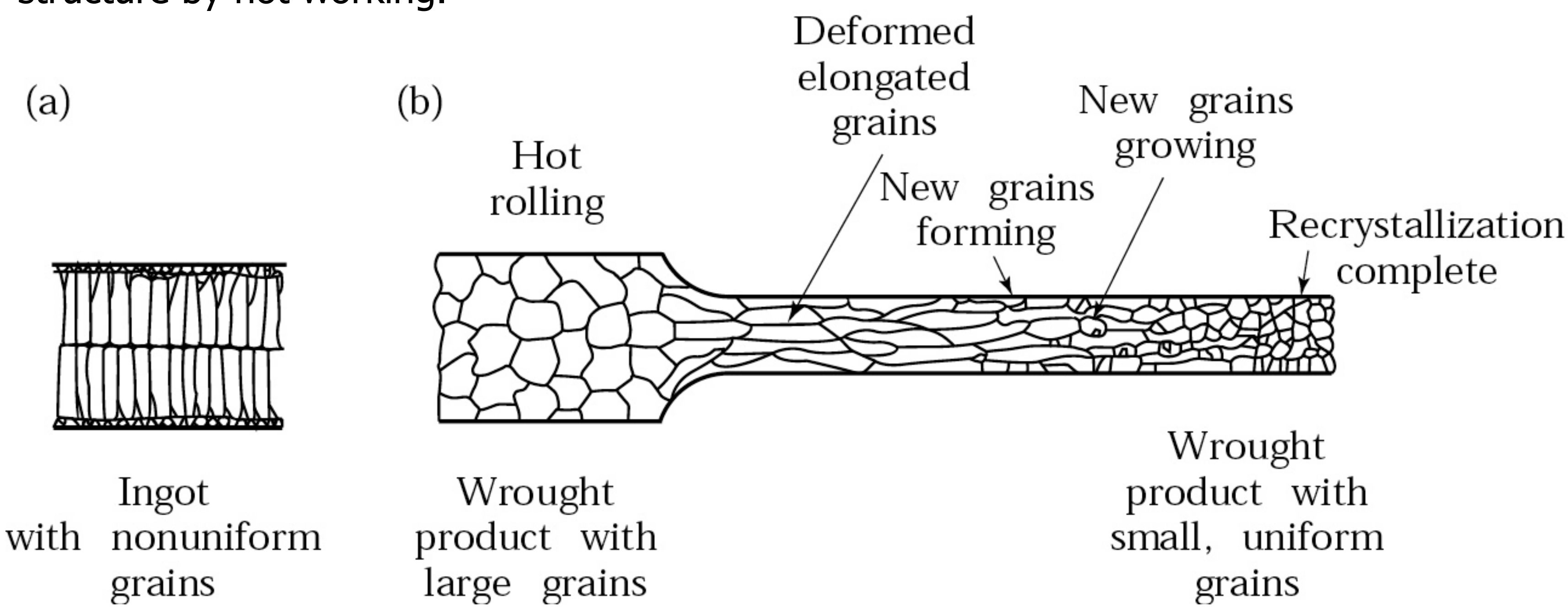


Figure 13.10 A general view of a rolling mill. *Source*: Inland Steel.



Grain Structure During Hot Rolling

Changes in the grain structure of cast or of 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 casting are converted to a wrought structure by hot working.



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Flat-Rolling

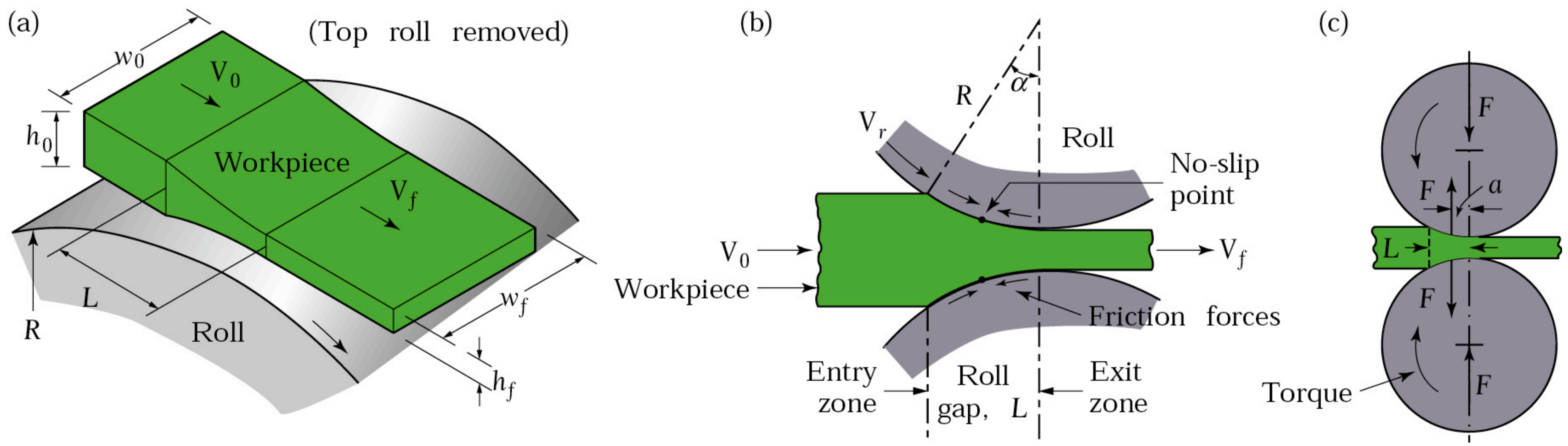


Figure 13.2 (a) Schematic illustration of the flat-rolling process. (b) Friction forces acting on strip surfaces. (c) The roll force, *F*, and the torque acting on the rolls. The width *w* of the strip usually increases during rolling, as is shown in Fig. 13.5.

Draft

Roll force, Roll strip contact length, Average True stress

Torque ?

Residual Stresses in Rolling

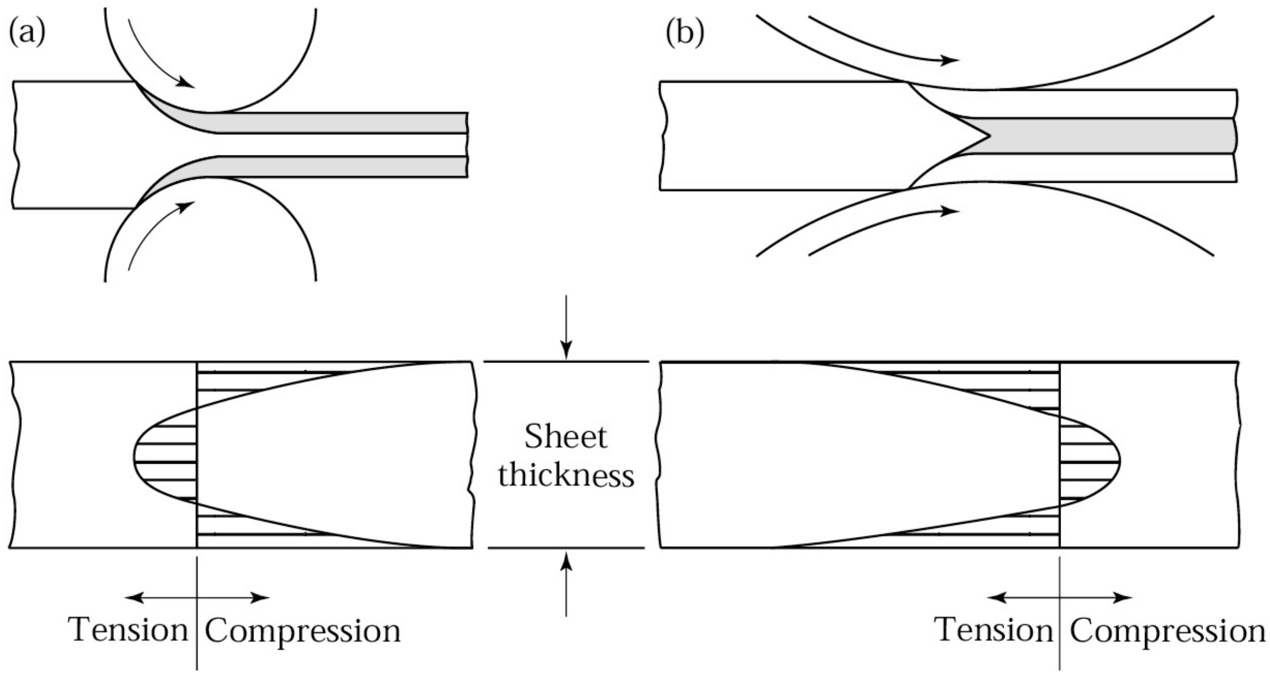
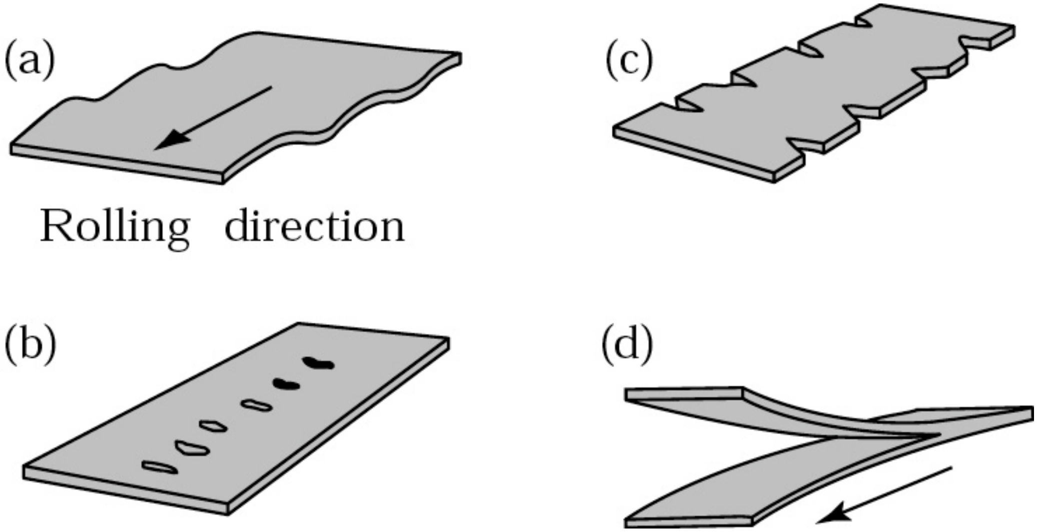
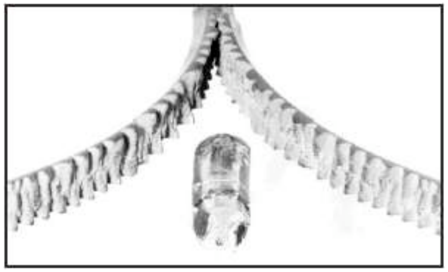


Figure 13.9 (a) Residual stresses developed in rolling with small rolls or at small reductions in thickness per pass. (b) Residual stresses developed in rolling with large rolls or at high reductions per pass. Note the reversal of the residual stress patterns.

Defects in Flat Rolling

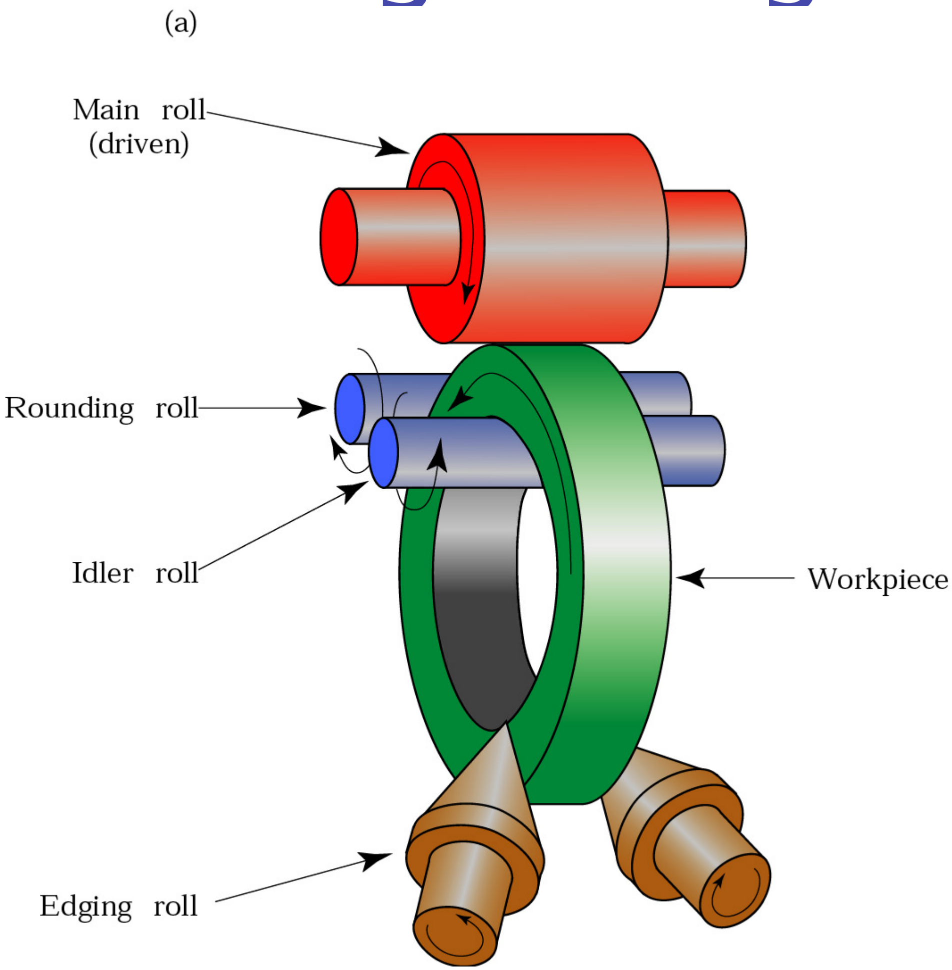
Figure 13.8 Schematic illustration of typical defects in flat rolling: (a) wavy edges; (b) zipper cracks in the center of the strip; (c) edge cracks; and (d) alligatoring.





alligatoring

Ring-Rolling



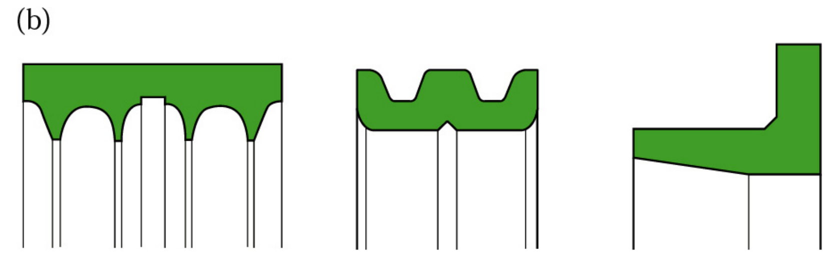


Figure 13.14 (a) Schematic illustration of a ring-rolling operation. Thickness reduction results in an increase in the part diameter. (b) Examples of cross-sections that can be formed by ring rolling.

Mannesmann Process

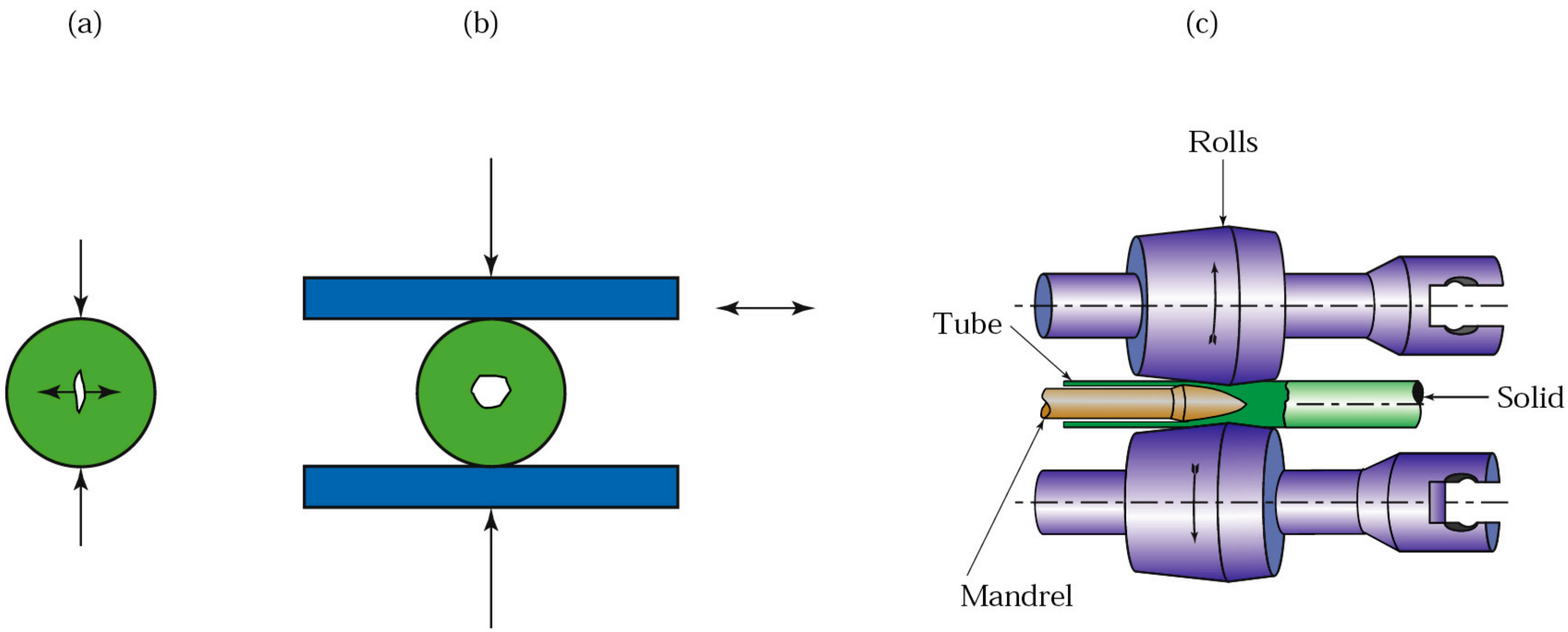


Figure 13.17 Cavity formation in a solid round bar and its utilization in the rotary tube piercing process for making seamless pipe and tubing. (The Mannesmann mill was developed in the 1880s.)

Spray Casting (Osprey Process)

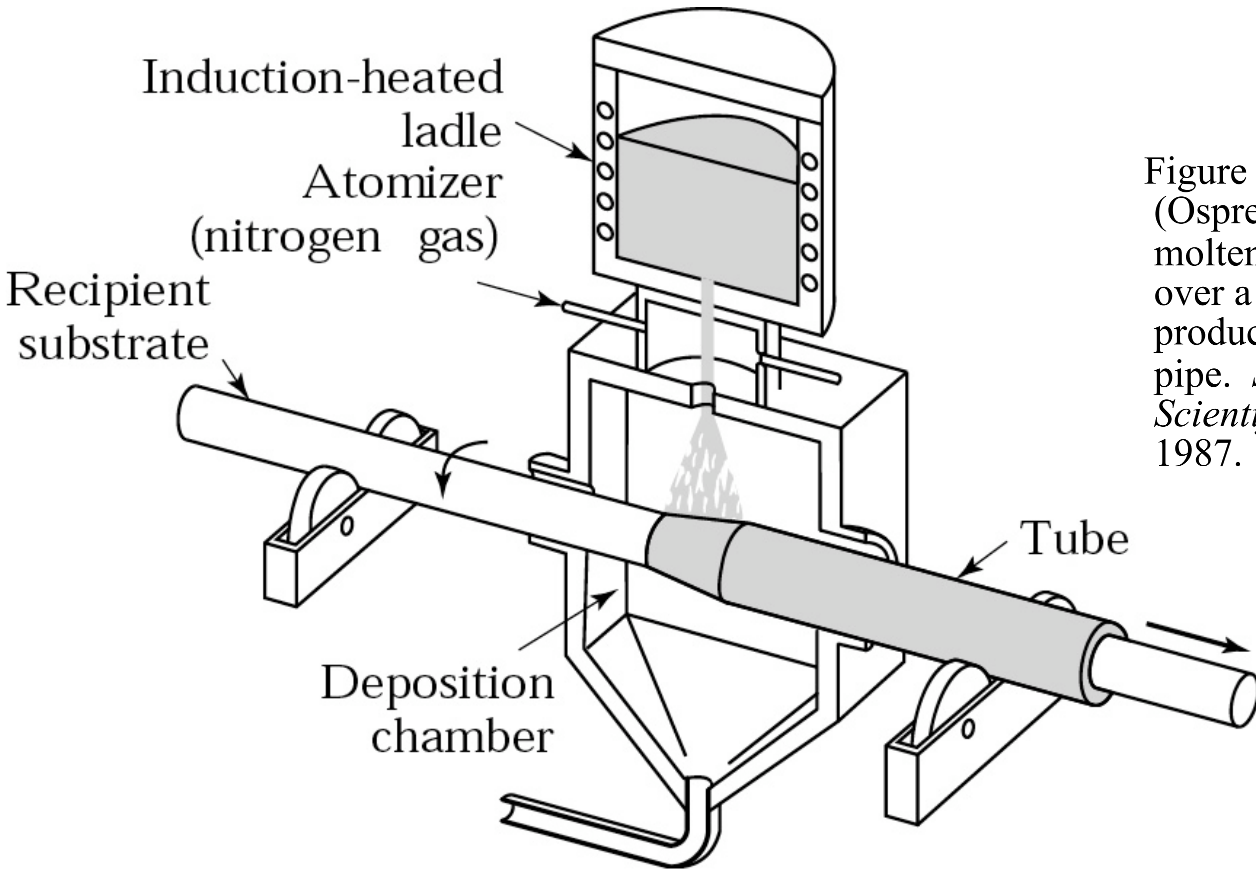


Figure 13.19 Spray casting (Osprey process), in which molten metal is sprayed over a rotating mandrel to produce seamless tubing and pipe. *Source*: J. Szekely, *Scientific American*, July 1987.

Forming Processes

- Forging
- Extrusion
- Rolling
- Sheet metal

Extrusions

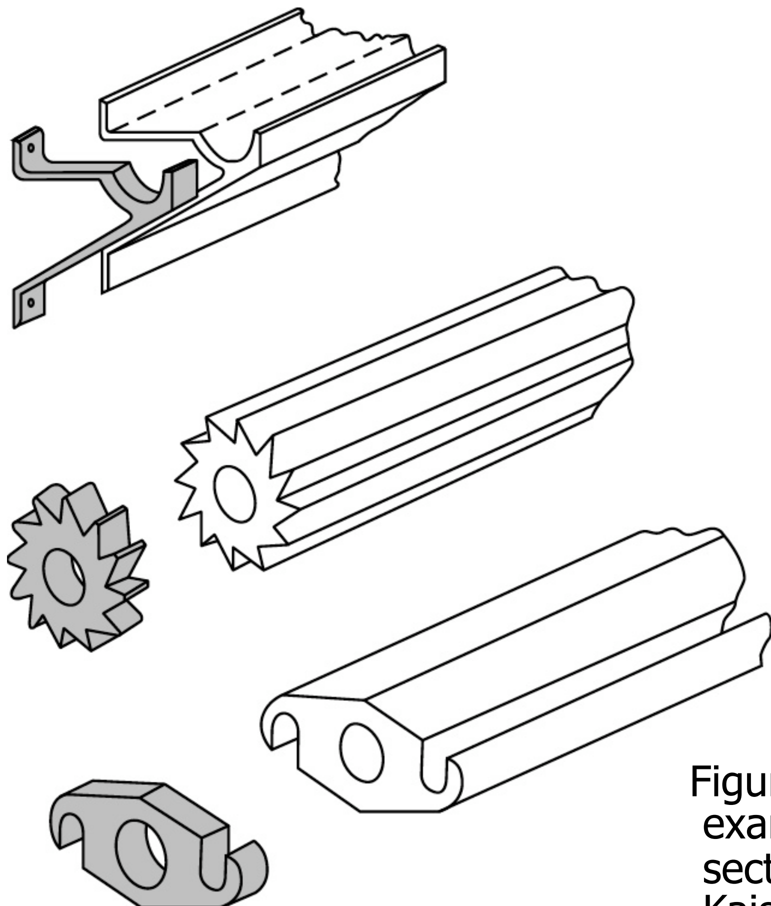


Figure 15.2 Extrusions, and examples of products made by sectioning off extrusions. *Source*: Kaiser Aluminum.

Direct Extrusion

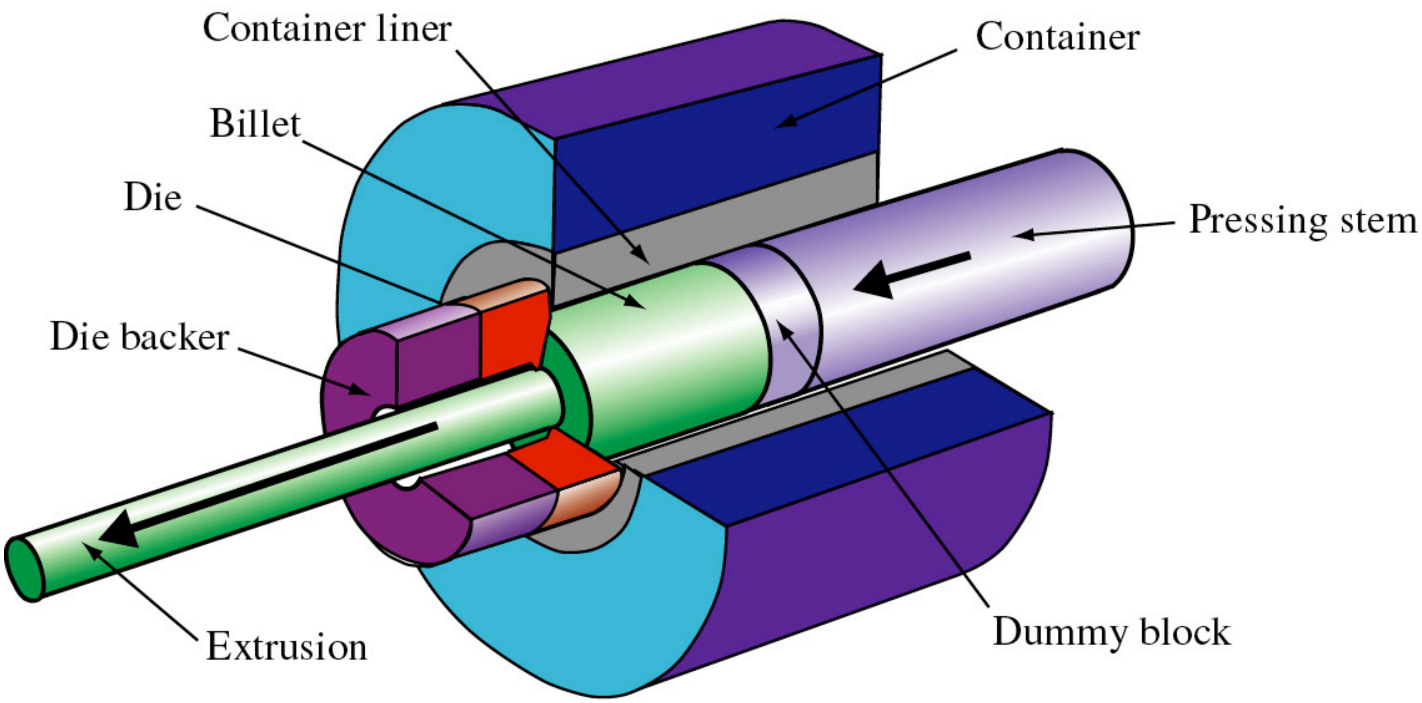


Figure 15.1 Schematic illustration of the direct extrusion process.

Types of Extrusion

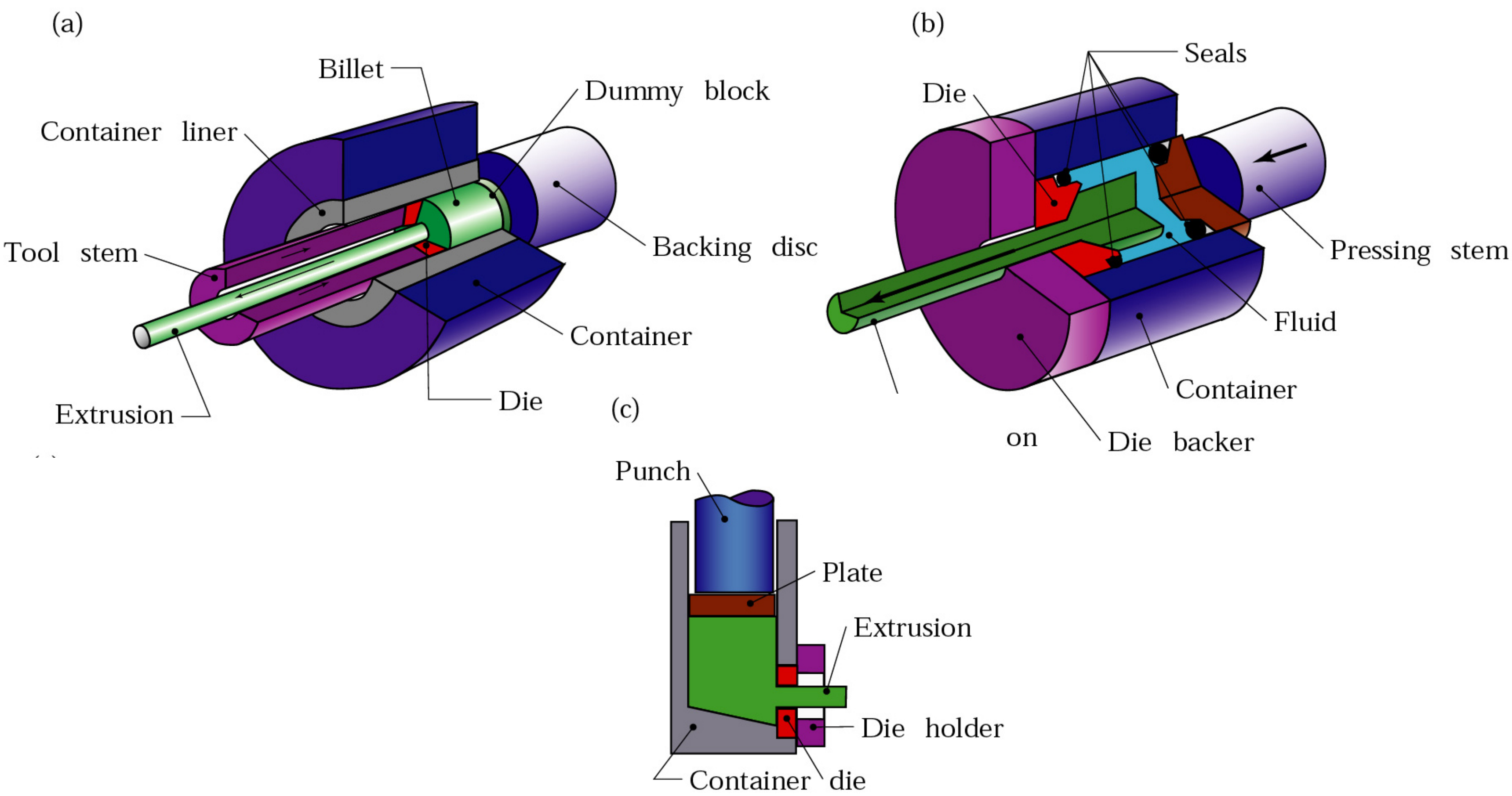


Figure 15.3 Types of extrusion: (a) indirect; (b) hydrostatic; (c) lateral.

Process Variables in Direct Extrusion

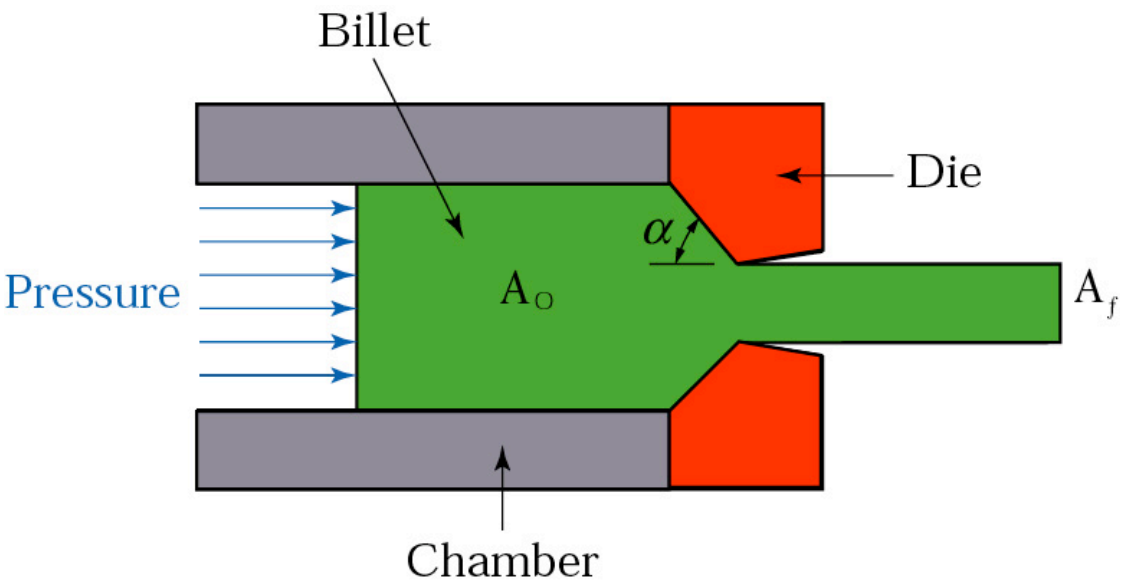
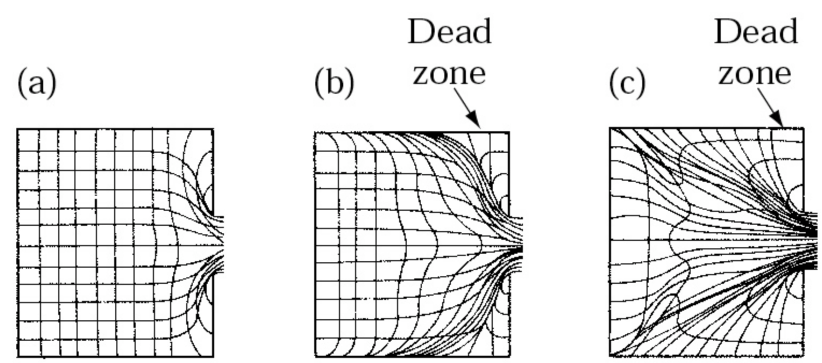


Figure 15.4 Process variables in direct extrusion. The die angle, reduction in cross-section, extrusion speed, billet temperature, and lubrication all affect the extrusion pressure.

$$F = A_o K \ln(\frac{A_o}{A_f})$$



Cold Extruded Spark Plug

Figure 15.12 Production steps for a cold extruded spark plug. *Source*: National Machinery Company.

Figure 15.13 A cross-section of the metal part in Fig. 15.12, showing the grain flow pattern. *Source*: National Machinery Company.

Extrusion Constant *k* for Various Metals

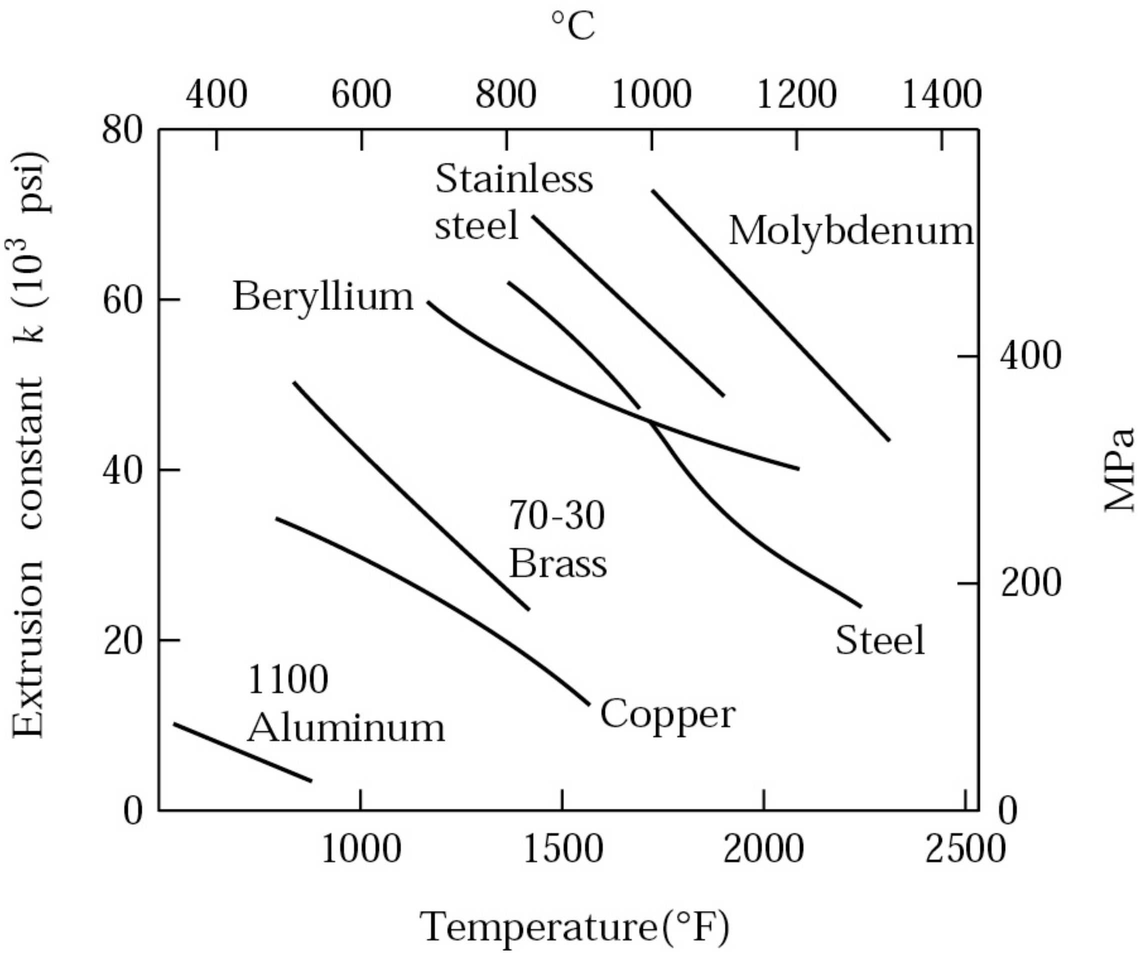


Figure 15.6 Extrusion constant *k* for various metals at different temperatures. *Source*: P. Loewenstein.

Process Variables in Wire Drawing

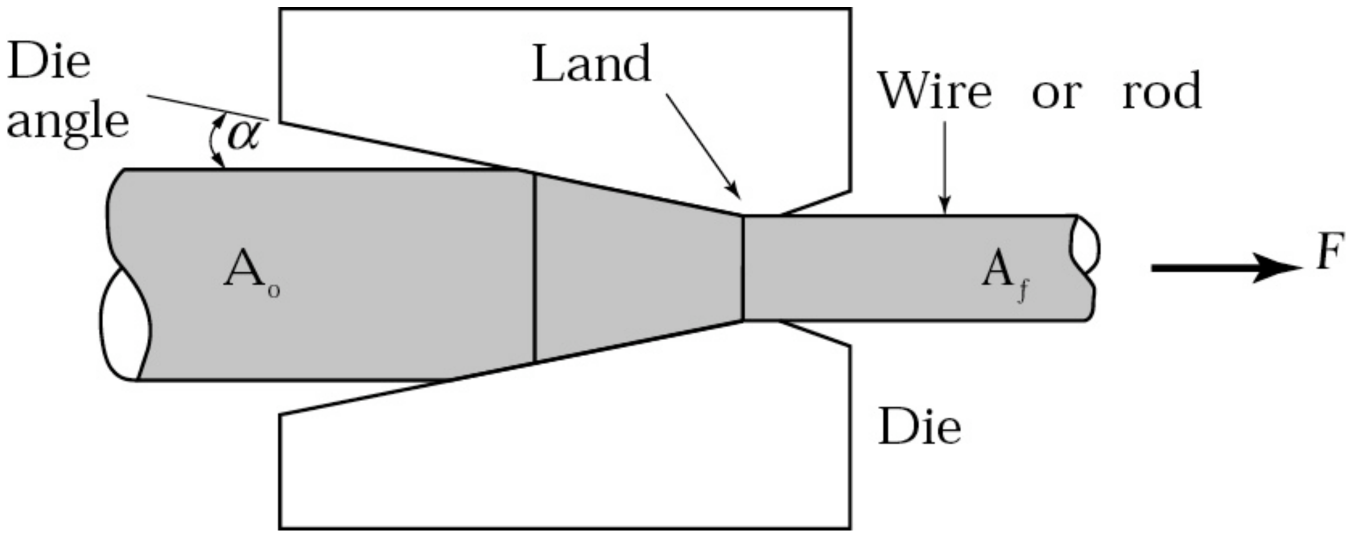


Figure 15.18 Process variables in wire drawing. The die angle, the reduction in cross-sectional area per pass, the speed of drawing, the temperature, and the lubrication all affect the drawing force, *F*.

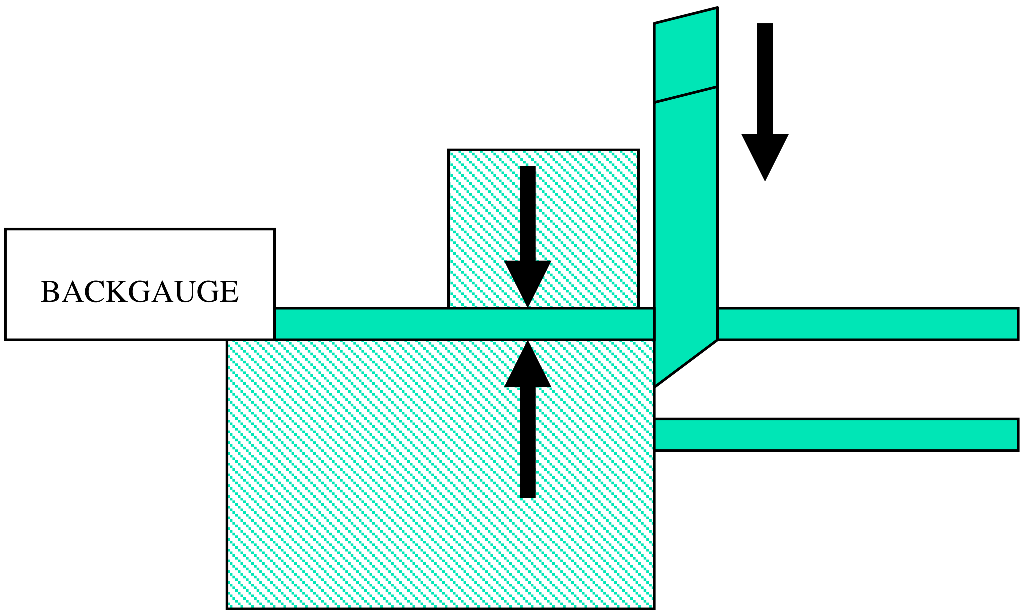
$$F = Y_{avg} A_f \ln\left(\frac{A_o}{A_f}\right)$$

Forming Processes

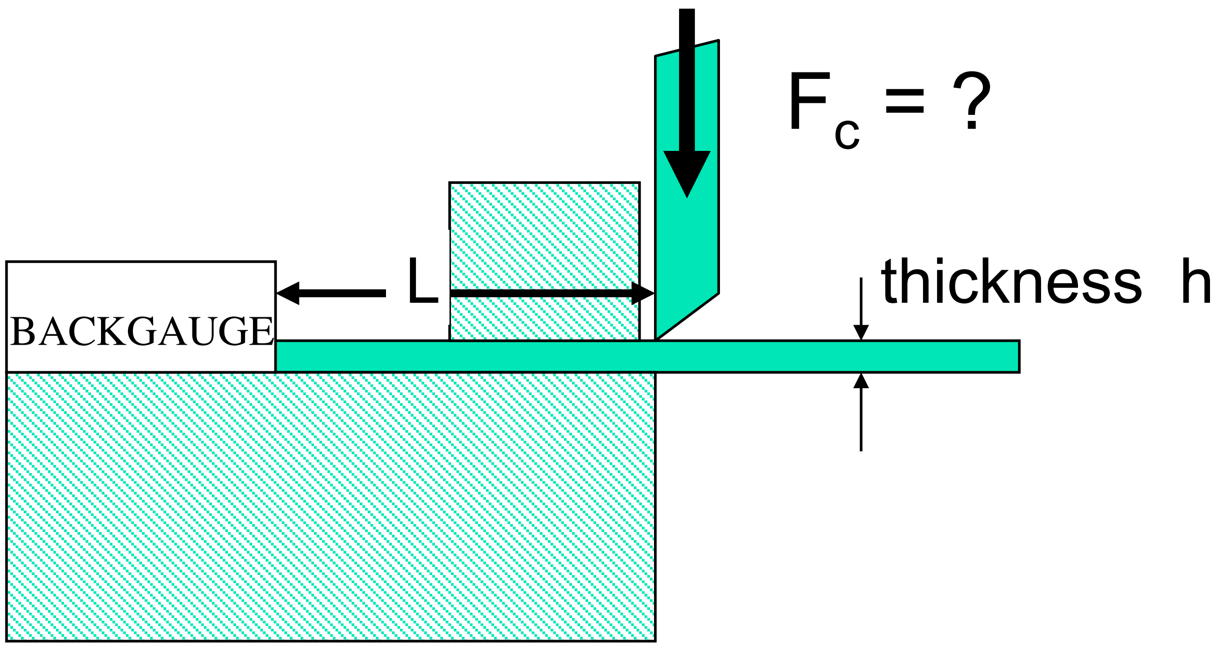
- Forging
- Extrusion
- Rolling
- Sheet metal

Sheet Shearing Modeling

- Parallel Case: (punching)

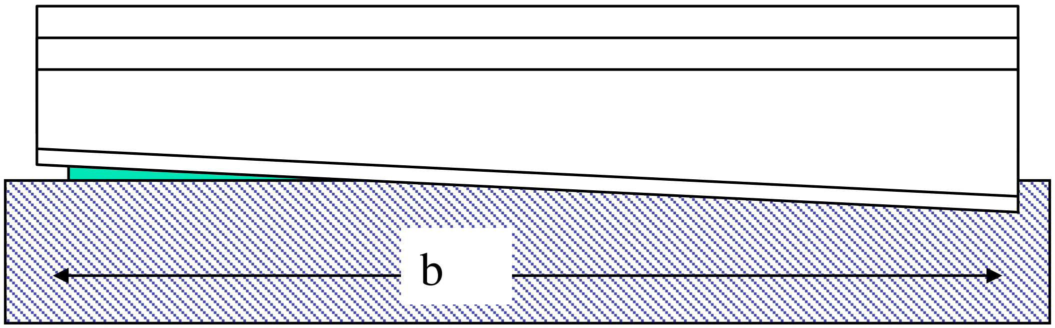


Dimensional Control



F_c =0.7 UTS * h * b

Serial Shearing



Why:

F_c =0.7* UTS * h * b

UTS ~ 30,000 psi

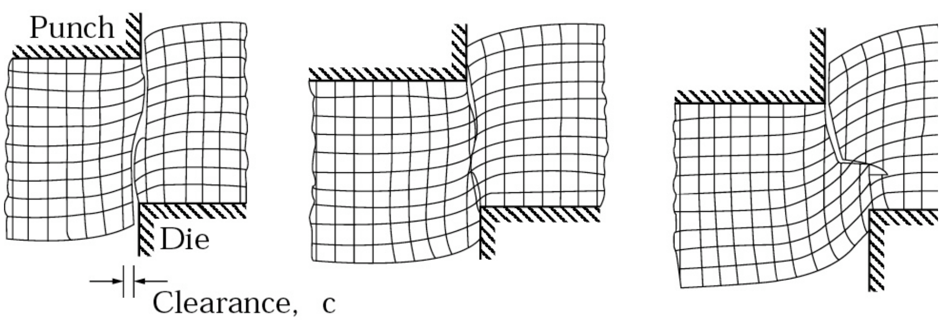
b=20 in.

h = 0.06

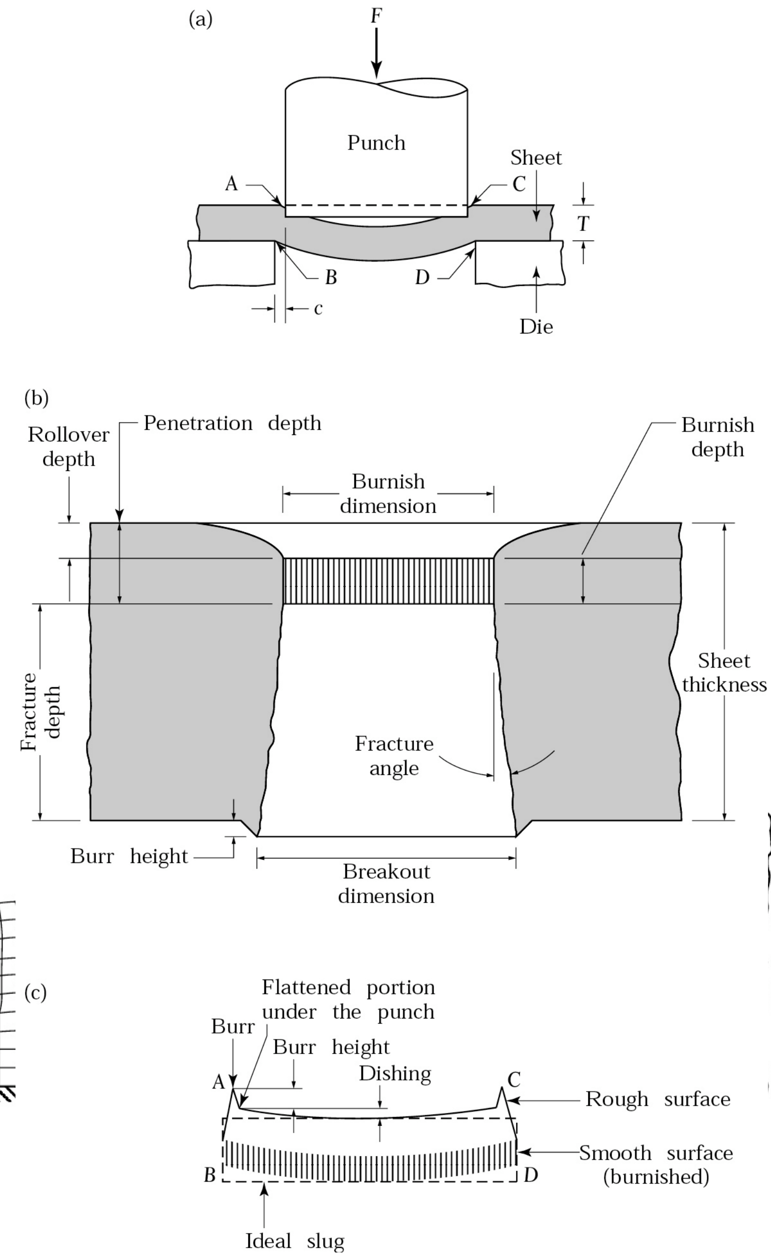
F_c = 25,200 lb.!

punching

(a)

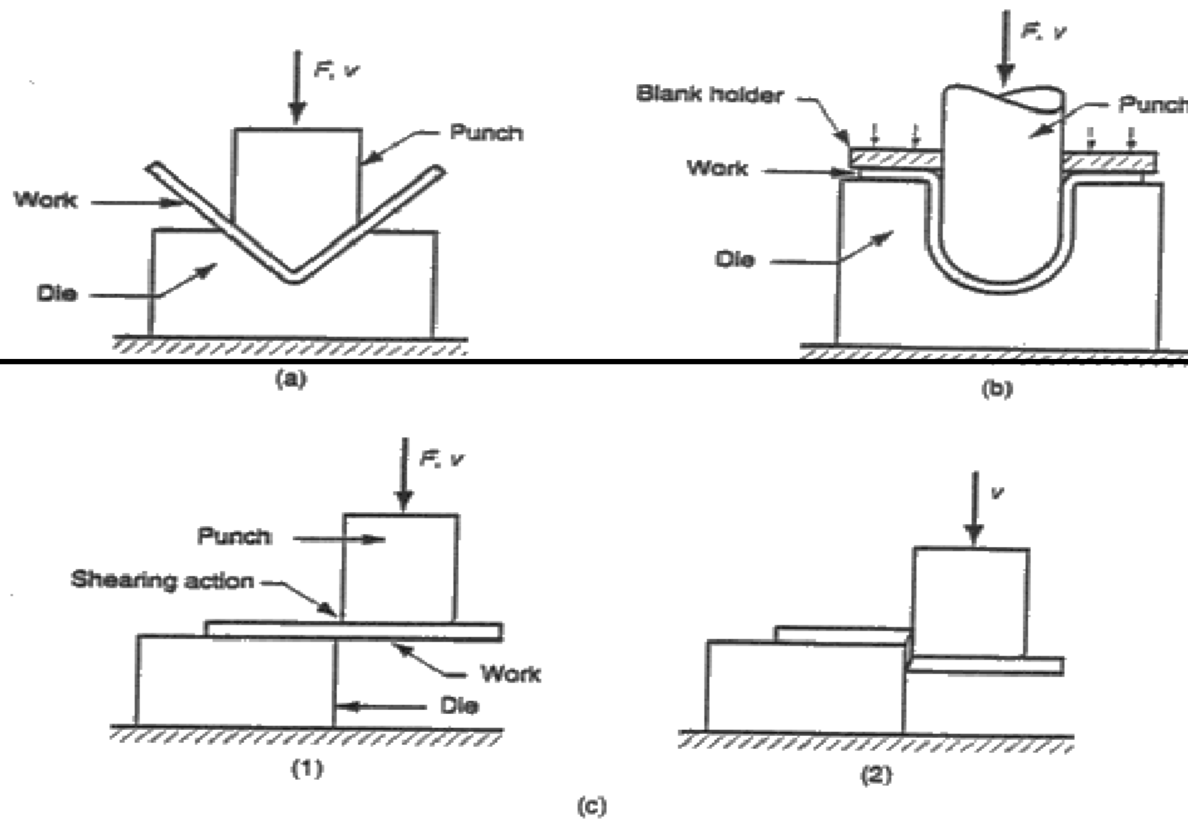


Punch
Die
Clearance, c

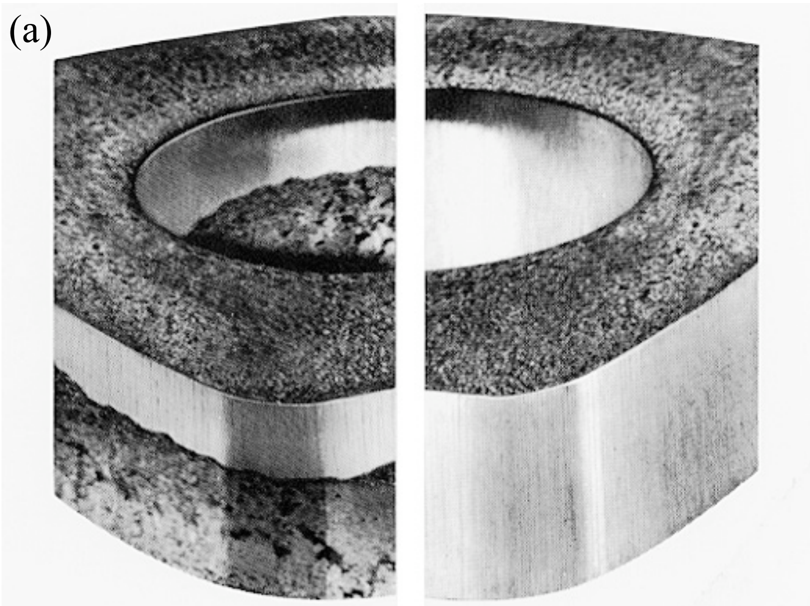


(a)
F
Punch
Sheet
A
C
T
B
D
c
Die
(b)
Rollover depth
Penetration depth
Burnish depth
Burnish dimension
Fracture depth
Sheet thickness
Fracture angle
Burr height
Breakout dimension
(c)
Flattened portion under the punch
Burr
Burr height
Dishing
A
C
Rough surface
Smooth surface (burnished)
B
D
Ideal slug

Bending and shearing/ sheet metal forming



Fine Blanking



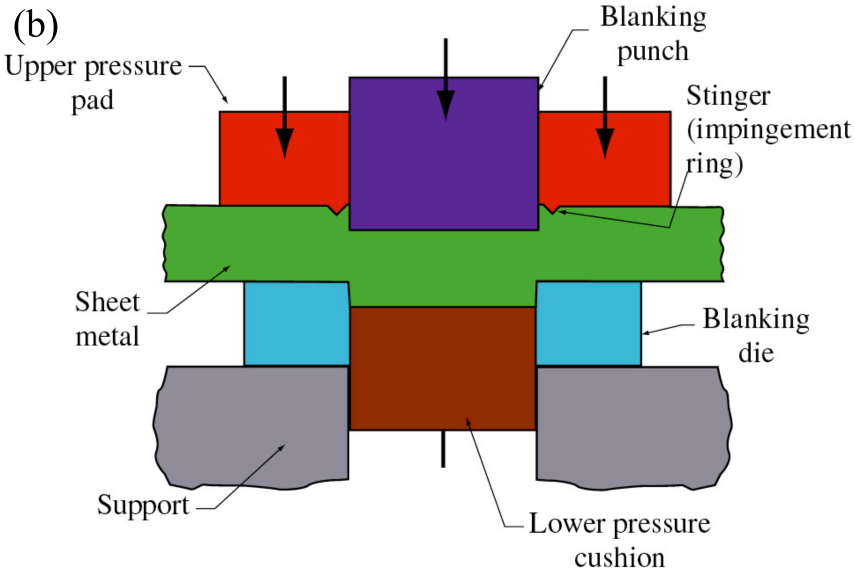
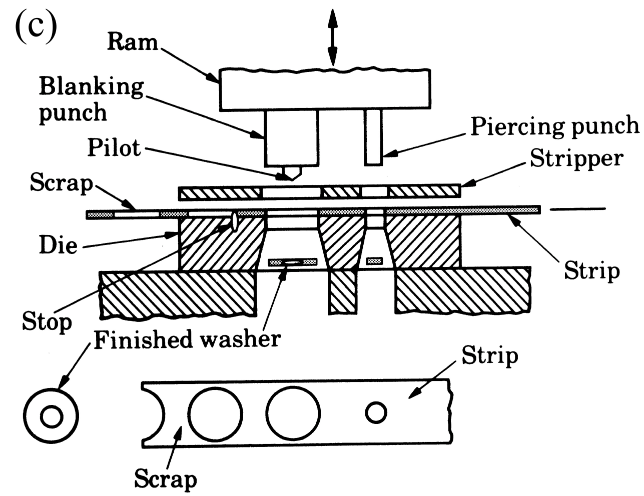


Figure 16.5 (a) Comparison of sheared edges produced by conventional (left) and by fine-blanking (right) techniques. (b) Schematic illustration of one setup for fine blanking. *Source*: Feintool U.S. Operations.

Compound and Progressive Die



Yield-Point Elongation

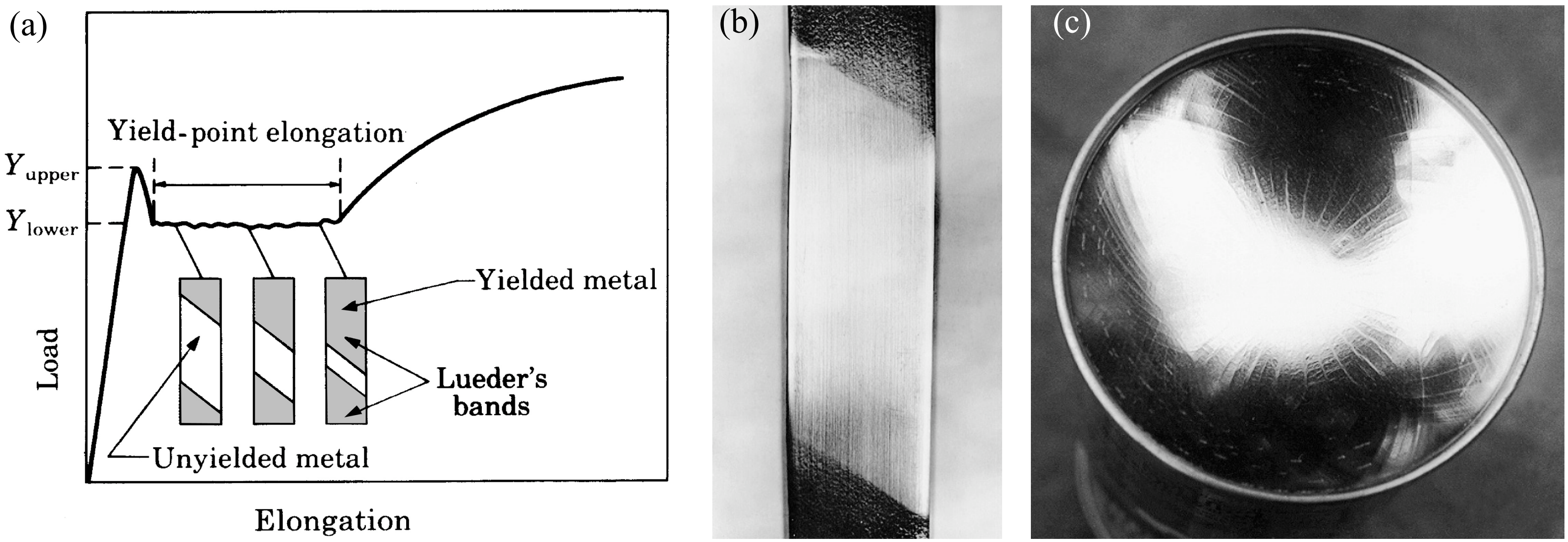


Figure 16.12 (a) Yield-point elongation in a sheet-metal specimen. (b) Lueder's bands in a low-carbon steel sheet. *Source*: Courtesy of Caterpillar Inc. (c) Stretcher strains at the bottom of a steel can for household products.

Erichsen and Bulge-Tests

(a)

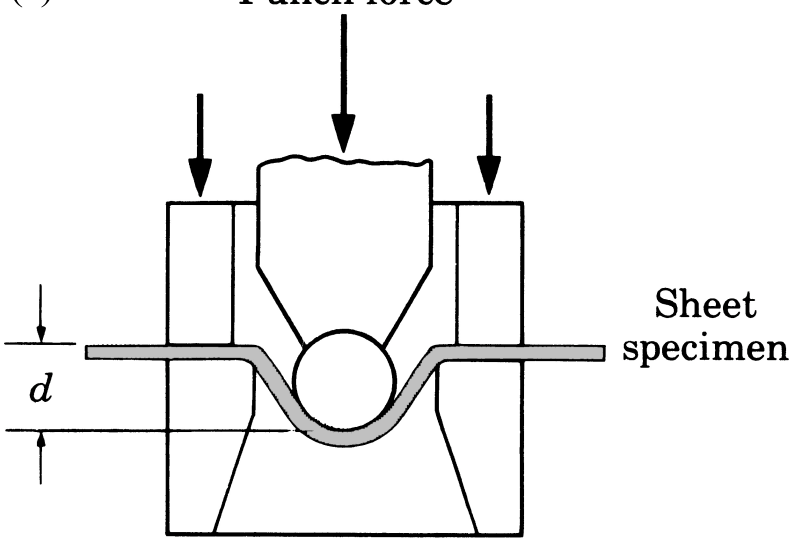
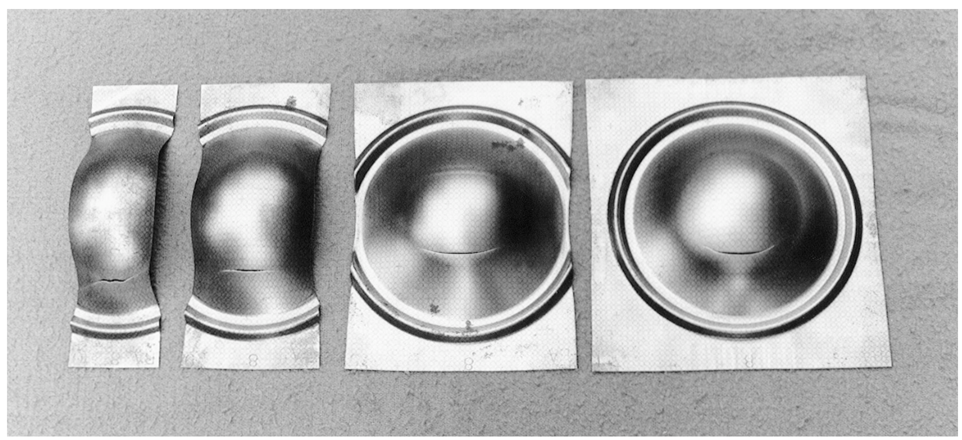
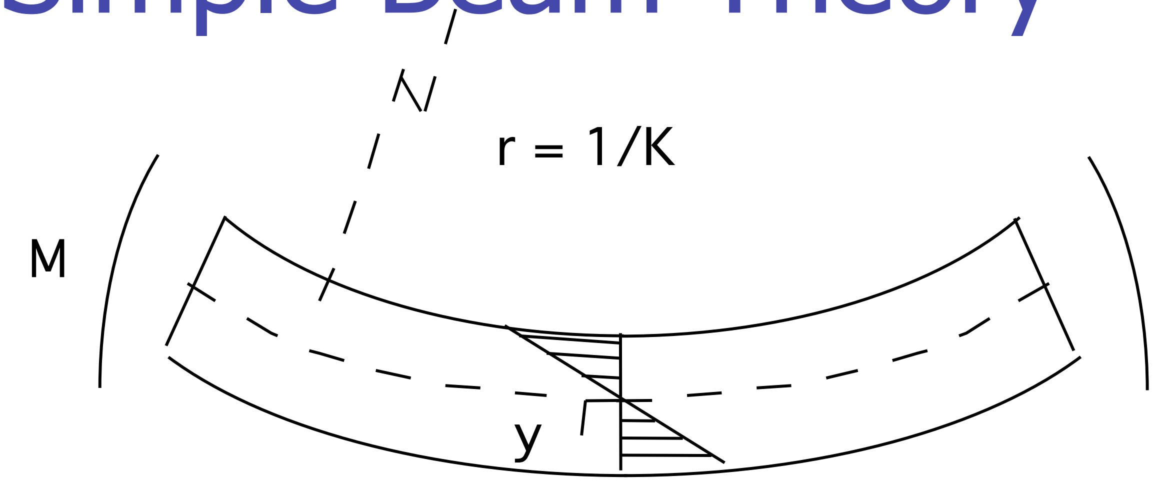


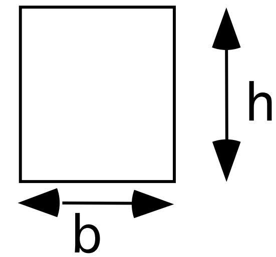
Figure 16.13 (a) A cupping test (the Erichsen test) to determine the formability of sheet metals. (b) Bulge-test results on steel sheets of various widths. The specimen farthest left is subjected to, basically, simple tension. The specimen farthest right is subjected to equal biaxial stretching. *Source*: Inland Steel Company.

(b)



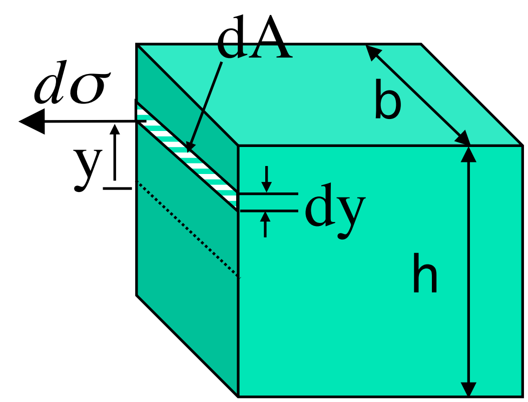
Simple Beam Theory





$\varepsilon(y) = Ky$

ε=K y



$$M = \int_{-h/2}^{h/2} \sigma(y)\, y\, b\, dy$$

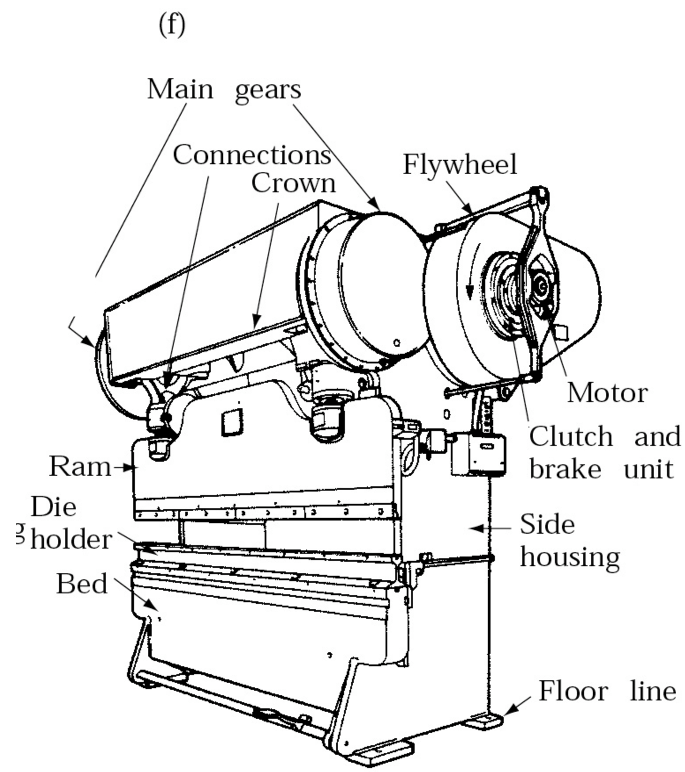
moment arm

dA

$$\sigma(y) = ?$$

Bending in a Press Brake

- Simple Bending
  - Bending Only
  - Large Springback



Springback

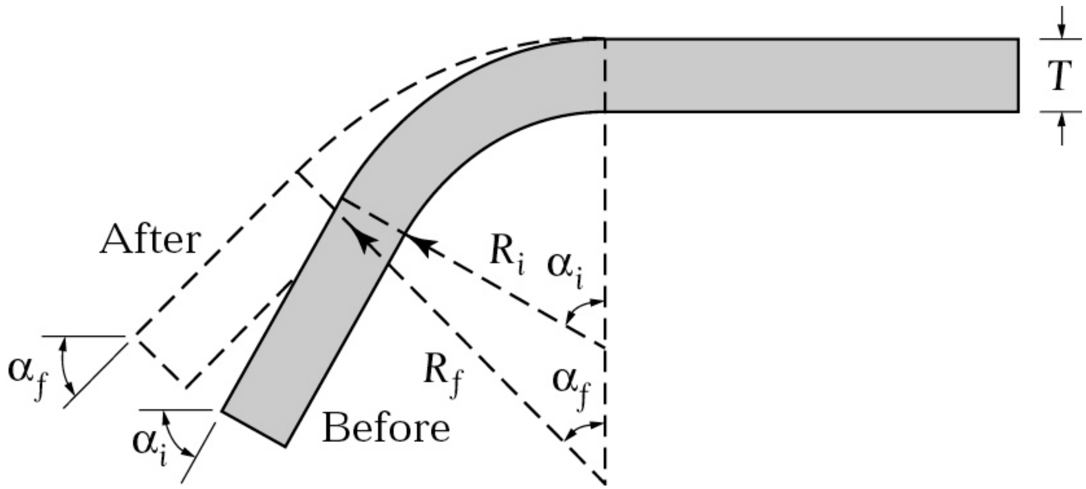


Figure 16.19 Springback in bending. The part tends to recover elastically after ending, and its bend radius becomes larger. Under certain conditions, it is possible for the final bend angle to be smaller than the original angle (negative springback).

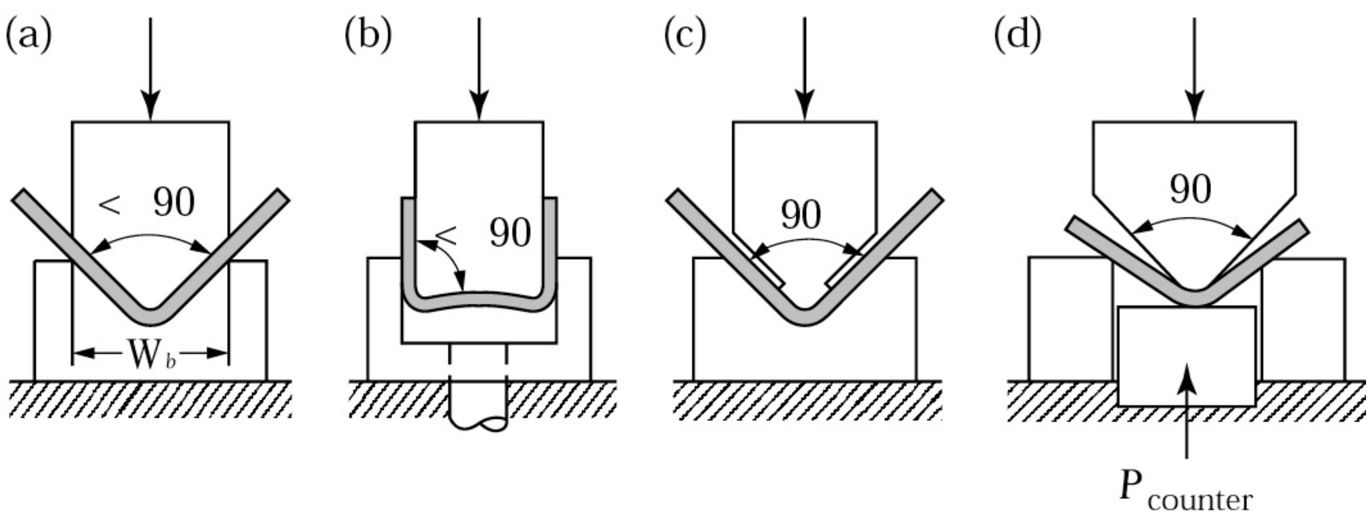
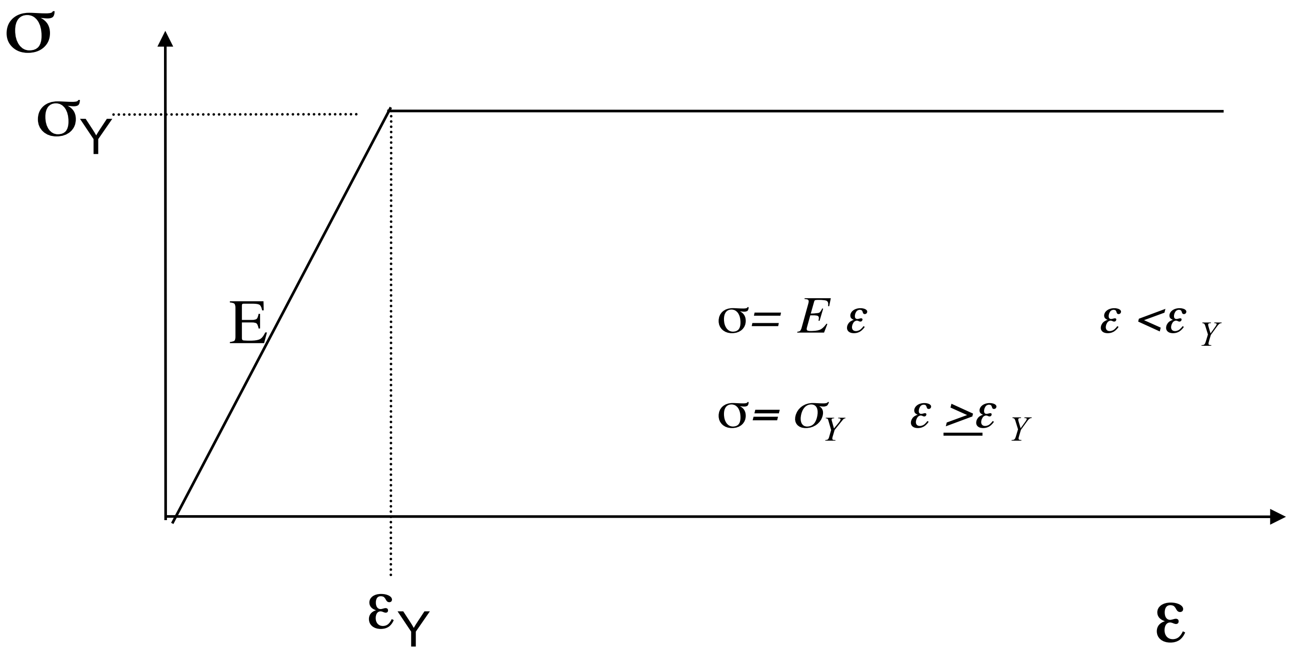


Figure 16.20 Methods of reducing or eliminating springback in bending operations. *Source*: V. Cupka, T. Nakagawa, and H. Tyamoto.

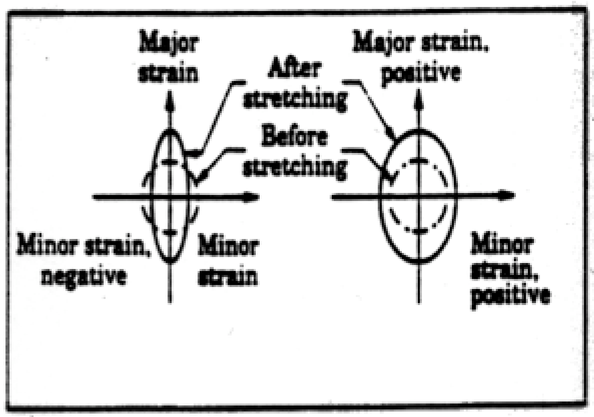
Material Model: Elastic Perfectly Plastic



$$\sigma = E\,\varepsilon \qquad \varepsilon < \varepsilon_Y$$

$$\sigma = \sigma_Y \qquad \varepsilon \geq \varepsilon_Y$$

(a)



(b)

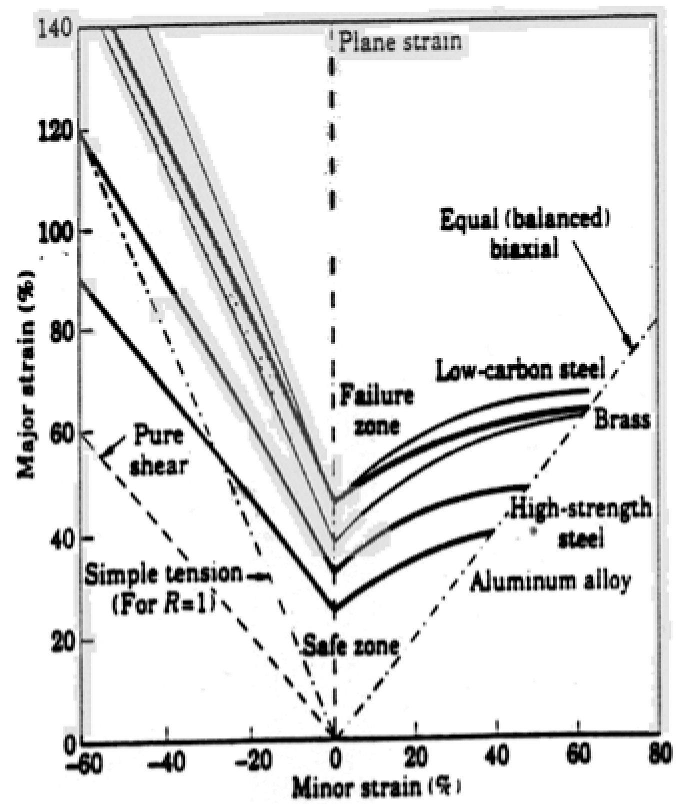


FIGURE 16.15

(a) Strains in deformed circular grid patterns. (b) Forming-limit diagram (FLD) for various sheet metals. Whereas the major strain is always positive (stretching), the minor strain may be either positive or negative. *Source:* S. S. Hecker and A. K. Ghosh.

Moment - Curvature Relationship M(K)

If the die curvature K is such that:

$$K\frac{h}{2} = \varepsilon_{\max} < \varepsilon_Y$$

Then only elastic deformation will take place and:

$$M = \int_{-h/2}^{h/2} \sigma(y)\, y b\, dy = \int_{-h/2}^{h/2} E K y^2 b\, dy$$

$$= KE\frac{bh^3}{12} = KEI$$ = loaded curvature x "bending" stiffness

Moment – Curvature Relationship

Now as K increases, eventually:

$$K\frac{h}{2} > \varepsilon_Y \therefore \text{yielding occurs}$$

But for all $\varepsilon > \varepsilon_Y$, $\sigma = \sigma_Y$

↓

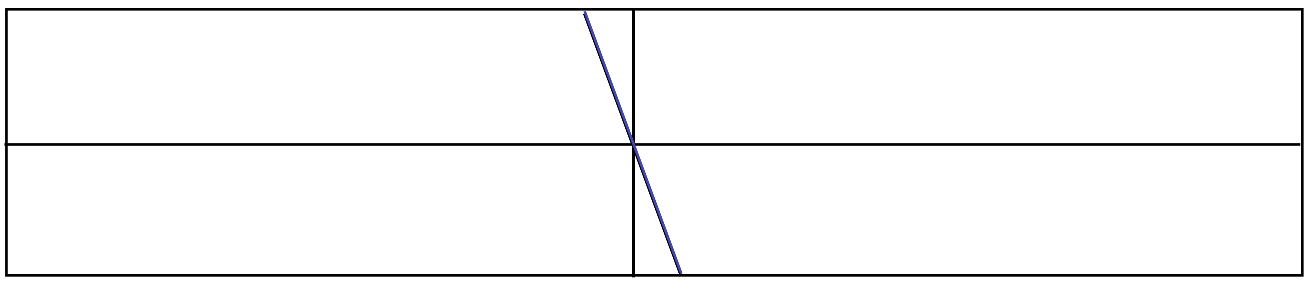
M = $M_{elastic}$ + $M_{Plastic}$

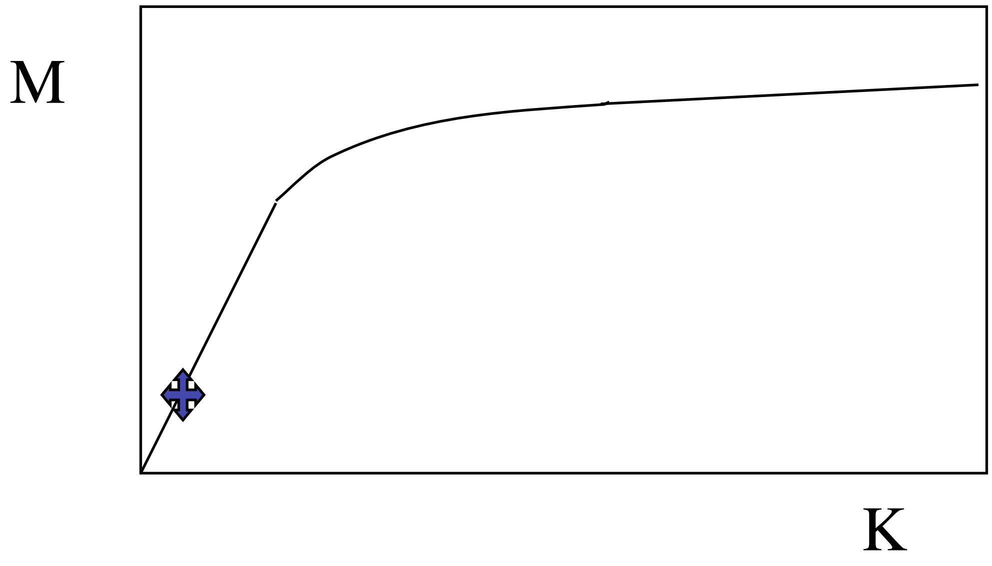
$$M = \frac{3}{2} M_y \left(1 - \tfrac{1}{3} \left(\frac{K_y}{K} \right)^2 \right)$$

$$K_Y = \varepsilon_Y / (h/2)$$

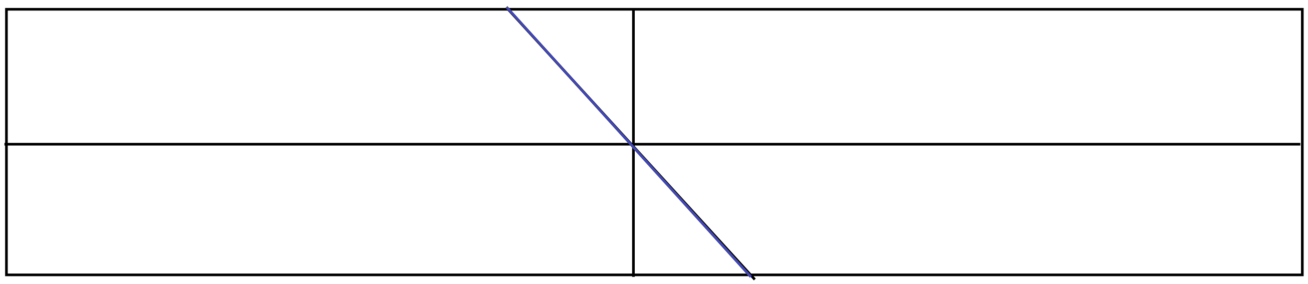
$$M_Y = EI \; K_Y$$

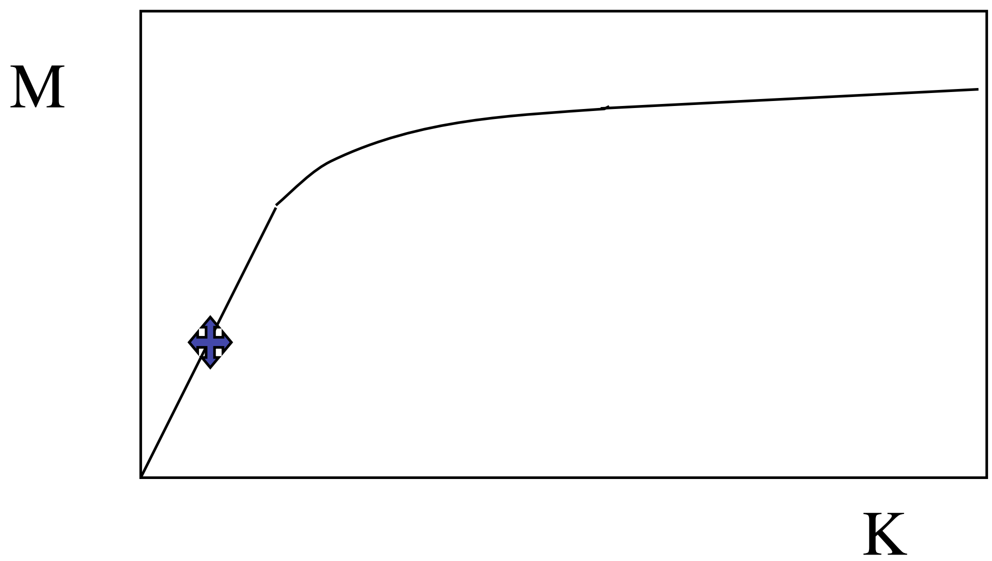
Stress and Strain in Bending



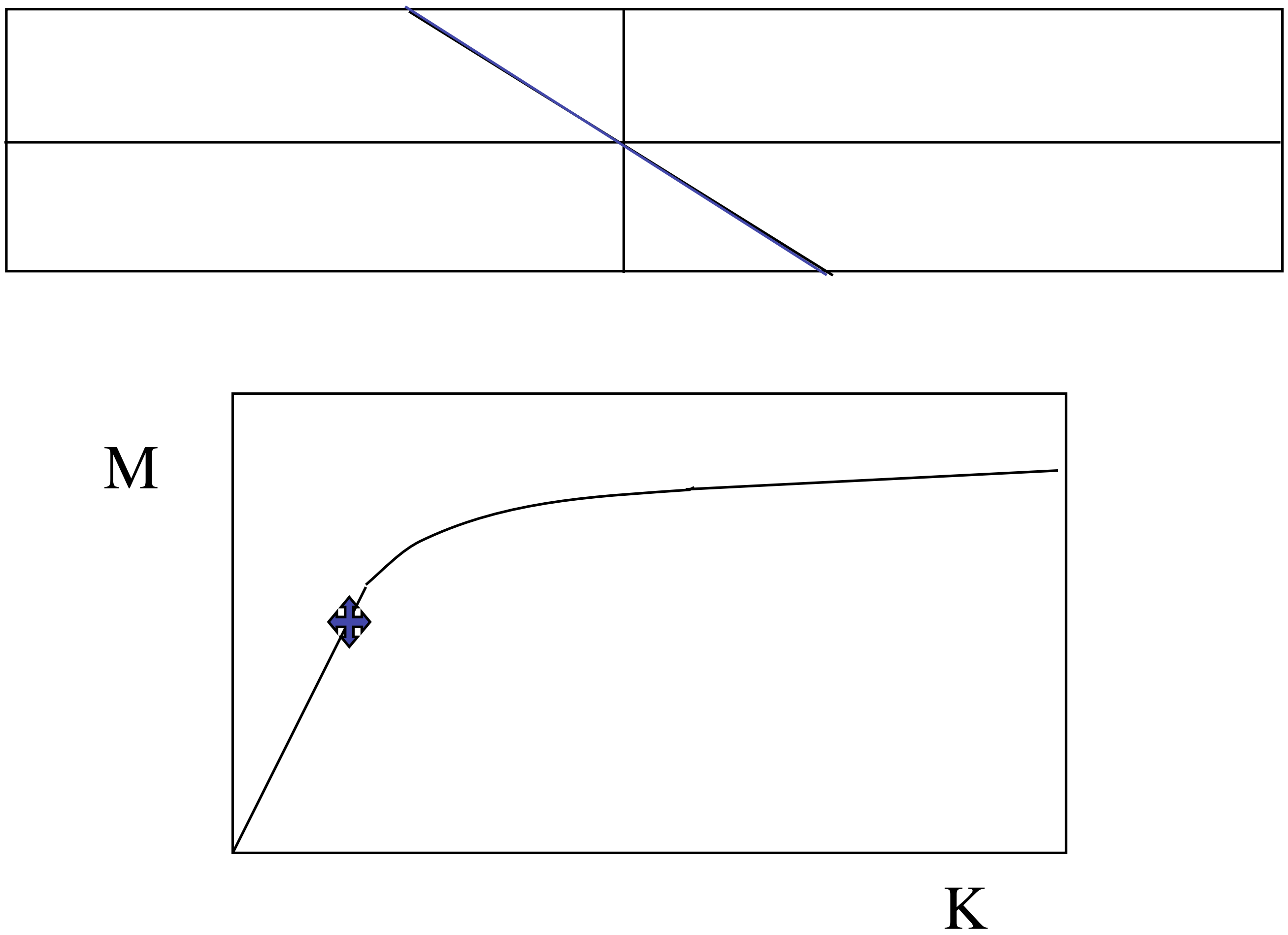


Stress and Strain in Bending

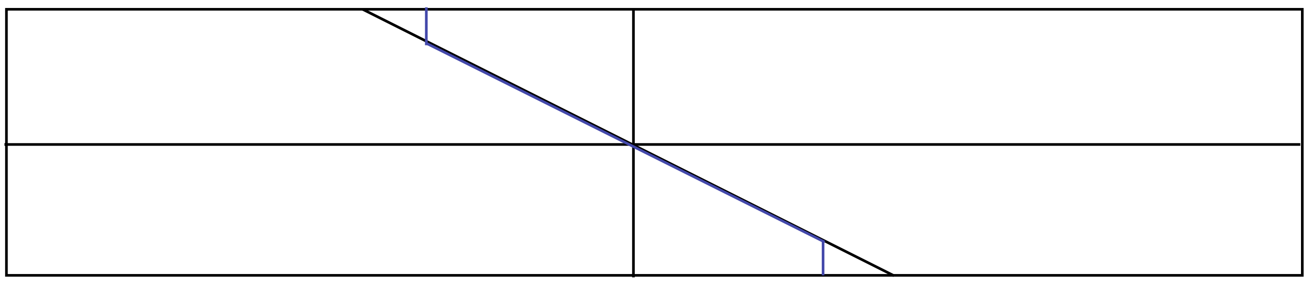


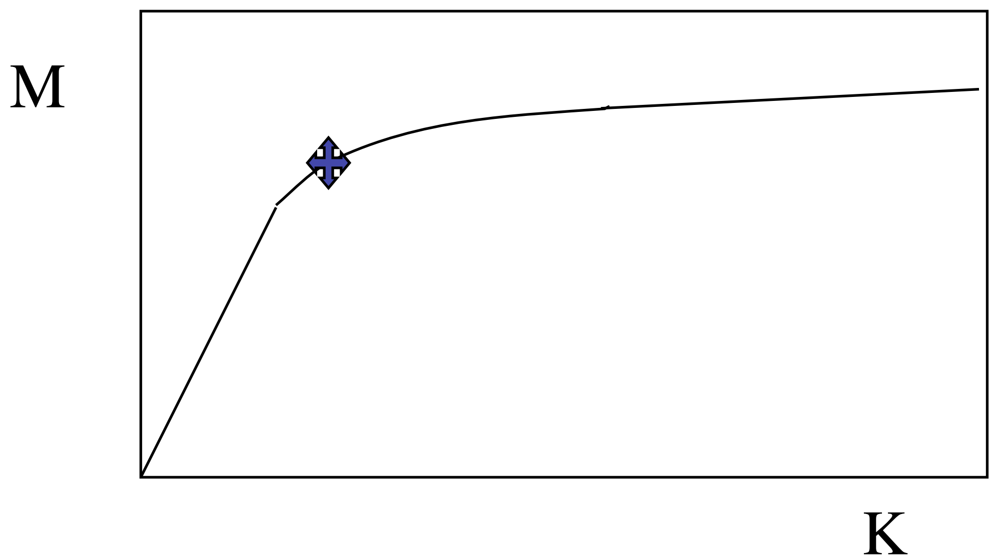


Stress and Strain in Bending

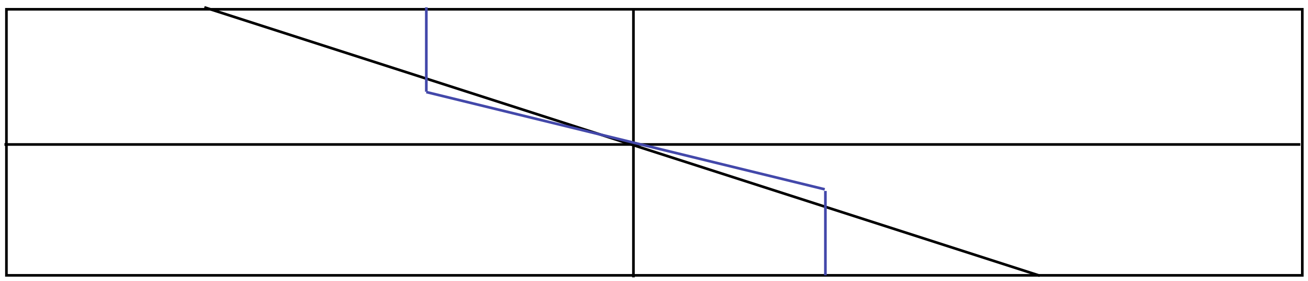


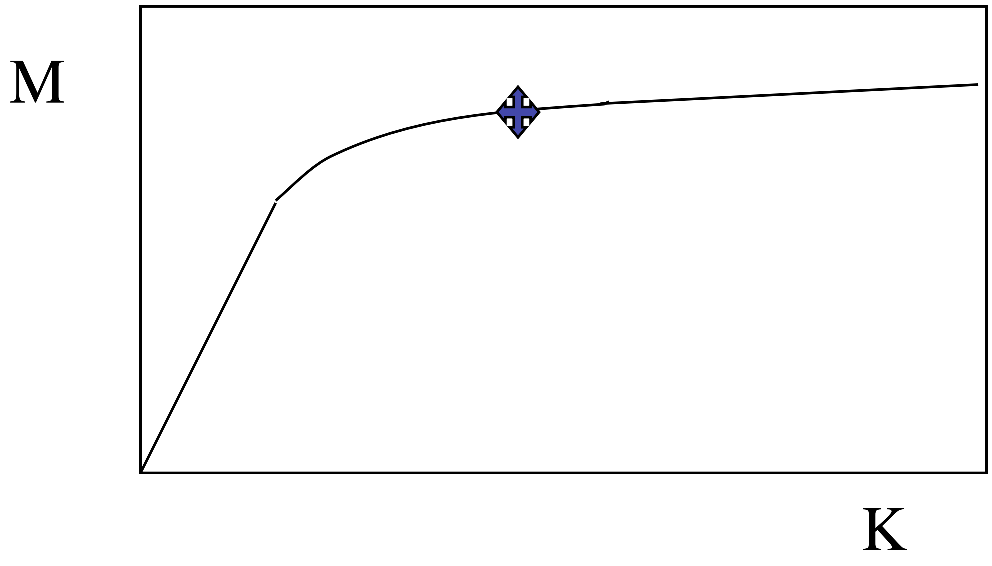
Stress and Strain in Bending



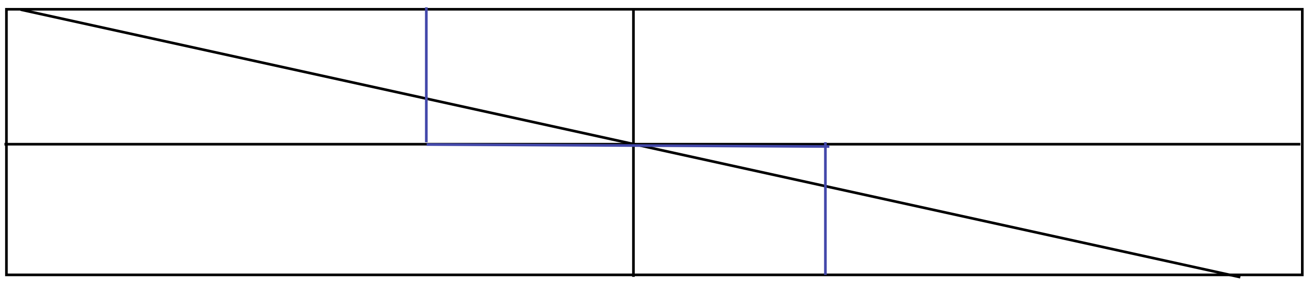


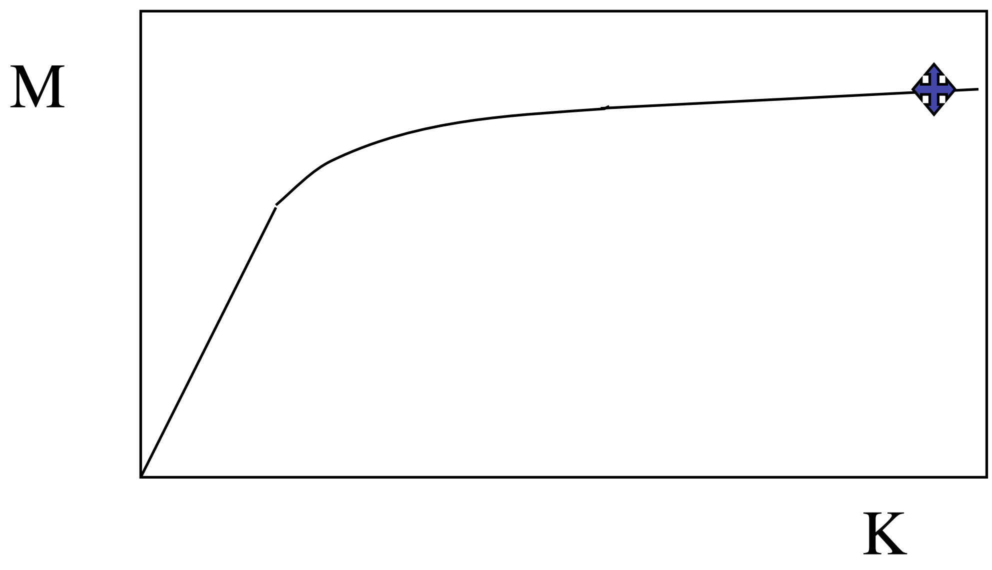
Stress and Strain in Bending



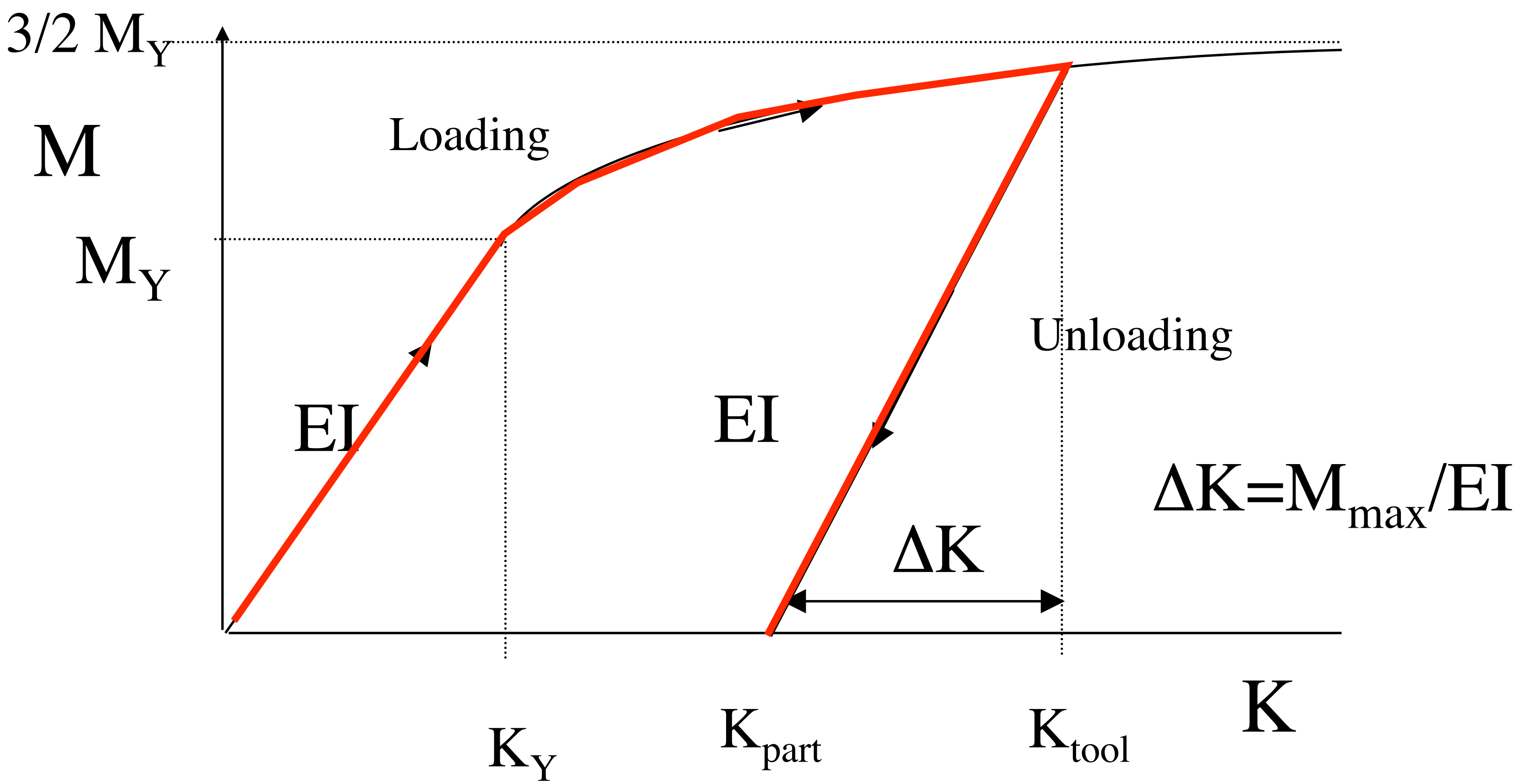


Stress and Strain in Bending





The M-K Curve



3/2 M_Y
M
M_Y
Loading
Unloading
EI
EI
ΔK
ΔK=M_max/EI
K_Y
K_part
K_tool
K

Final Shape: Springback

$$\Delta K = \frac{M_{\max}}{EI} \therefore K_{part} = K_{tool} - \Delta K$$

K = shape of tool

E= material property

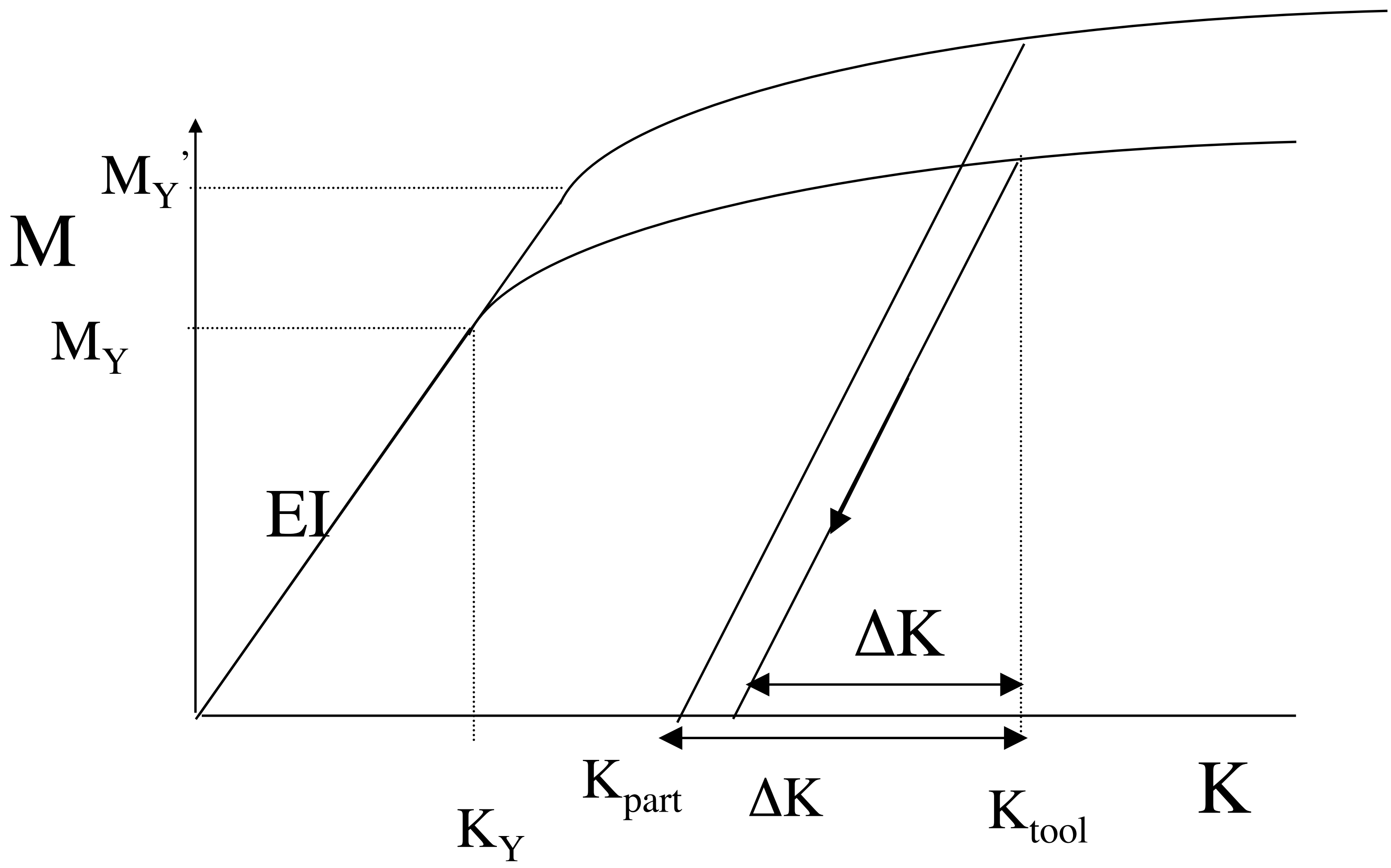
$$I = \frac{1}{12} bh^3$$ *cubic* dependence on thickness

$$M_{\max} = ?$$

$$M_{\max} = \Phi\,(K_Y, EI)$$

Strong Dependence on yield properties

Effect of Material Variations: Increase in Yield Stress



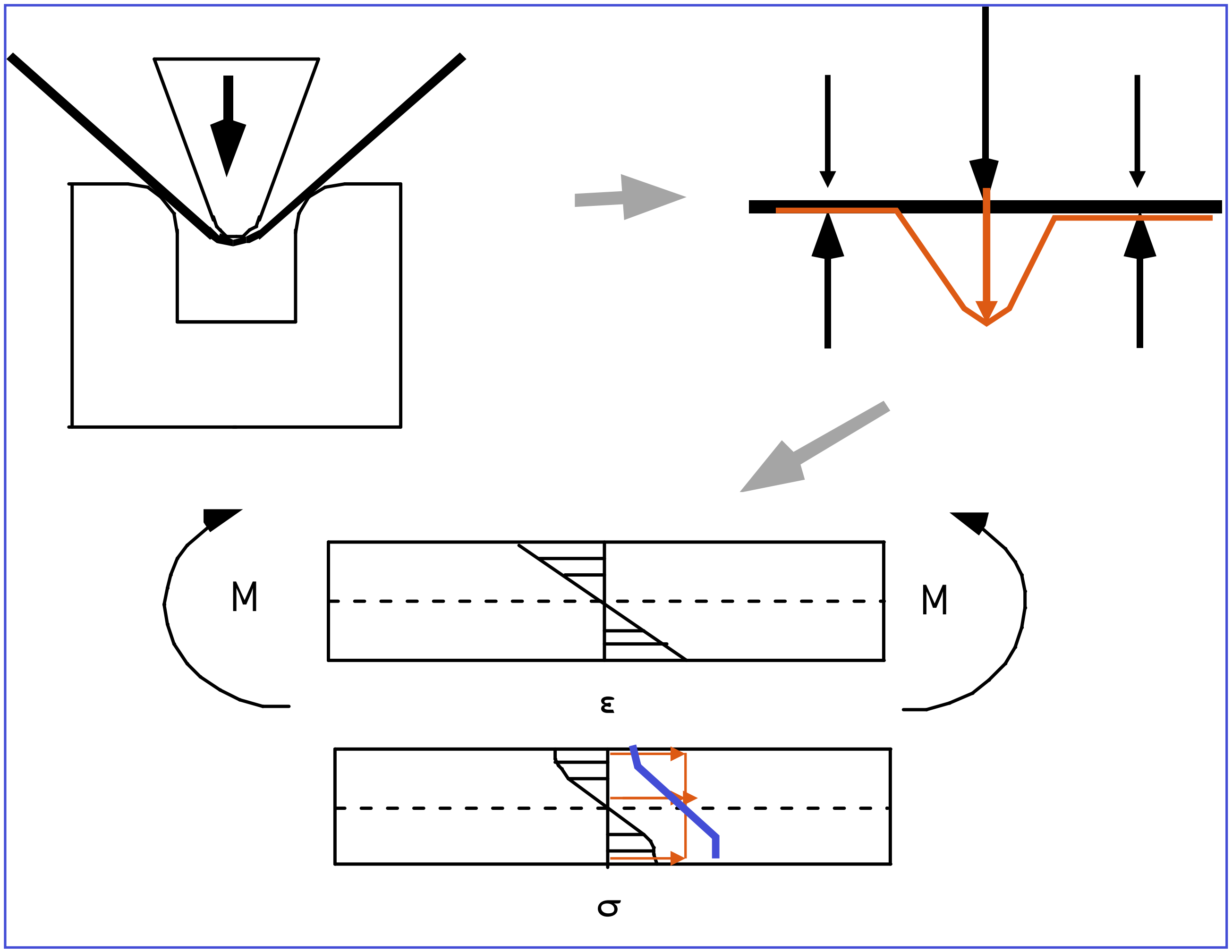
Other Possible Variations

- Yield Stress (+ 10% reported)
  - Chemistry, working history
- Thickness
  - Rolling mill quality
  - Design vs. manufacturing specs
- Tooling Errors

Issues of Simple Bending

- High Degree of Springback
  - Strong Material Dependence
    - Yield Strength
    - Strain Hardening
    - Thickness
- Stretch Bending?

Brake Bending of Sheet



Processes and Mechanics

- Deep Drawing (3D Bend + Stretch)
  - Extreme Deformation
  - Large Compressive Strains
    - Buckling Failure possible
  - Large Forces
  - Critical “Flow” Control

Steps in Manufacturing an Aluminum Can

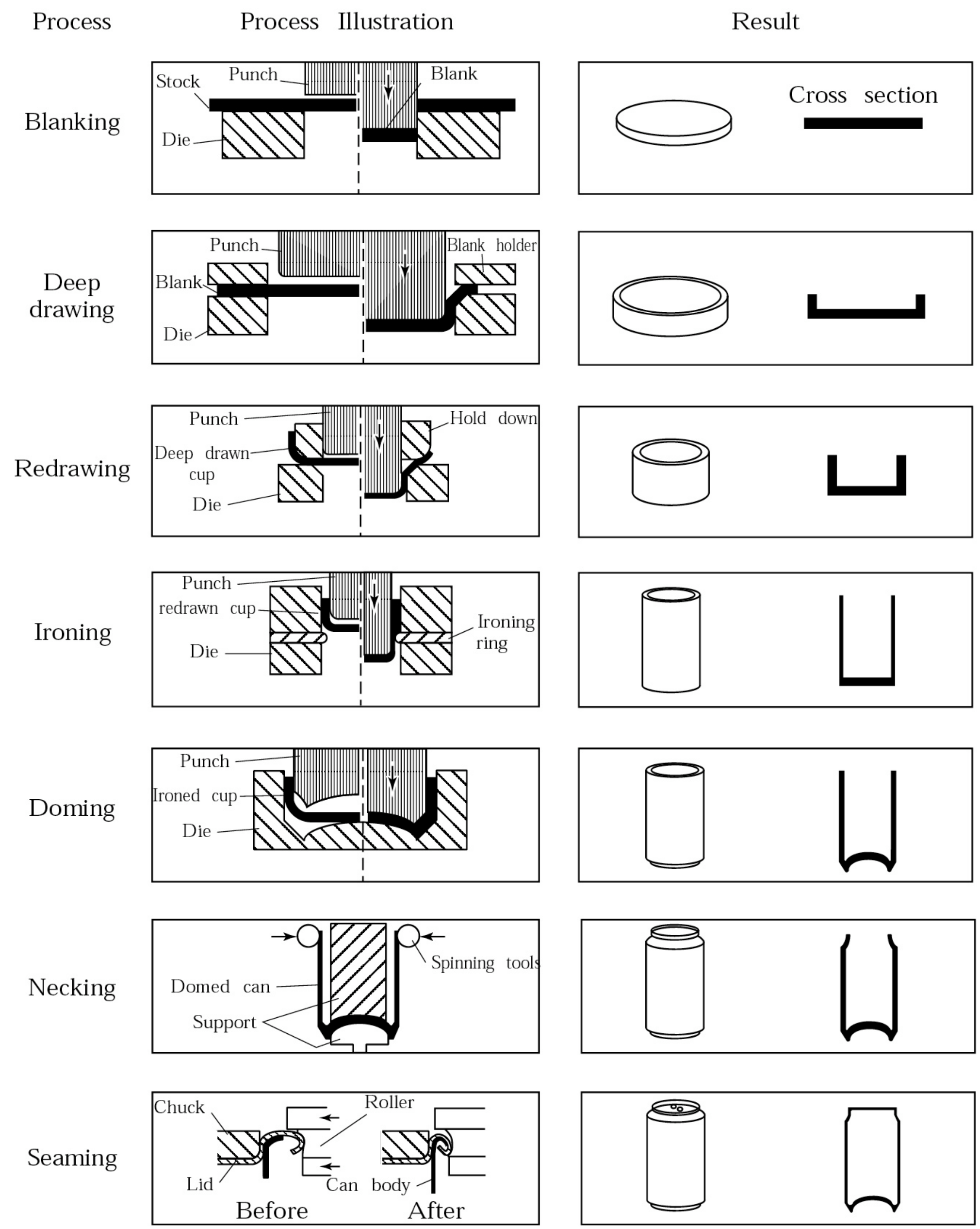


Figure 16.31 The metal-forming processes involved in manufacturing a two-piece aluminum beverage can

Deep Drawing

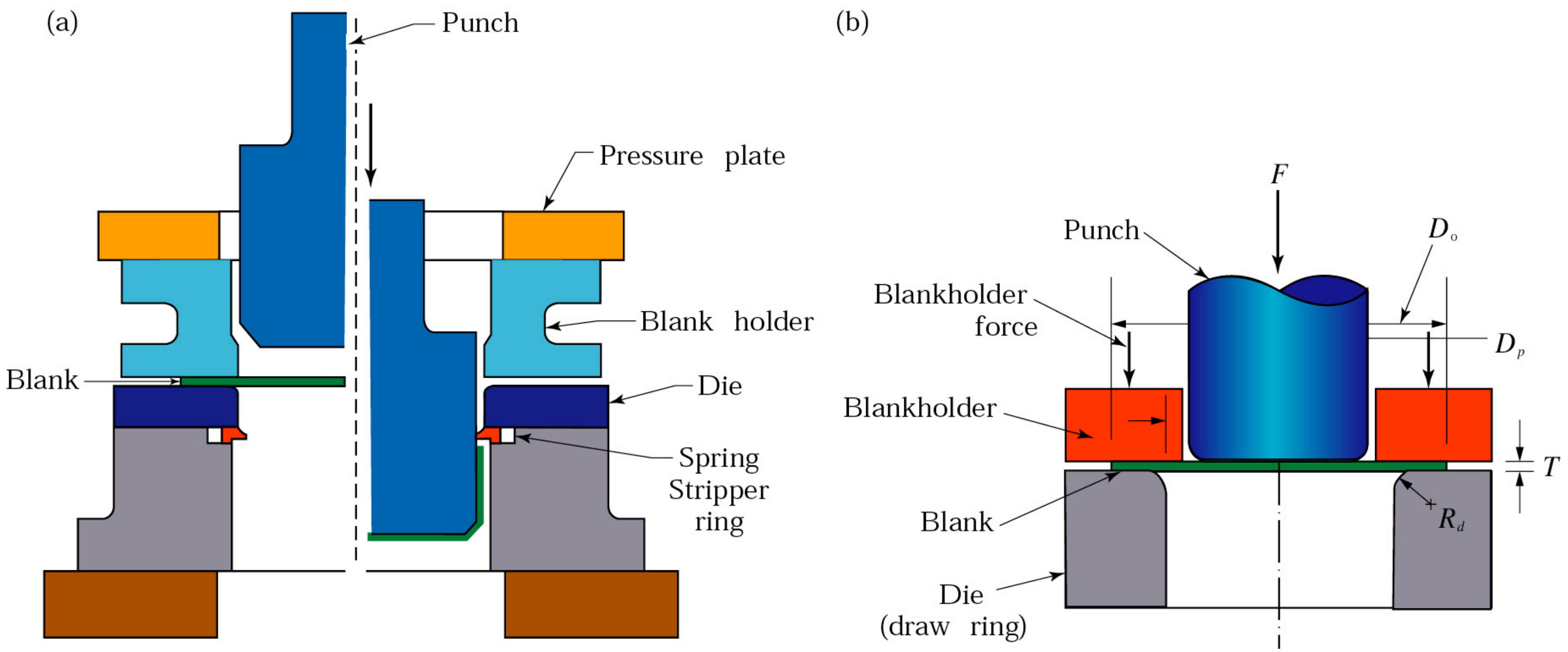


Figure 16.32 (a) Schematic illustration of the deep-drawing process on a circular sheet-metal blank. The stripper ring facilitates the removal of the formed cup from the punch. (b) Process variables in deep drawing. Except for the punch force, *F*, all the parameters indicated in the figure are independent variables.

Explosive Forming

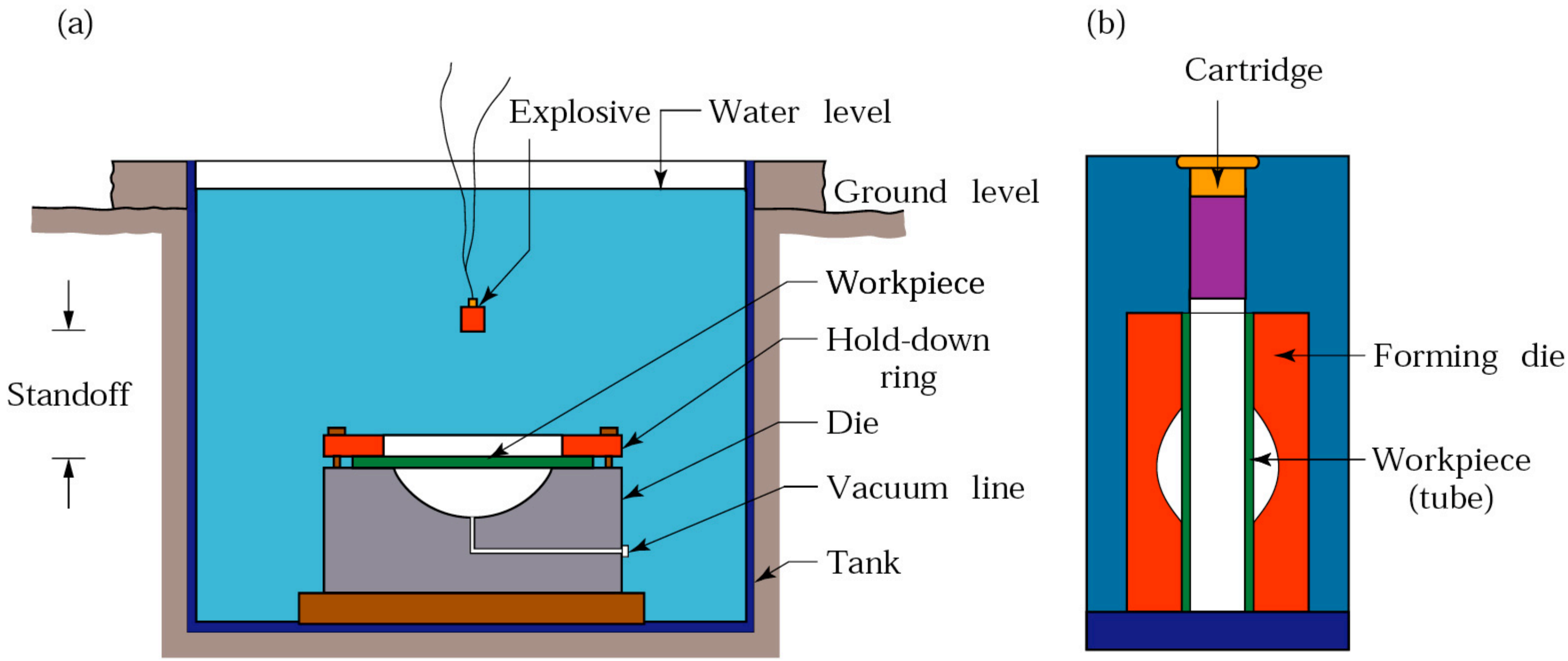


Figure 16.44 (a) Schematic illustration of the explosive forming process. (b) Illustration of the confined method of explosive bulging of tubes.

Advantages and disadvantages

- Advantages
  - Parallel process: rapid bulk formation
  - Overall material properties improved

- Disadvantages
  - Cost of equipment and dies
  - Limited flexibility in shapes and sizes (i.e. compared to machining)
  - Accuracy
  - Repeatability

Process Comparisons

	Sheet Forming	Machining
Rate	High	Low
Quality	Moderate	High
Cost	Low	Moderate-High
Flexibility	Low	High