PRODUCTION TECHNIQUES

SHEET-METAL FORMING PROCESSES

DEPARTMENT OF MECHANICAL ENGINEERING
ISFAHAN UNIVERSITY OF TECHNOLOGY
Dep. of Mech. Eng.

Sheet-metal forming

- ✓ Includes cutting and forming operations performed on relatively thin sheet of metal
- ✓ Typical sheet metal thicknesses: 0.4 mm to 6.0 mm
- ✓ Generally are performed on *presses* using a set of dies (**pressworking** or **pressforming**)
- ✓ Characteristics: high strength, good dimensional accuracy, good surface finish, and relatively low cost
- ✓ Mostly is performed at room temperature but sometimes as warm working
- ✓ Typical applications: wide range of consumer and industrial products, such as car bodies, airplanes, appliances, office furniture, beverage cans and so on

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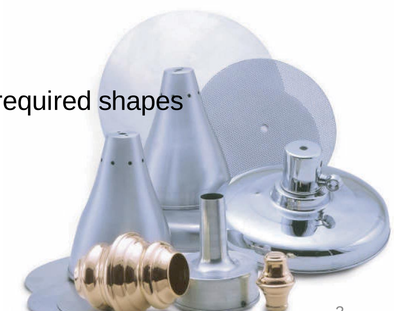
Sheet-metal forming

The three major categories:

- ✓ Cutting/Shearing
  - ✓ To separate large sheets into smaller pieces
  - ✓ To cut out a part perimeter
  - ✓ To make holes in a part
  - ✓ Accomplished by a shearing action between two sharp cutting edges
- ✓ Bending
- ✓ Drawing
  - ✓ To form sheet metal parts into their required shapes

Courtesy of Aphase II, Inc.



Courtesy of Hialeah Metal Spinning, Inc.

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Characteristics of Sheet-Metal Forming Processes

TABLE 16.1

General Characteristics of Sheet-Metal Forming Processes (In alphabetic order)

Forming process	Characteristics
Drawing	Shallow or deep parts with relatively simple shapes, high production rates, high tooling and equipment costs
Explosive	Large sheets with relatively simple shapes, low tooling costs but high labor cost, low-quantity production, long cycle times
Magnetic-pulse	Shallow forming, bulging, and embossing operations on relatively low-strength sheets, requires special tooling
Peen	Shallow contours on large sheets, flexibility of operation, generally high equipment costs, process also used for straightening formed parts
Roll	Long parts with constant simple or complex cross-sections, good surface finish, high production rates, high tooling costs
Rubber	Drawing and embossing of simple or relatively complex shapes, sheet surface protected by rubber membranes, flexibility of operation, low tooling costs
Spinning	Small or large axisymmetric parts, good surface finish, low tooling costs but labor costs can be high unless operations are automated
Stamping	Includes a wide variety of operations, such as punching, blanking, embossing, bending, flanging, and coining; simple or complex shapes formed at high production rates; tooling and equipment costs can be high, but labor cost is low
Stretch	Large parts with shallow contours, low-quantity production, high labor costs, tooling and equipment costs increase with part size
Superplastic	Complex shapes, fine detail and close dimensional tolerances, long forming times (hence production rates are low), parts not suitable for high-temperature use

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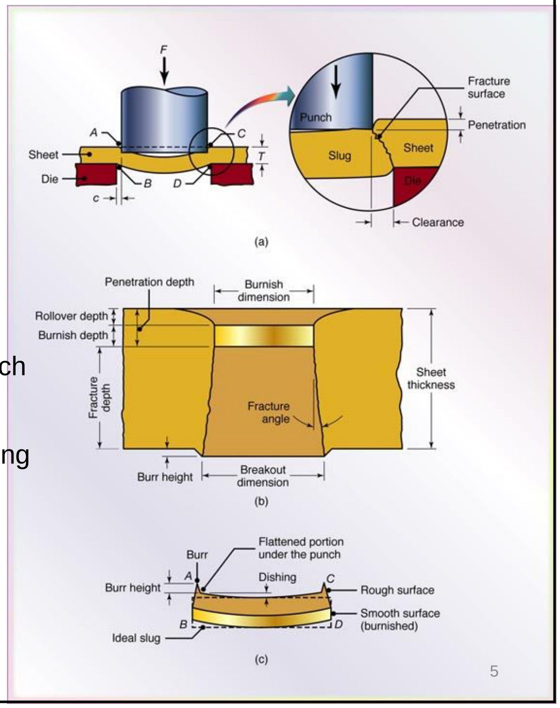
Shearing with a Punch and Die

Major Processing parameters in shearing:

- The shape of the punch and die
- The speed of punching
- Lubrication
- The clearance between the punch and the die



(a) Schematic illustration of shearing with a punch and die, indicating some of the process variables. Characteristic features of (b) a punched hole and (c) the slug.

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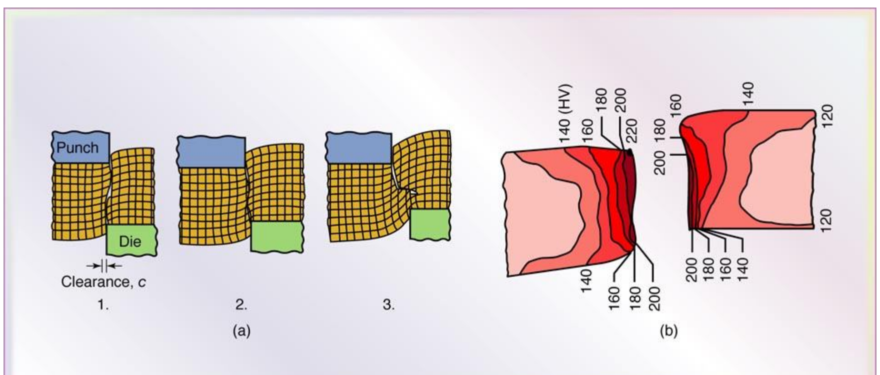
Shearing



(a) Effect of the clearance, *c*, between punch and die on the deformation zone in shearing. As the clearance increases, the material tends to be pulled into the die rather than be 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.

Dep. of Mech. Eng. *Source:* After H.P Weaver and K.J. Weinmann. 6

Clearance

- Clearance depends on:
  - ✓ The type of material and its temper
  - ✓ The thickness and size of the blank
  - ✓ Its proximity to the edges of other sheared edges or the edges of the original blank
- Clearances generally range between 2 and 8% of the sheet thickness, but they may be as small as 1% (as fine blanking) or as large as 30%.
- As a general guideline:
  a. Clearances for soft materials are less than those for harder grades
  b. The thicker the sheet, the larger the clearance must be
  c. As the ratio of hole diameter to sheet thickness decreases, clearances should be larger

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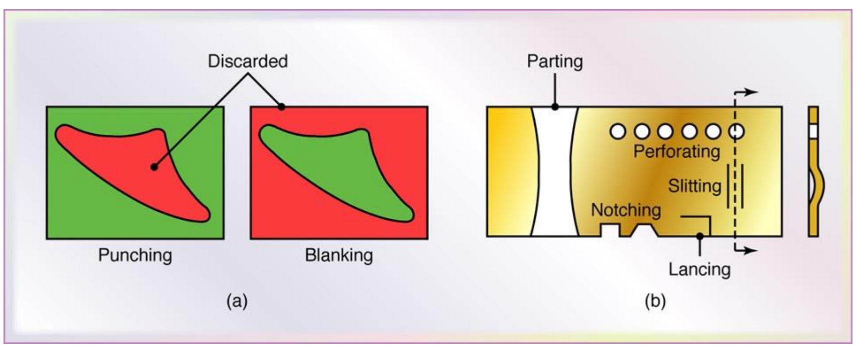
Die-Cutting Operations



(a) Punching (piercing) and blanking.

(b) Examples of various die-cutting operations on sheet metal.

Perforating: Punching a number of holes in a sheet

Parting: shearing the sheet into two or more pieces

Notching: removing pieces from the edges

Lancing: leaving a tab without removing any material

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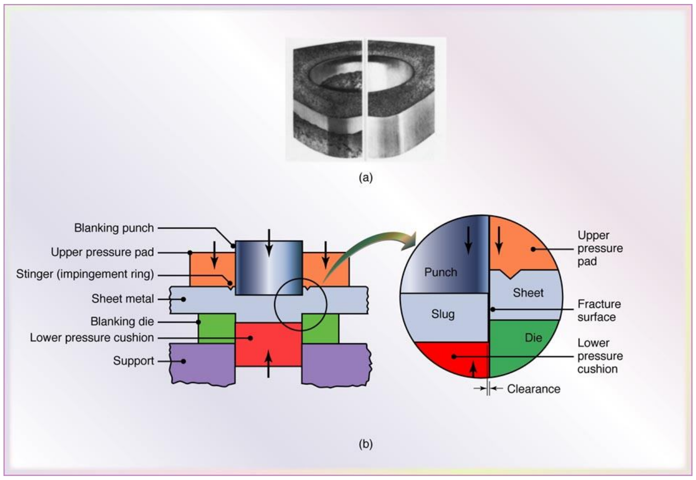
Conventional Versus Fine-Blanking



(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:* Courtesy of Feintool U.S. Operations.

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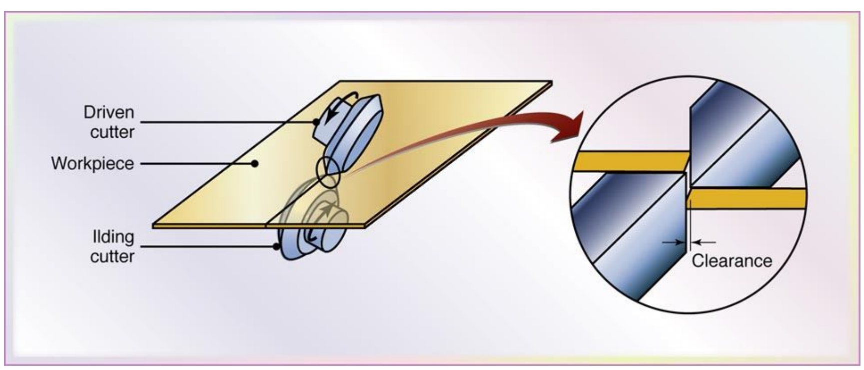
Slitting with rotary knives



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

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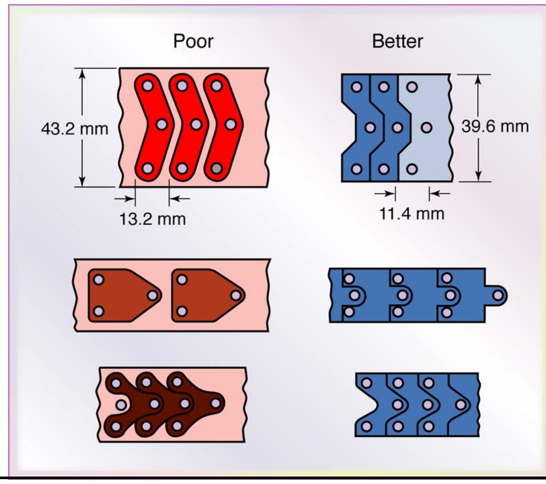
Scrap in shearing

- ✓ Significant amount of scrap (trim loss)
- ✓ As high as 30% on large stampings
- ✓ Significant factor in manufacturing cost



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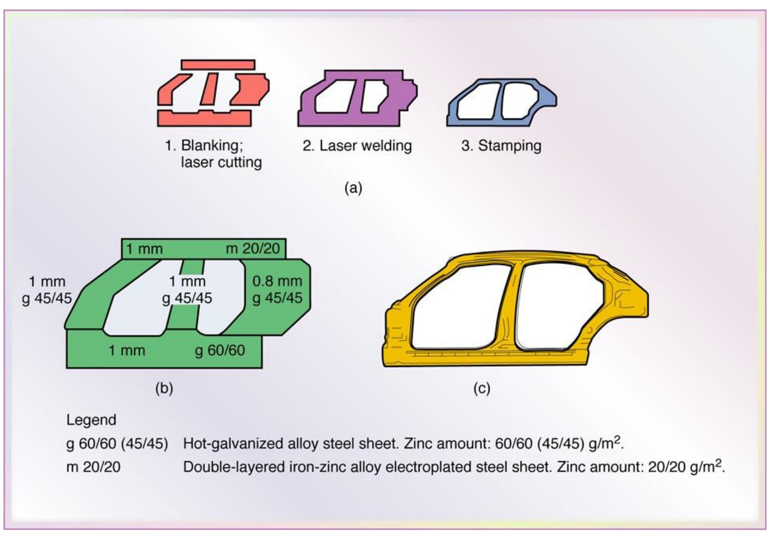
Tailor-Welded Blanks



Production of an outer side panel of a car body by laser butt-welding and stamping. *Source:* After M. Geiger and T. Nakagawa.

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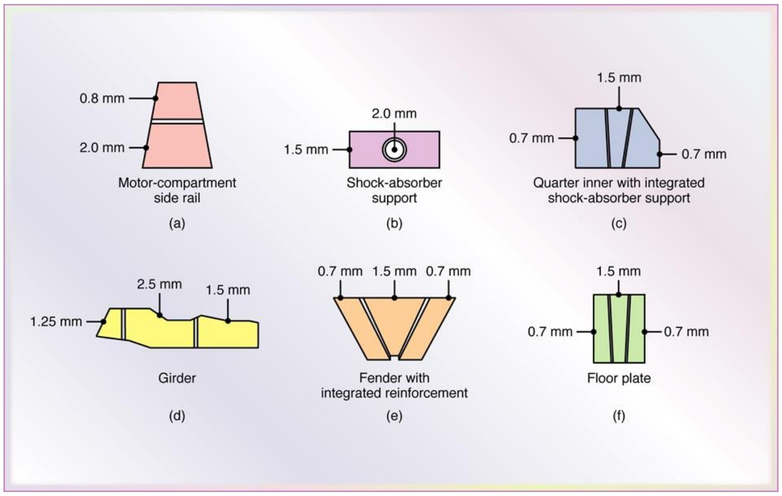
Examples of automotive components produced from tailor-welded blanks



Examples of laser butt-welded and stamped automotive-body components. *Source:* After M. Geiger and T. Nakagawa.

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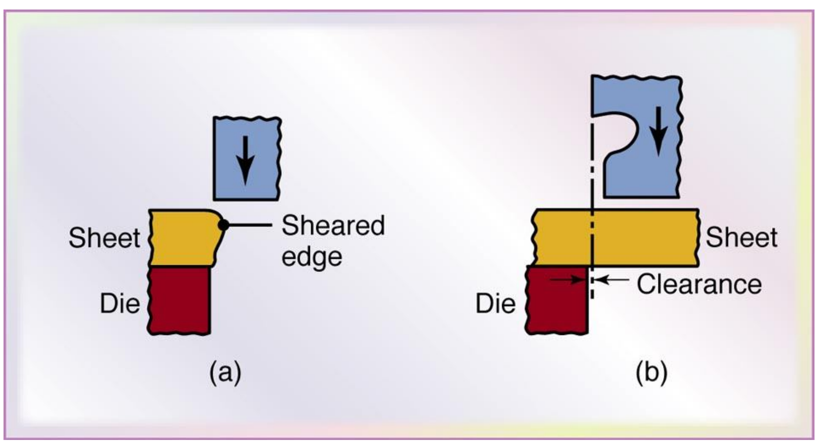
The Shaving Process



Schematic illustrations of the shaving process.

(a) Shaving a sheared edge.

(b) Shearing and shaving combined in one stroke.

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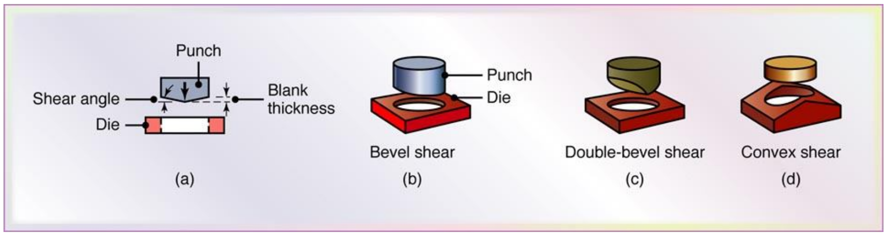
Shear Angles



Examples of the use of shear angles on punches and dies.

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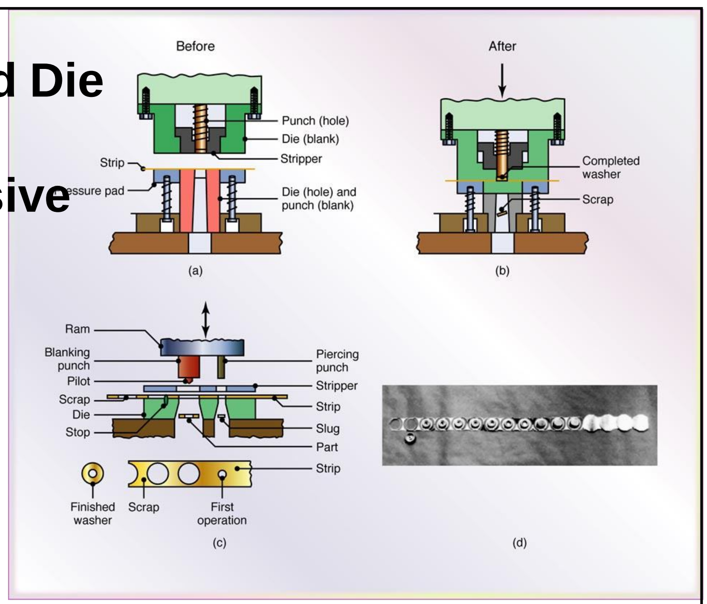
Compound Die and Progressive Die



(a) before and (b) after blanking a common washer in a compound die.

(c) Schematic illustration of making a washer in a progressive die. (d) Forming of the top piece of an aerosol spray can in a progressive die.

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Characteristics of Metals Used in Sheet-Forming

TABLE 16.2

Characteristics of Metals Important in Sheet-Forming Operations

Characteristic	Importance
Elongation	Determines the capability of the sheet metal to stretch without necking and failure; high strain-hardening exponent (n) and strain-rate sensitivity exponent (m) are desirable
Yield-point elongation	Typically observed with mild-steel sheets (also called Lüder's bands or stretcher strains), flamelike depressions on the sheet surface, can be eliminated by temper rolling but sheet must be formed within a certain time after rolling
Anisotropy (planar)	Exhibits different behavior in different planar directions, present in cold-rolled sheets because of preferred orientation or mechanical fibering, causes earing in deep drawing, can be reduced or eliminated by annealing but at lowered strength
Anisotropy (normal)	Determines thinning behavior of sheet metals during stretching, important in deep drawing
Grain size	Determines surface roughness on stretched sheet metal, the coarser the grain—the rougher the appearance (orange peel), also affects material strength.
Residual stresses	Typically caused by nonuniform deformation during forming, results in part distortion when sectioned, can lead to stress-corrosion cracking, reduced or eliminated by stress relieving.
Springback	Due to elastic recovery of the plastically deformed sheet after unloading, causes distortion of part and loss of dimensional accuracy, can be controlled by techniques such as overbending and bottoming of the punch
Wrinkling	Caused by compressive stresses in the plane of the sheet, can be objectionable, depending on its extent, can be useful in imparting stiffness to parts by increasing their section modulus, can be controlled by proper tool and die design
Quality of sheared edges	Depends on process used; edges can be rough, not square, and contain cracks, residual stresses, and a work-hardened layer, which are all detrimental to the formability of the sheet; edge quality can be improved by fine blanking, reducing the clearance, shaving, and improvements in tool and die design and lubrication
Surface condition of sheet	Depends on sheet rolling practice; important in sheet forming as it can cause tearing and poor surface quality

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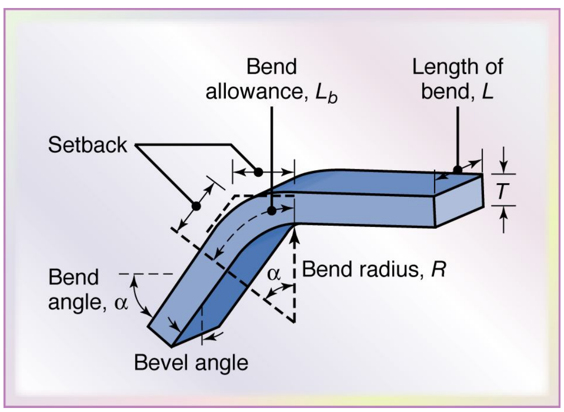
Bending Terminology



Bending terminology. Note that the bend radius is measured to the inner surface of the bent part.

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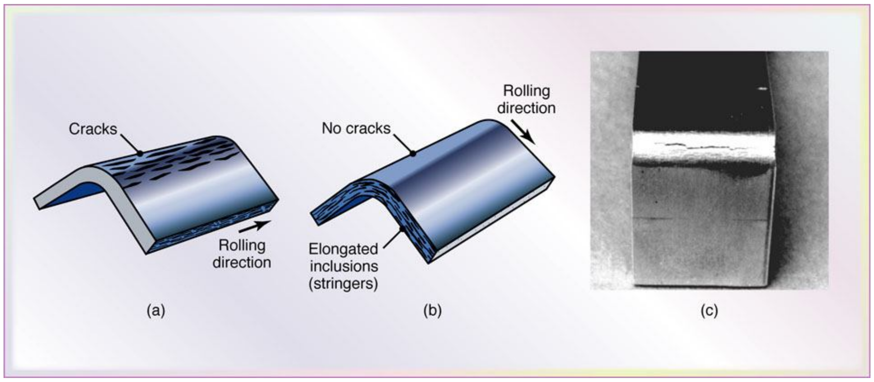
Effect of Elongated Inclusions



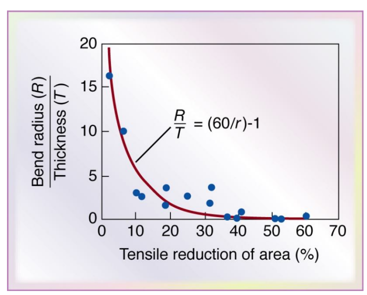
(a) and (b) The effect of elongated inclusions (stringers) on cracking as a function of the direction of bending with respect to the original rolling direction of the sheet. (c) Cracks on the outer surface of an aluminum strip bent to an angle of 90 degrees. Note also the narrowing of the top surface in the bend area (due to Poisson effect).

Minimum bend radius

TABLE 16.3

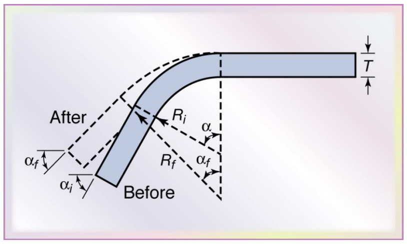
Minimum Bend Radius for Various Materials at Room Temperature

	Condition	
Material	Soft	Hard
Aluminum alloys	0	6*T*
Beryllium copper	0	4*T*
Brass (low-leaded)	0	2*T*
Magnesium	5*T*	13*T*
Steels		
Austenitic stainless	0.5*T*	6*T*
Low-carbon, low-alloy, and HSLA	0.5*T*	4*T*
Titanium	0.7*T*	3*T*
Titanium alloys	2.6*T*	4*T*



Relationship between *R/T* ratio and tensile reduction of area for sheet metals. Note that sheet metal with 50% tensile reduction of area can be bent over itself in a process like the folding of a piece of paper without cracking. *Source*: After J. Datsko and C. T. Yang.

Springback in Bending



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

Springback in bending. The part tends to recover elastically after bending, 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).

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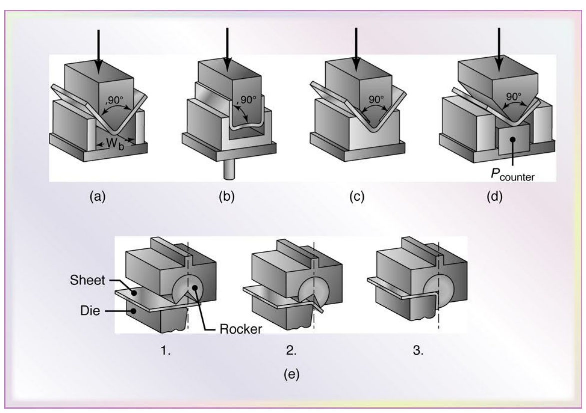
Methods of Reducing or Eliminating Springback



Methods of reducing or eliminating springback in bending operations.

Source: After V. Cupka, T. Nakagawa, and H. Tyamoto.

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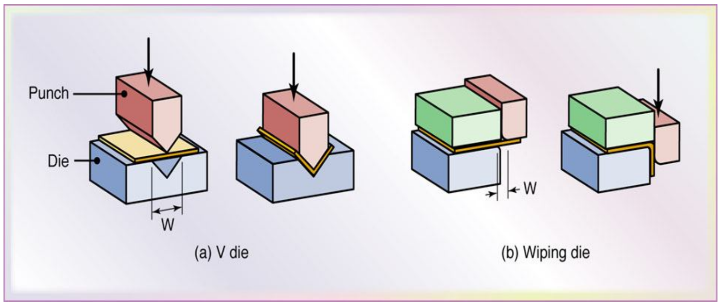
Common Die-Bending Operations



Common die-bending operations showing the die-opening dimension, *W,* used in calculating bending forces.

Bending Force:

$$P = \frac{kYLT^2}{W}$$

where

$k = 0.3$ for wiping die,

$k = 0.7$ for a U-die,

$k = 1.3$ for a V-die

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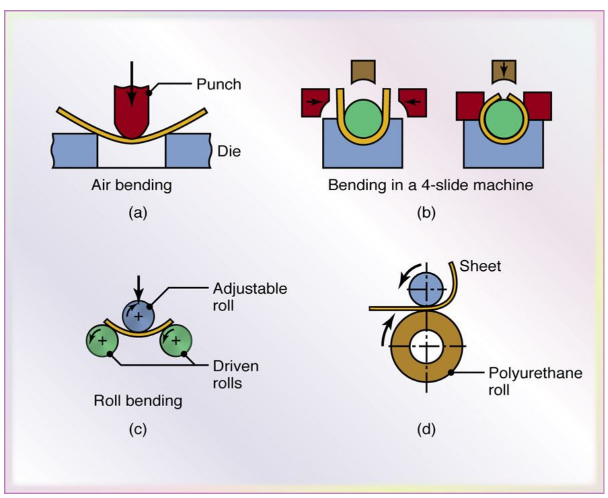
Bending Operations



Examples of various bending operations.

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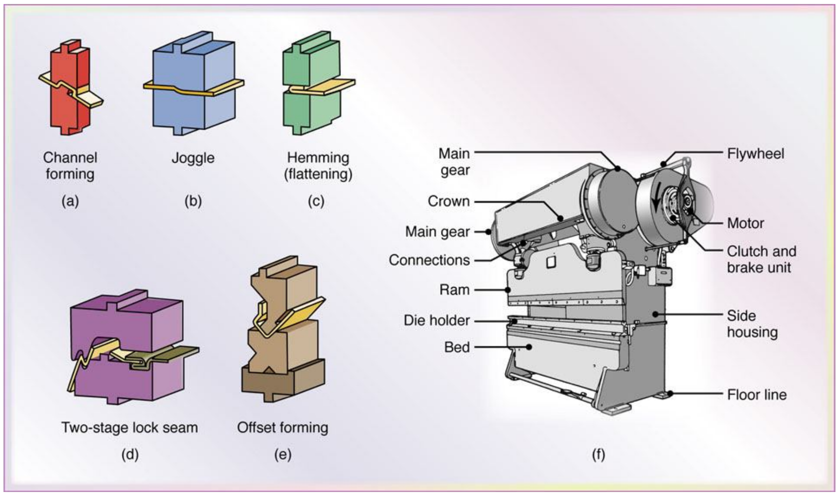
Press Brake



(a) through (e) Schematic illustrations of various bending operations in a press brake. (f) Schematic illustration of a press brake.

Source: Courtesy of Verson Allsteel Company.

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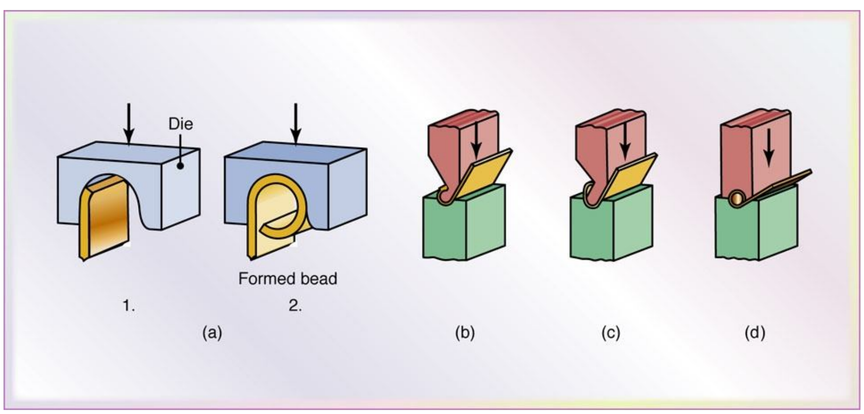
Bead Forming



(a) Bead forming with a single die.

(b) and (c) Bead forming with two dies in a press brake.

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Flanging operations

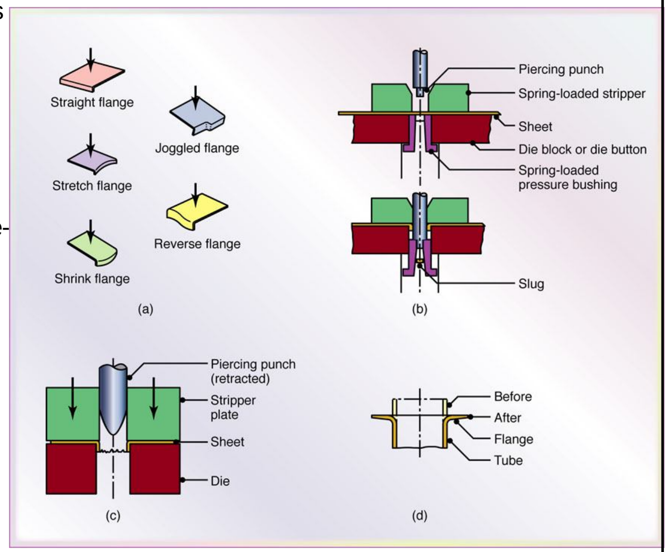
Various flanging operations

(a) Flanges on a flat sheet

(b) Dimpling

(c) The piercing of sheet metal to form a flange. In this operation, a hole does not have to be pre-punched before the punch descends.

(d) The flanging of a tube. Note the thinning of the edges of the flange.



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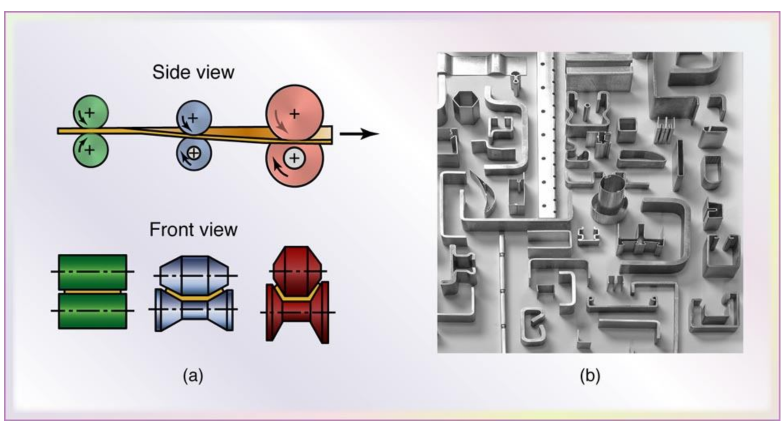
Roll-Forming Process



(a) Schematic illustration of the roll-forming process.

(b) Examples of roll-formed cross-sections.

Source: (b) Courtesy of Sharon Custom Metal Forming, Inc.

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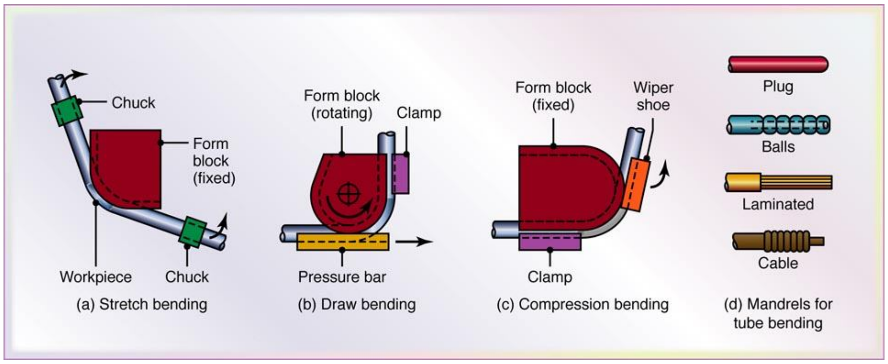
Methods of bending tubes



Methods of bending tubes. Internal mandrels or filling of tubes with particulate materials such as sand are often necessary to prevent collapse of the tubes during bending. Tubes also can be bent by a technique consisting if a stiff, helical tension spring slipped over the tube. The clearance between the OD of the tube and the ID of the spring is small, thus the tube cannot kick and the bend is uniform.

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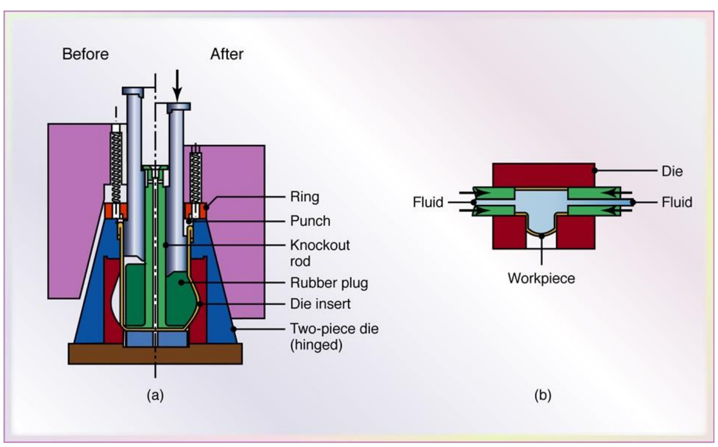
Tubular Parts



(a) The 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 under internal pressure. The bottom of the piece is then punched out to produce a "T." *Source*: After J. A. Schey.

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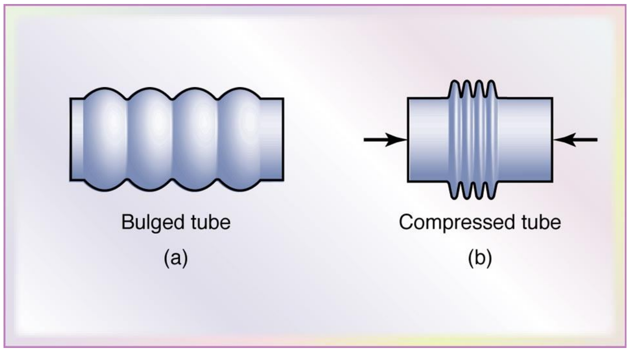
Manufacturing of Bellows



Steps in manufacturing a bellows.

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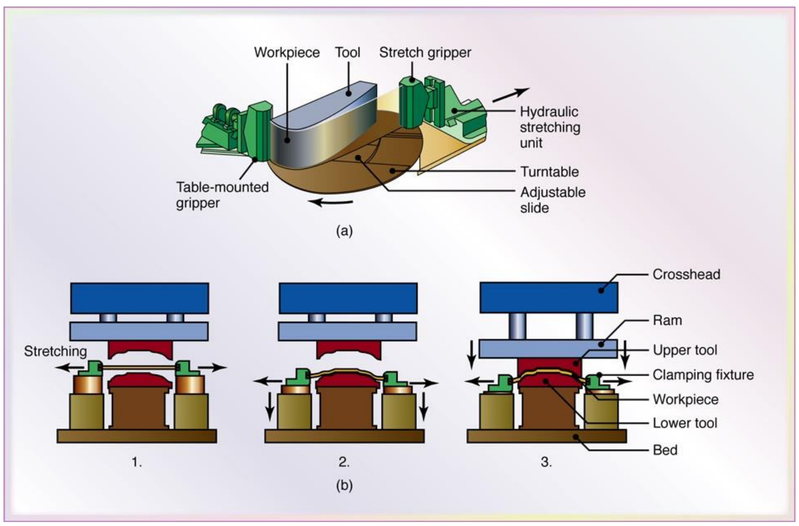
Stretch-Forming Process



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

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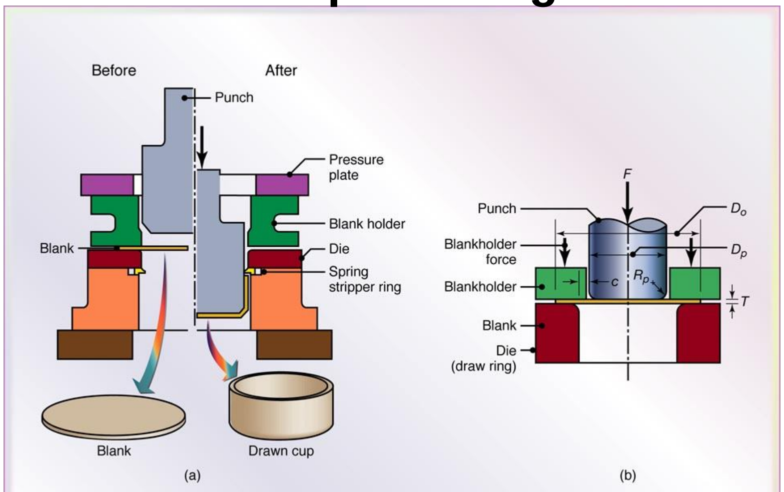
Deep-drawing



(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 on the figure are independent variables.

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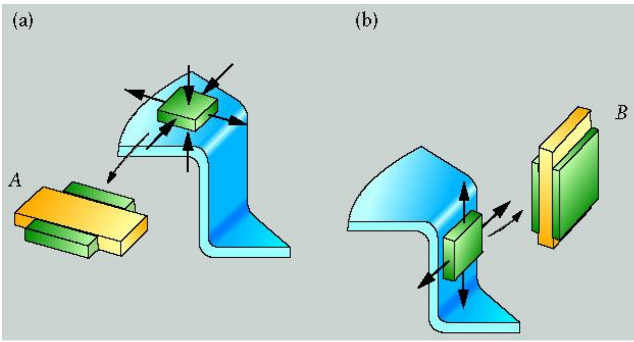
Deformation in Flange and Wall in Deep Drawing



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

$$F_{max} = \pi D_p T (\text{UTS}) \left[\left(\frac{D_o}{D_p} \right) - 0.7 \right]$$

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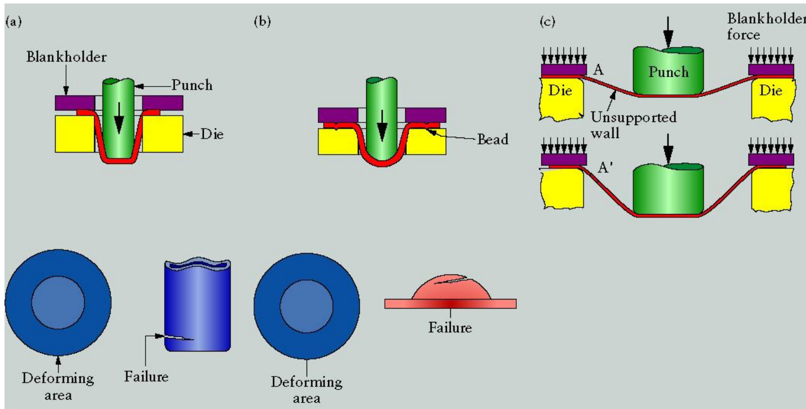
Drawing Operations



Examples of drawing operations:

(a) pure drawing

(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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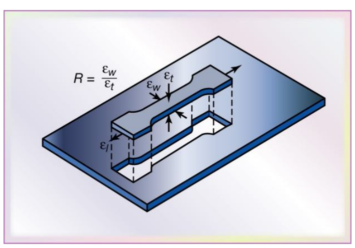
Normal and Average Anisotropy



Strains on a tensile-test specimen removed form a piece of sheet metal.

These strains are used in determining the normal and planar anisotropy of the sheet metal.

$$\text{Normal anisotropy, } R = \frac{\text{Width strain}}{\text{Thickness strain}} = \frac{\varepsilon_w}{\varepsilon_t}$$

$$\text{Average anisotropy, } R_{avg} = \frac{R_0 + 2R_{45} + R_{90}}{4}$$

TABLE 16.4

Typical Ranges of Average Normal Anisotropy, R_{avg}, for Various Sheet Metals

Zinc alloys	0.4–0.6
Hot-rolled steel	0.8–1.0
Cold-rolled, rimmed steel	1.0–1.4
Cold-rolled, aluminum-killed steel	1.4–1.8
Aluminum alloys	0.6–0.8
Copper and brass	0.6–0.9
Titanium alloys (α)	3.0–5.0
Stainless steels	0.9–1.2
High-strength, low-alloy steels	0.9–1.2

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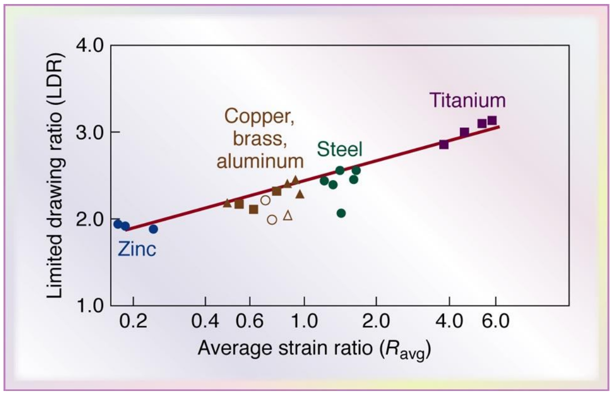
Deep drawability



The relationship between average normal anisotropy and the limiting drawing ratio for various sheet metals. *Source:* After M. Atkinson.

$$\text{LDR} = \frac{\text{Maximum blank diameter}}{\text{Punch diameter}} = \frac{D_o}{D_p}$$

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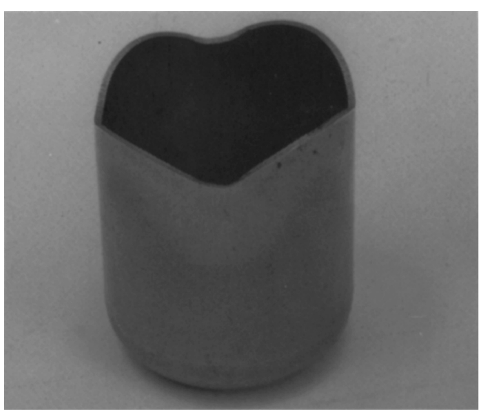
Earing and Planar Anisotropy



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

$$\text{Planar anisotropy, } \Delta R = \frac{R_0 - 2R_{45} + R_{90}}{2}$$

Note: If ΔR=0, no ears form.
The height of ears increases as Δ R increases.

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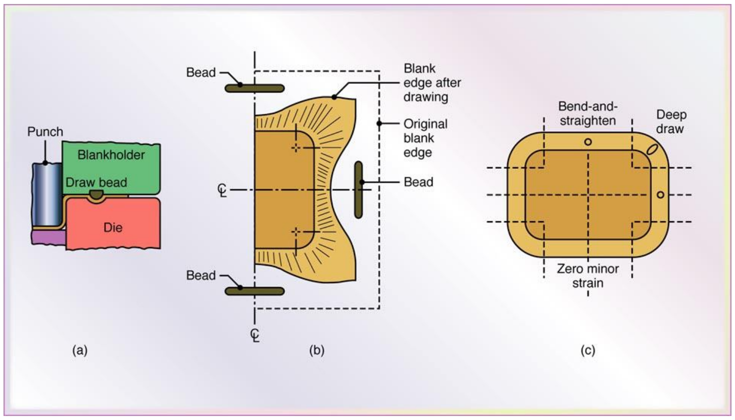
Draw beads



(a) Schematic illustration of a draw bead.

(b) Metal flow during the drawing of a box-shaped part while using beads to control the movement of the material.

(c) Deformation of circular grids in the flange in deep drawing.

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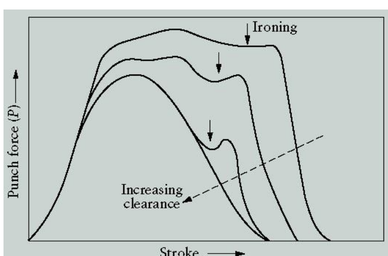
Deep Drawing

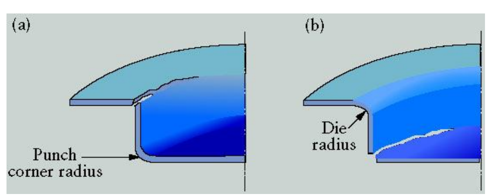


Schematic illustration of the variation of punch force with stroke in deep drawing. Note that ironing does not begin until after the punch has traveled a certain distance and the cup is formed partially. Arrows indicate the beginning or ironing.

Effect of die and punch corner radii in deep drawing on fracture of a cylindrical cup

(a) Die corner radius too small. The die corner radius should generally be 5 to 10 times the sheet thickness.

(b) Punch corner radius too small. Because friction between the cup and the punch aids in the drawing operation, excessive lubrication of the punch is detrimental to drawability.



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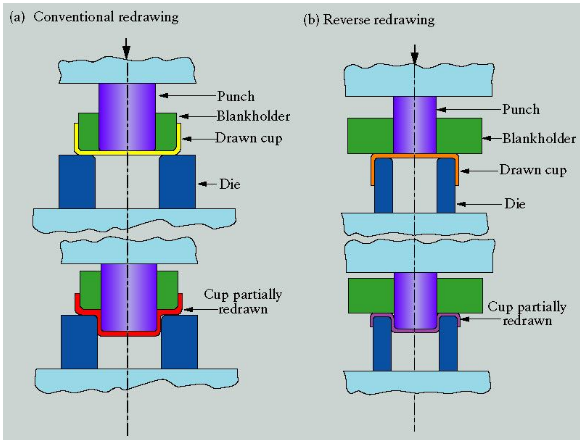
Redrawing Operations



Reducing the diameter of drawn cups by redrawing operations:

(a) conventional redrawing

(b) reverse redrawing. Small-diameter deep containers undergo many drawing and redrawing operations.

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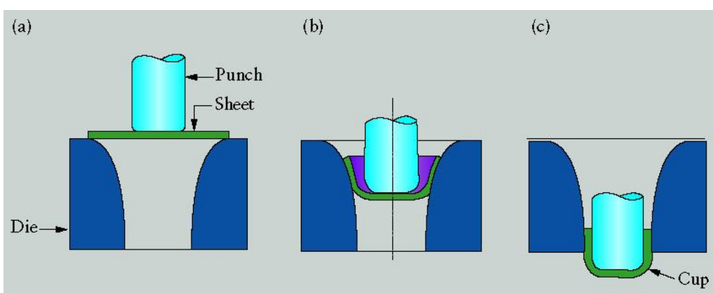
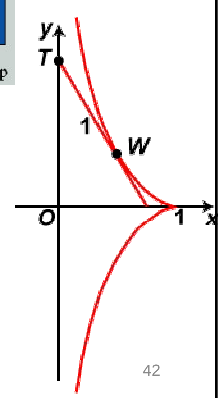
Tractrix Die Profile



- Deep drawing without a blankholder, using a tractrix die profile. The tractrix is a special curve as below

$$\frac{dy}{dx} = \frac{-y}{\sqrt{k^2 - y^2}}$$

$$x = k \text{ Log}\left[\frac{k + \sqrt{k^2 - y^2}}{y}\right] - \sqrt{k^2 - y^2}$$



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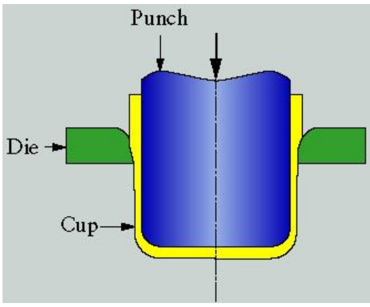
Ironing Process



Schematic illustration of the ironing process.
Note that the cup wall is thinner than its bottom.

All beverage cans without seams (known as two-piece cans) are ironed, generally in three steps, after being deep drawn into a cup. (Cans with separate tops and bottoms are known as three-piece cans.)

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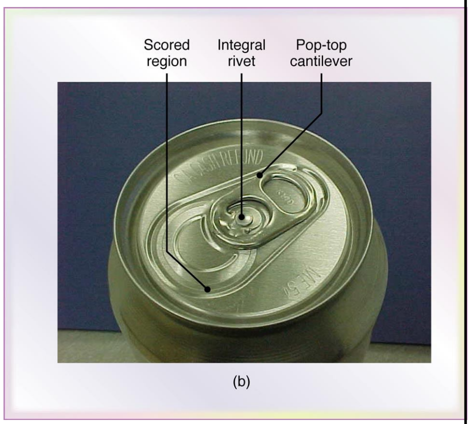
Aluminum Beverage Cans



(b)

(a) Aluminum beverage cans. Note the excellent surface finish.

(b) Detail of the can lid showing integral rivet and scored edges for the pop-top.

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Manufacturing of food and beverage cans

- ✓ 100-billion beverage cans and 30-billion food cans produced each year in the US
- ✓ Strong and light weight (less than 15g), under internal pressure of 620 kPa, without leakage
- ✓ Excellent surface finish (shiny cans are preferred)
- ✓ Very inexpensive: $40 per 1000 cans
- ✓ Two- or three piece cans
- ✓ Two-piece cans consists of can body and the lid; the body is drawn and ironed (D&I)
- ✓ 3004-H19 aluminum and electrolytic tin-plated ASTM A623 steel for the body

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Manufacturing of food and beverage cans

- ✓ Lids from aluminum 5182-H19 or 5182-H48 (sufficient formability to enable forming of the integral rivet without cracking and ability to be scored)
- ✓ A plastic seal around the periphery of the lid to seal the can's contents after the lid is seamed to the can body
- ✓ One method: 140 mm diameter blank; deep drawn to 90 mm; redrawn to the final diameter of around 65 mm; ironed through two or three ironing rings in one pass; domed for the can bottom
- ✓ Operation presses over 400 strokes per minute
- ✓ Necking by spinning or die necking and then spin-flanged

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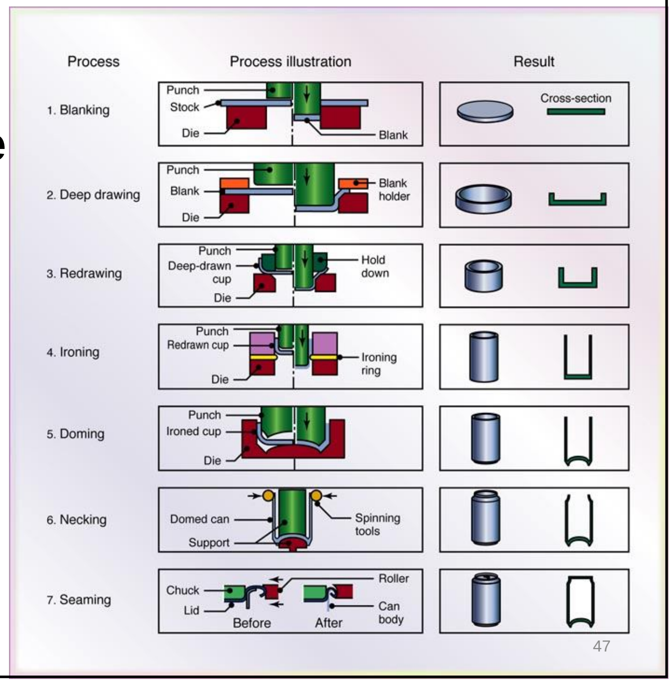
Can Manufacture



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

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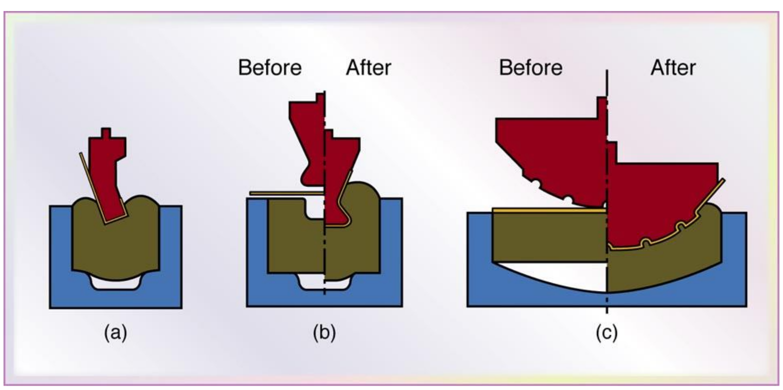
Rubber forming



Examples of the bending and embossing of sheet metal with a metal punch and with a flexible pad serving as the female die. [die material: polyurethane; order of pressures: 10 MPa] *Source*: Courtesy of Polyurethane Products Corporation.

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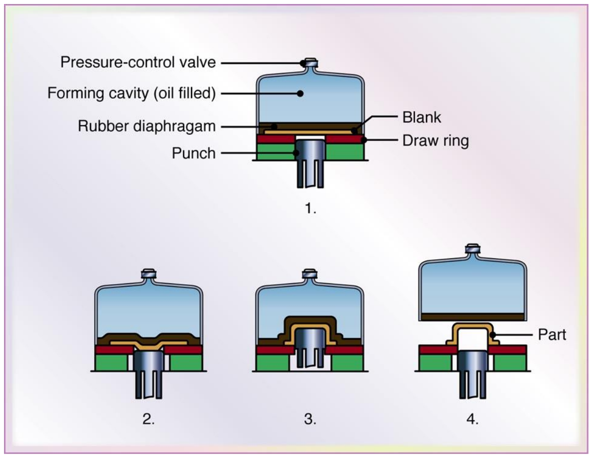
Hydroform Process



The hydroform (or fluid-forming) process. Note that in contrast to the ordinary deep-drawing process, the pressure in the dome forces the cup walls against the punch. The cup travels with the punch; in this way, deep drawability is improved.

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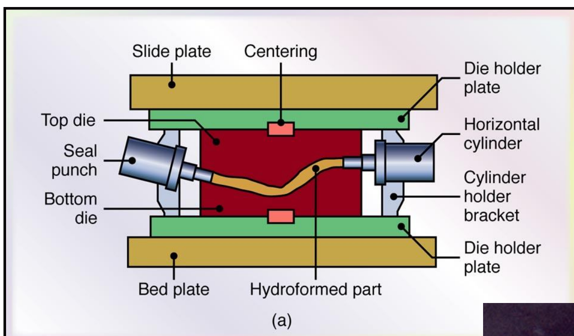
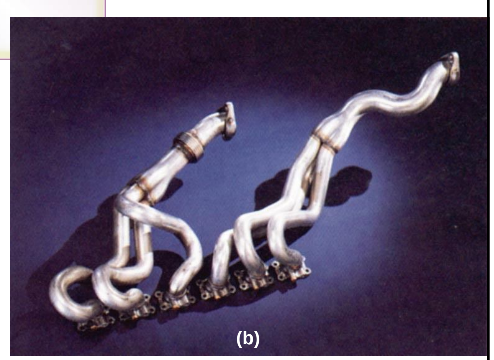


Tube-Hydroforming



(a) Schematic illustration of the tube-hydrofroming process.

(b) Example of tube-hydroformed parts. Automotive exhaust and structural components, bicycle frames, and hydraulic and pneumatic fittings are produced through tube hydroforming. *Source:* Courtesy of Schuler GmBH.

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Spinning

- *Spinning* is a process which involves the forming of axisymmetric parts over a mandrel by the use of various tools and rollers
- **Conventional spinning**, a circular blank of flat or preformed sheet metal is placed and held against a mandrel and rotated while a rigid toll deforms and shapes the material over the mandrel
- **Shear spinning**, also known *flow turning*, *hydrospinning*, and *spin forging.* Single or two forming roller(s) is/are used to reduce sheet's thickness while maintaining its maximum blank diameter
- **Tube spinning**, reducing or shaping the thickness of hollow cylindrical blanks by spinning them on a solid and round mandrel using rollers

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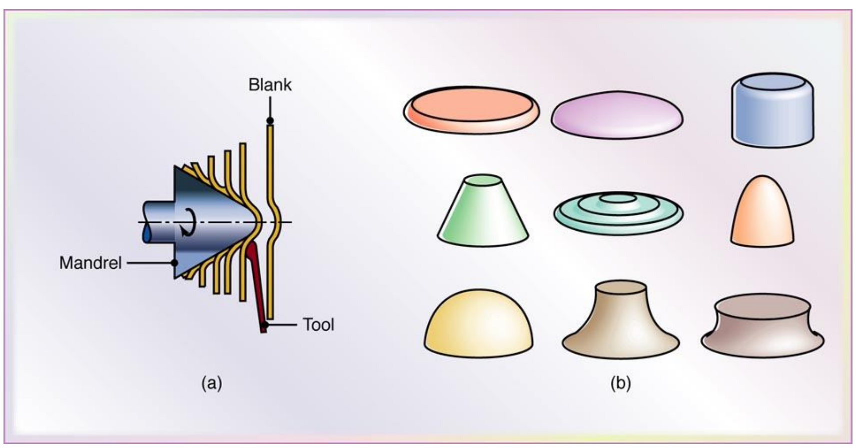
Conventional Spinning



(a) Schematic illustration of the conventional spinning process.

(b) Types of parts conventionally spun. All parts are axisymmetric.

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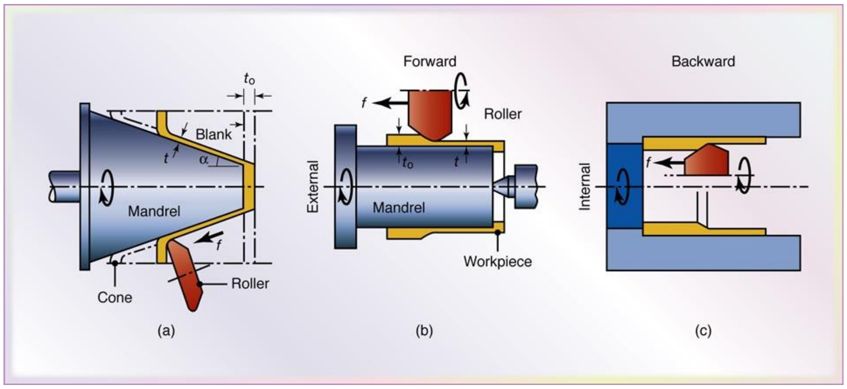
Shear-Spinning and Tube-Spinning



(a) Schematic illustration of the shear-spinning process for making conical parts. The mandrel can be shaped so that curvilinear parts can be spun.

(b) and (c) Schematic illustrations of the tube-spinning process

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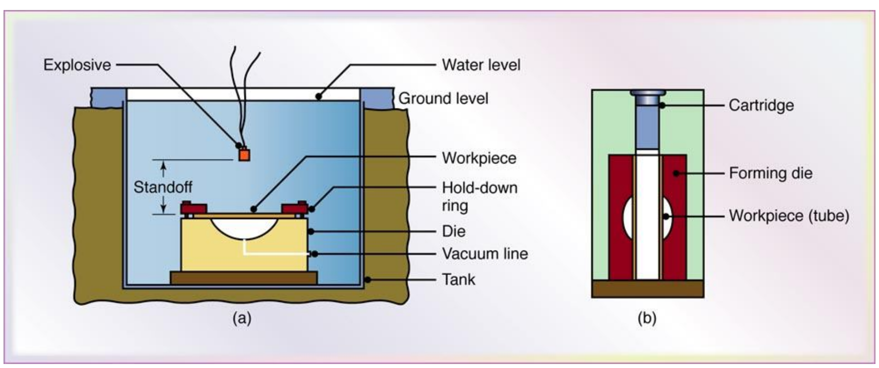
Explosive Forming



(a) Schematic illustration of the explosive forming process.

(b) Illustration of the confined method of the explosive bulging of tubes.

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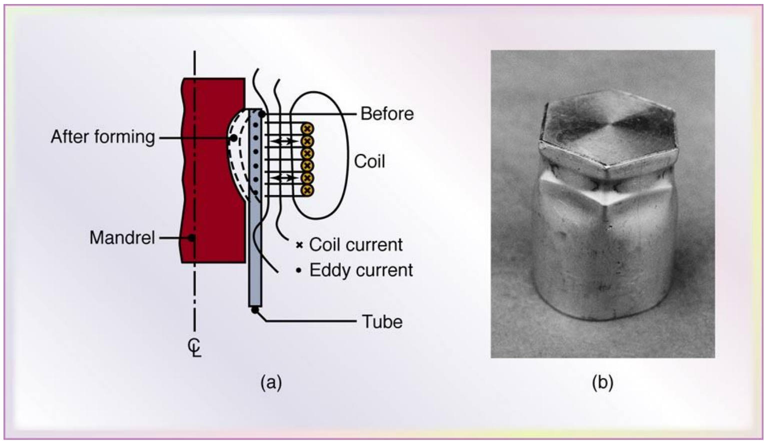
Magnetic-Pulse Forming Process



(a) Schematic illustration of the magnetic-pulse forming process used to form a tube over a plug.

(b) Aluminum tube collapsed over a hexagonal plug by the magnetic-pulse forming process.

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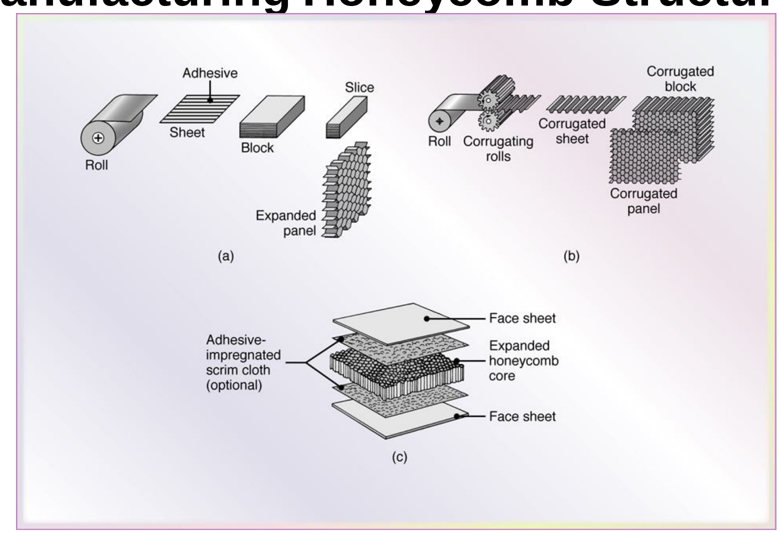
Manufacturing Honeycomb Structures



(a) expansion process; (b) corrugation process; (c) assembling a honeycomb structure into a laminate.

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Design considerations in sheet-metal forming

- ✓ **Blank design**, material scrap is the primary concern in blanking operations
- ✓ **Bending**, the main concerns are material fracture, wrinkling, and the inability to form the bend
  - ✓ Relief notch cut to limit the stresses and to avoid tearing
  - ✓ Design modification to remove stress concentrations
- ✓ **Stamping and progressive-die**, cost of the tooling and the number of stations are determined by the number of features and spacing of the features on the part

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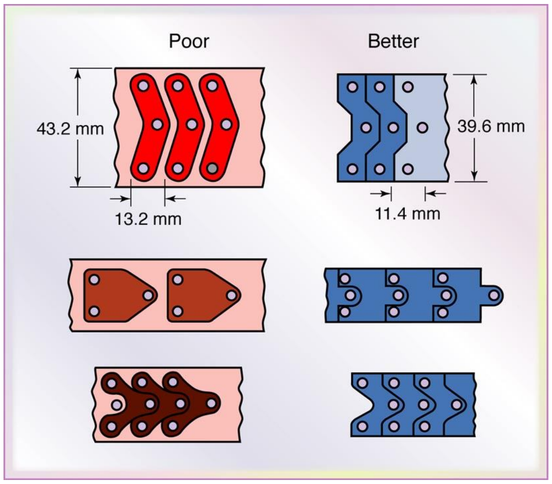
Blank design



Efficient nesting of parts for optimum material utilization in blanking.
Source: Courtesy of Society of Manufacturing Engineers.

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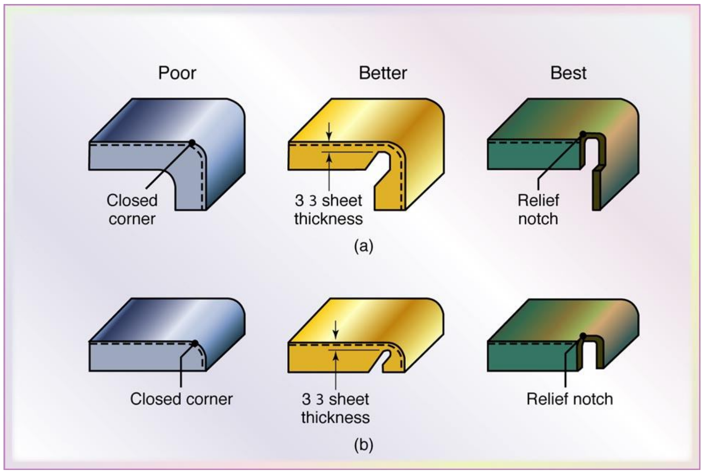
Control of defects in bending



Control of tearing and buckling of a flange in a right angle bend.
Source: Courtesy of Society of Manufacturing Engineers.

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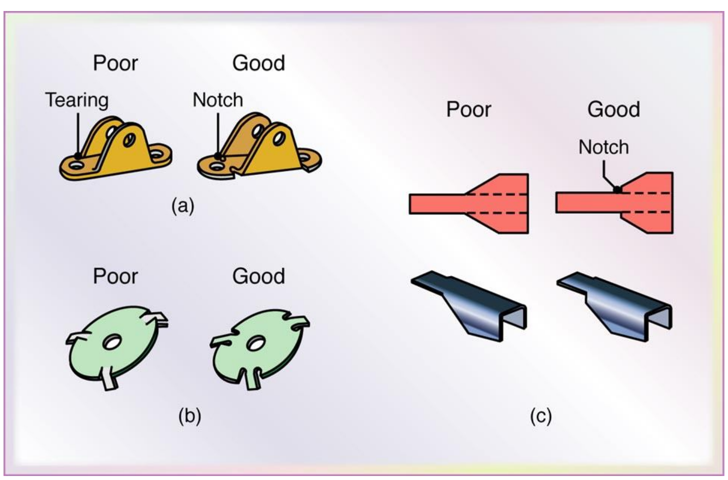
Application of notches in bending



Application of notches to avoid tearing and wrinkling in right-angle bending operations. *Source*: Courtesy of Society of Manufacturing Engineers.

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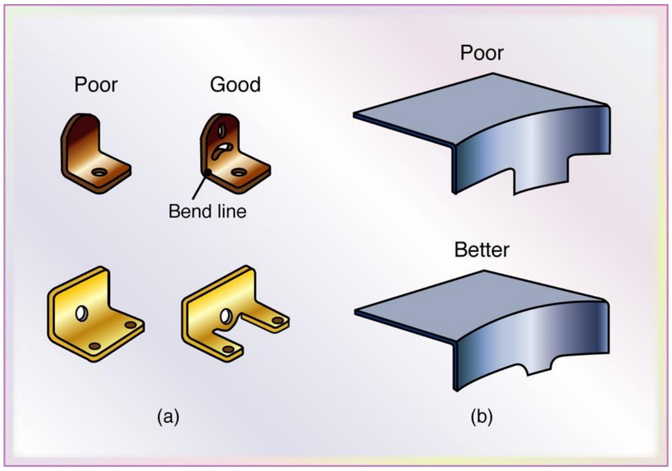
Stress concentration near bends



(a) Use of a crescent or ear for a hole near a bend.

(b) Reduction of severity of tab in flange.

Source: Courtesy of Society of Manufacturing Engineers.

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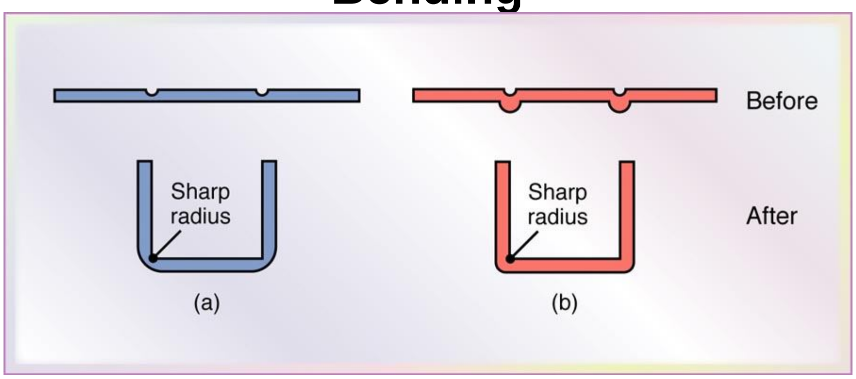
Obtaining a Sharp Radius in Bending



Application of scoring or embossing to obtain a sharp inner radius in bending. Unless properly designed, these features can lead to fracture. *Source*: Courtesy of Society of Manufacturing Engineers.

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Equipment for sheet-metal forming

- ✓ Mechanical, hydraulic, pneumatic, or pneumatic-hydraulic presses as the basic equipment
- ✓ Characteristics: design, features, capacity, and stiffness
- ✓ Press selection:
  1. Type of forming operation, the size and shape of dies
  2. Size and shape of workpiece
  3. Length of stroke of the slide, the number of strokes per minute
  4. Number of slides (single, double, and triple-action)
  5. Maximum force required
  6. Type of mechanical, hydraulic, and computer controls
  7. Features for changing dies
  8. Safety features

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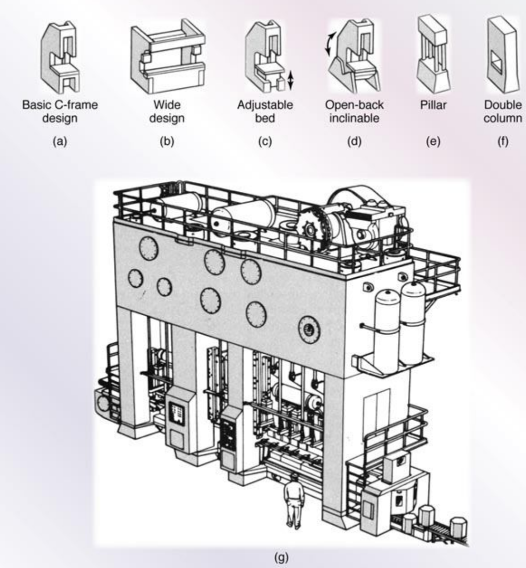
Presses

(a) through (f) Schematic illustrations of types of press frames for sheet-forming operations. Each type has its own characteristics of stiffness, capacity, and accessibility. (g) A large stamping press

Source: (a) through (f) *Engineer's Handbook*, VEB Fachbuchverlag, 1965. (g) Verson Allsteel Company.



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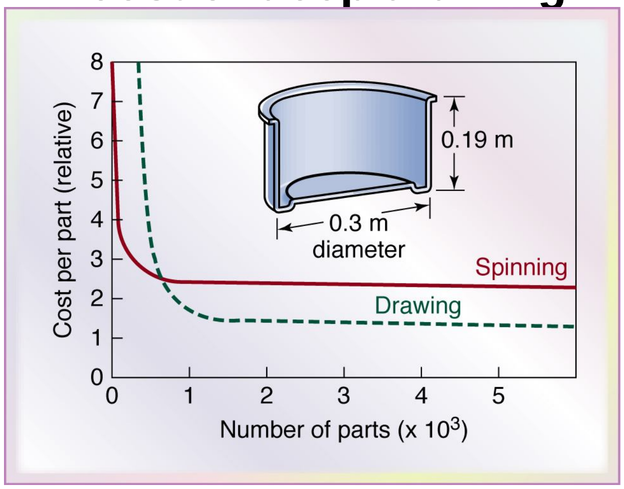
Cost of conventional spinning versus cost of deep drawing



Cost comparison for manufacturing a round sheet-metal container either by conventional spinning or by deep drawing.

Note that for small quantities, spinning is more economical.

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