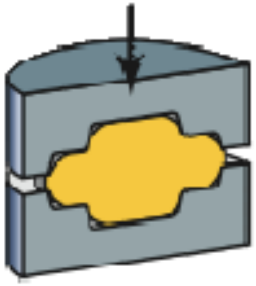
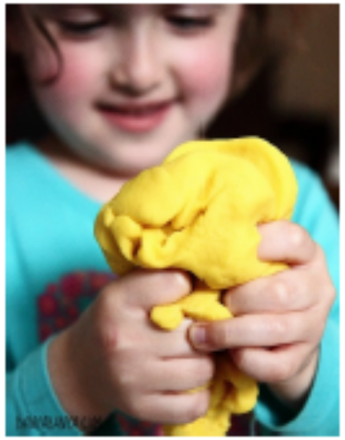
ME2300: Manufacturing Processes
Jan-May 2020

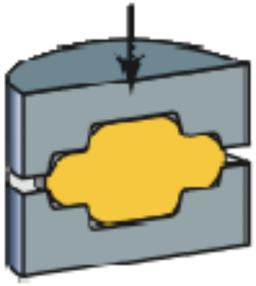
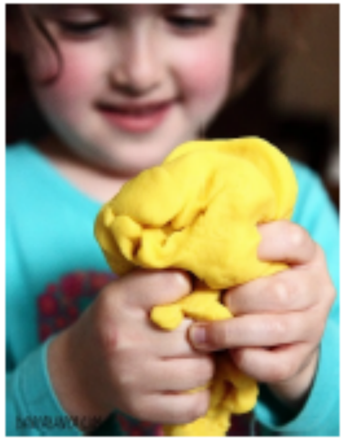
Bulk vs. Sheet





Starting material: sheets made by deformation of bulk material

Bulk vs. Sheet

 :  ::  : 

Sheet forming unlike bulk deformation processes, involves workpieces with a high ratio of surface area to thickness

Sheet metalworking

1. Cutting Operations
2. Bending Operations
3. Drawing
4. Sheet Metal Operations Not Performed on Presses

Sheet metalworking

Cutting and forming operations performed on relatively thin sheets of metal

- Thickness of <u>sheet metal</u> = 0.4 mm (1/64 in) to 6 mm (1/4 in)
- Thickness of <u>plate stock</u> > 6 mm
- Operations usually performed as cold working

Sheet and plate metal products

- Sheet and plate metal parts for consumer and industrial products such as
  - Automobiles and trucks
  - Airplanes
  - Railway cars and locomotives
  - Farm and construction equipment
  - Small and large appliances
  - Office furniture
  - Computers and office equipment

Advantage of sheet metal parts

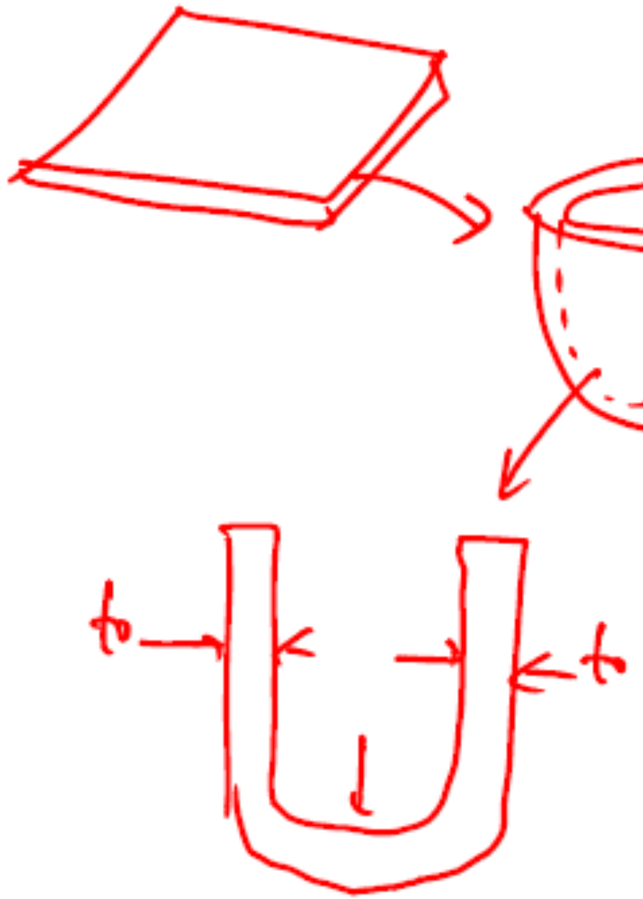
- High strength
- Good dimensional accuracy
- Good surface finish
- Relatively low cost
- For large quantities, economical mass production operations are available

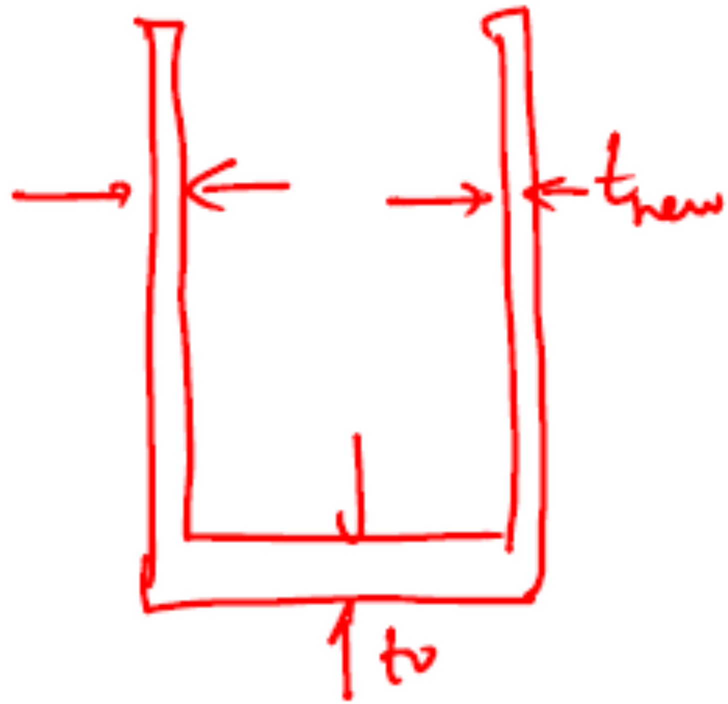
Different ways to deform sheets

1. Shearing
2. Blanking
3. Rotary shearing
4. Shaving
5. Bending
6. Deep drawing
7. Roll forming

Different ways to deform sheet metals

Without change in thickness **With change in thickness**





Bulk vs. Sheet deformation

There are several ways in which sheet metal works differs from bulk deformation:

-Type of deformation: compression vs. tension

-Amount of plastic strain and closeness to elastic region

-Grain size effects

-Anisotropy (directionally dependent property)

We will explore all these concepts in the next few slides

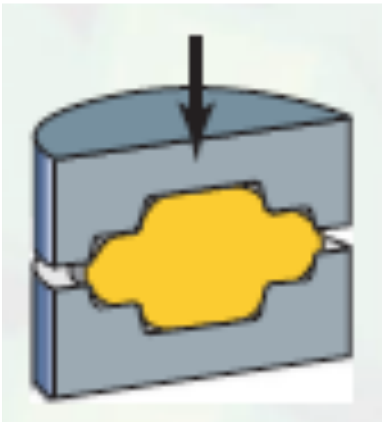
Bulk vs. Sheet: Compression vs. tension

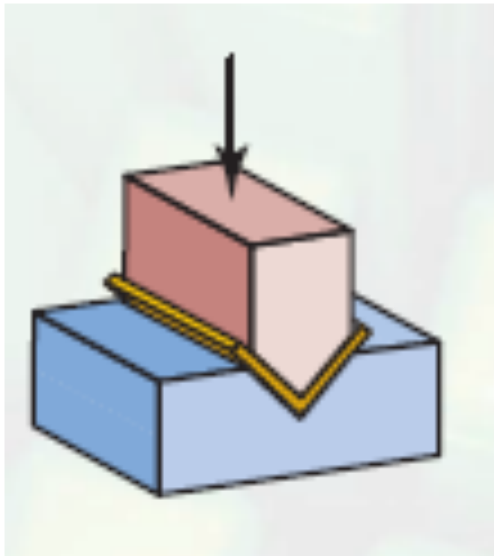
• Bulk deformation predominantly involves compressive stresses

-Some tensile stress regions will be there

• Sheet deformation predominantly involve stretching the sheet in tension

-Some areas will go into compression





Sheets are not good under compression

Sheets will buckle-wrinkle

Tensile test

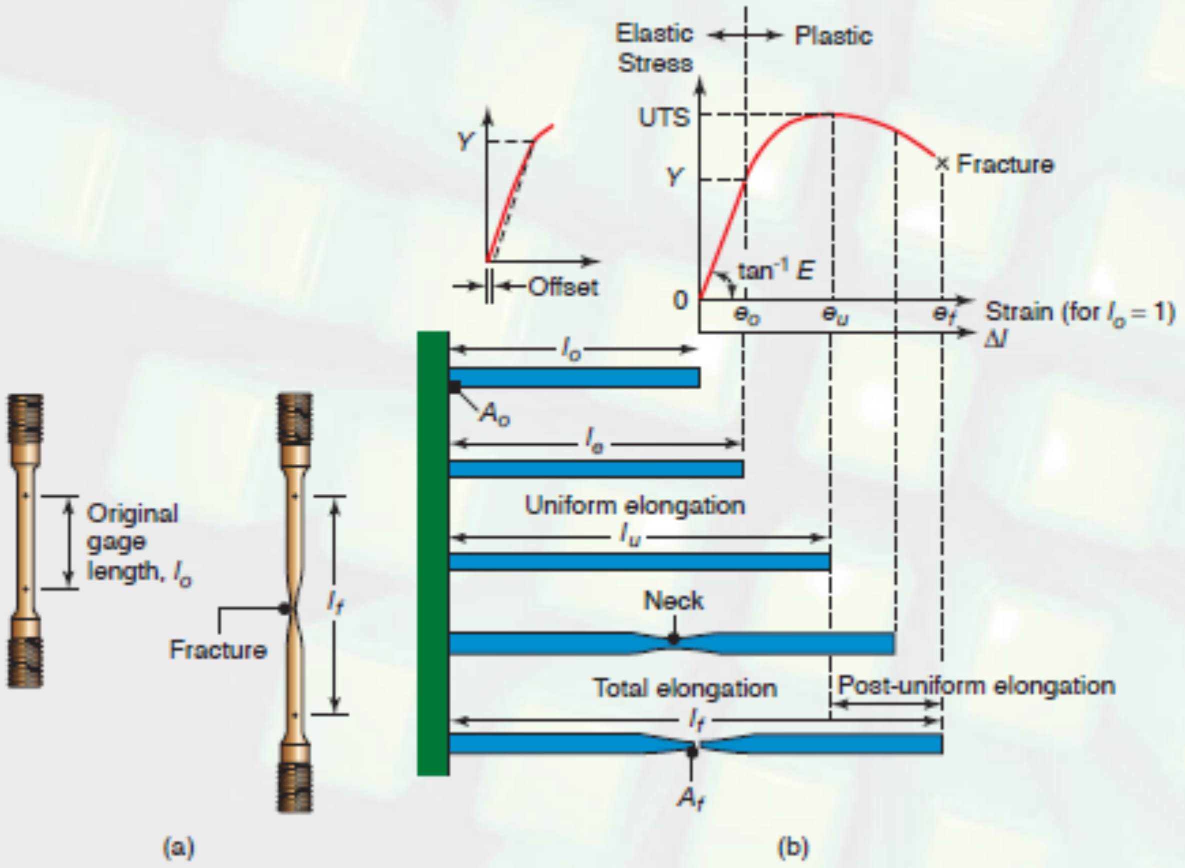
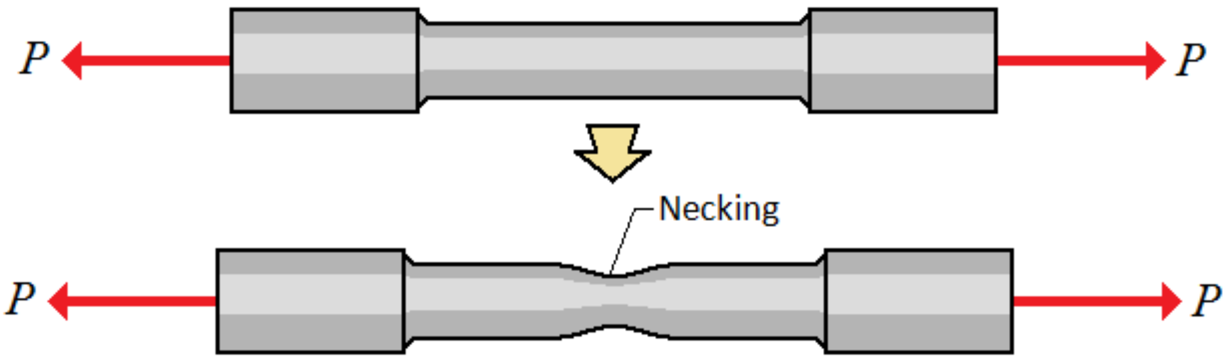


FIGURE 2.2 (a) Original and final shape of a standard tensile-test specimen. (b) Outline of a tensile-test sequence showing different stages in the elongation of the specimen.

Bulk vs. Sheet: Necking is important in sheet (tension effect)

When does necking occurs in tension?

Strain at which necking occurs?



Rate of decrease in cross sectional area is greater than the rate of increase in strength

Example

Q: A material has true stress-strain curve given by $\sigma=K\varepsilon^n$ where K= 690 kPa and n=0.5). Calculate the ultimate tensile strength and the engineering UTS of this material.

Bulk vs. Sheet: Necking is important in sheet (tension effect)

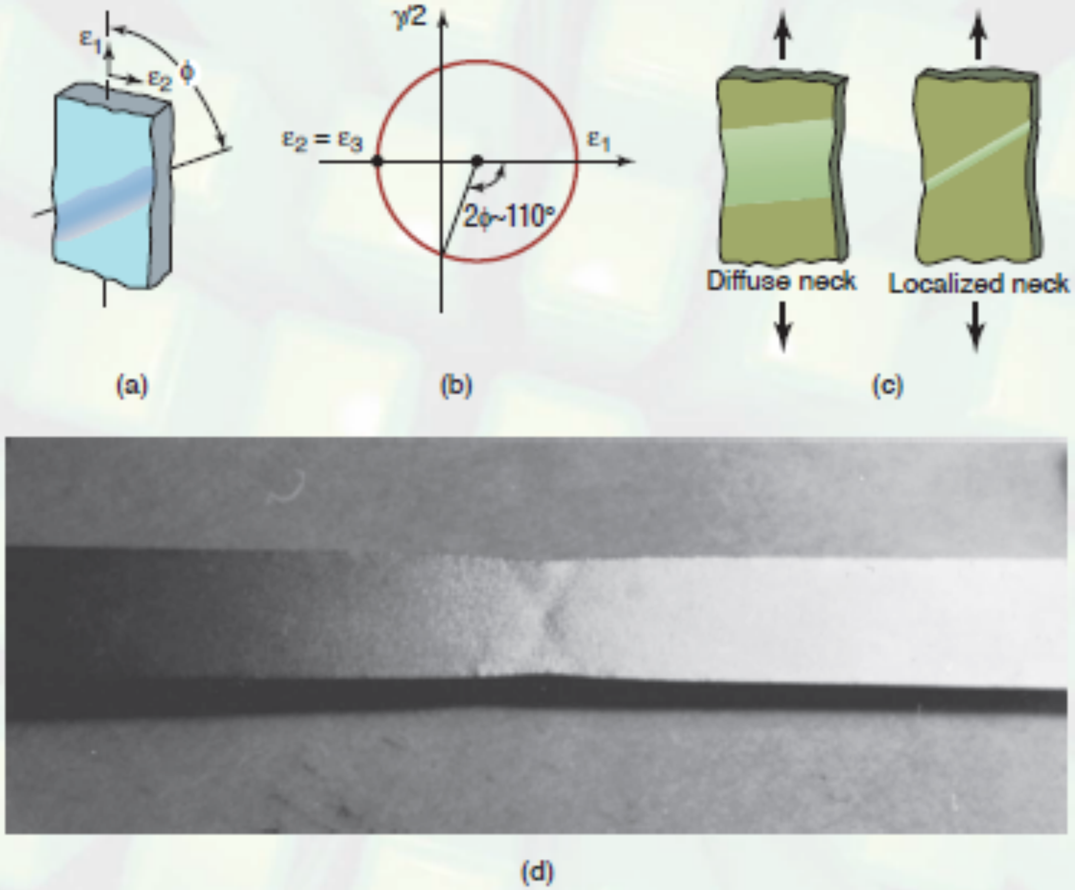


FIGURE 7.1 (a) Localized necking in a sheet-metal specimen under tension. (b) Determination of the angle of neck from the Mohr's circle for strain. (c) Schematic illustrations for diffuse and localized necking, respectively. (d) Localized necking in an aluminum strip in tension; note the double neck. *Source:* S. Kalpakjian.

Necking dependence on strain rate sensitivity

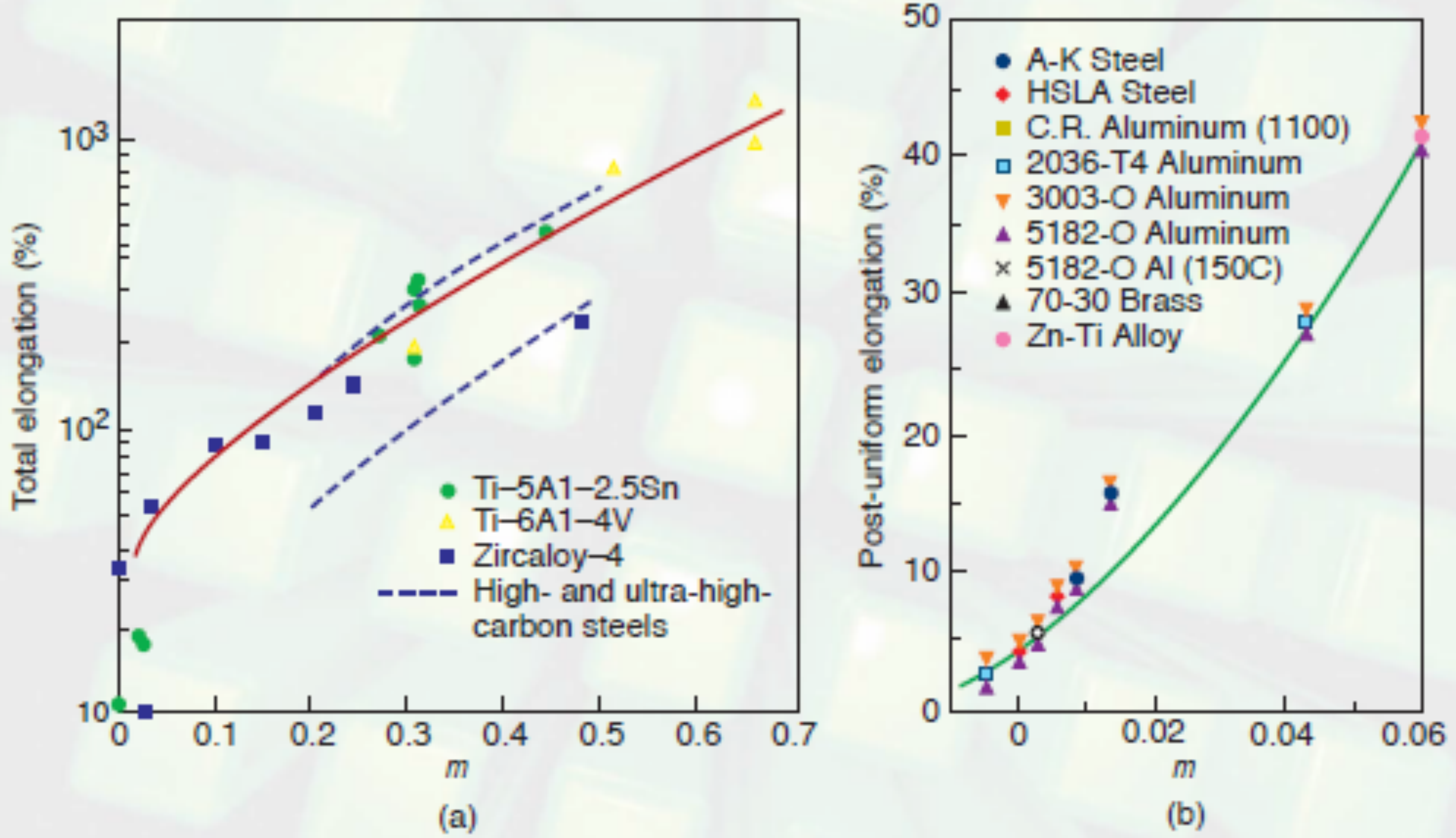


FIGURE 2.12 (a) The effect of strain-rate sensitivity exponent *m* on the total elongation for various metals. Note that elongation at high values of *m* approaches 1000%. *Source:* After D. Lee and W.A. Backofen. (b) The effect of strain-rate sensitivity exponent *m* on the post uniform (after necking) elongation for various metals. *Source:* After A.K. Ghosh.

Bauschinger effect

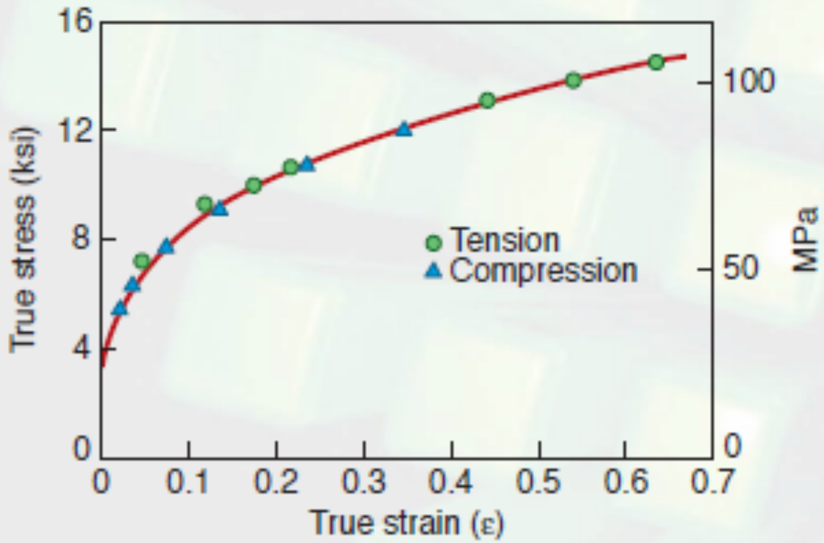


FIGURE 2.16 True stress-true strain curve in tension and compression for aluminum. For ductile metals, the curves for tension and compression are identical. *Source:* After A.H. Cottrell.

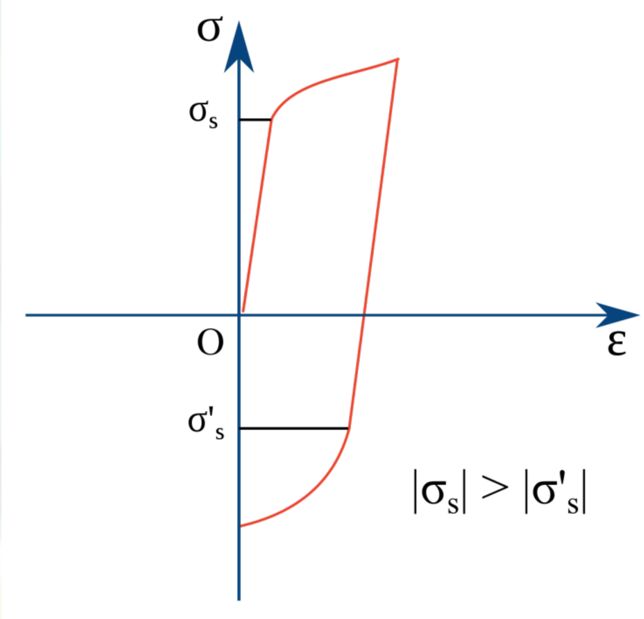
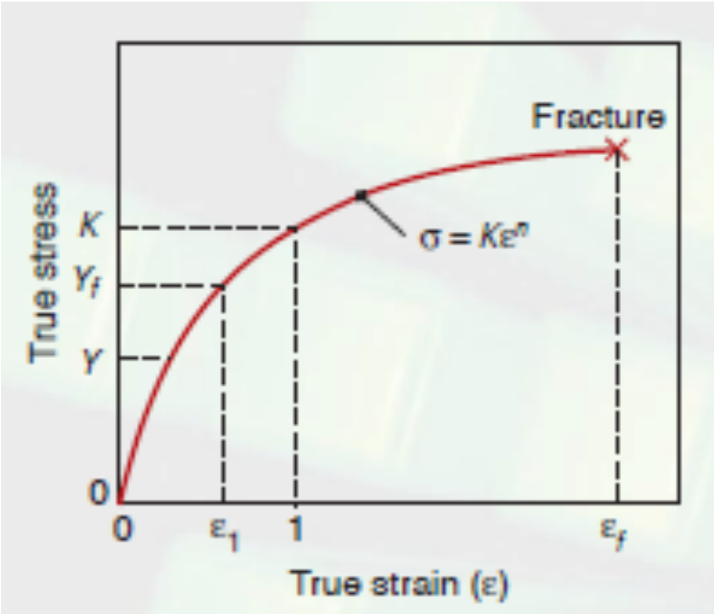


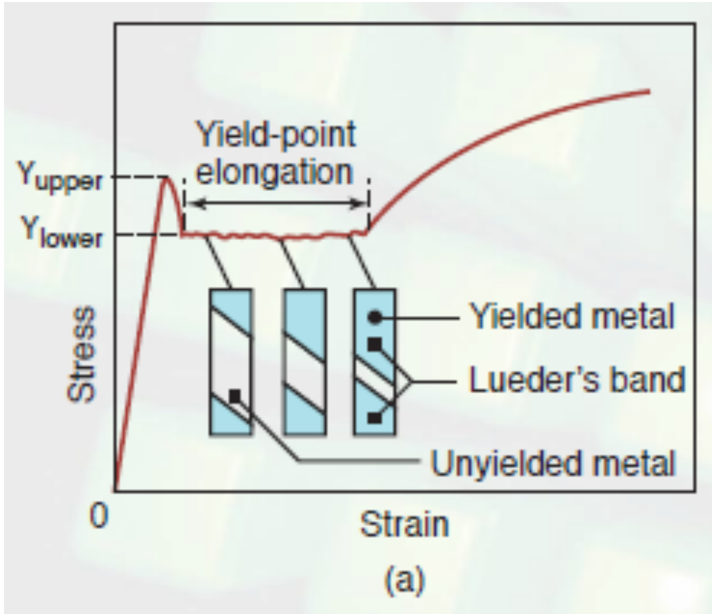
FIGURE 2.17 Schematic illustration of the Bauschinger effect. Arrows show loading and unloading paths. Note the decrease in the yield stress in compression after the specimen has been subjected to tension. The same result is obtained if compression is applied first, followed by tension, whereby the yield stress in tension decreases.

Bulk vs. Sheet: amount of plastic strain

- Bulk deformation involves large plastic strains – far away from the elastic region
- Sheet deformation involves lower plastic strains – closer to the elastic region

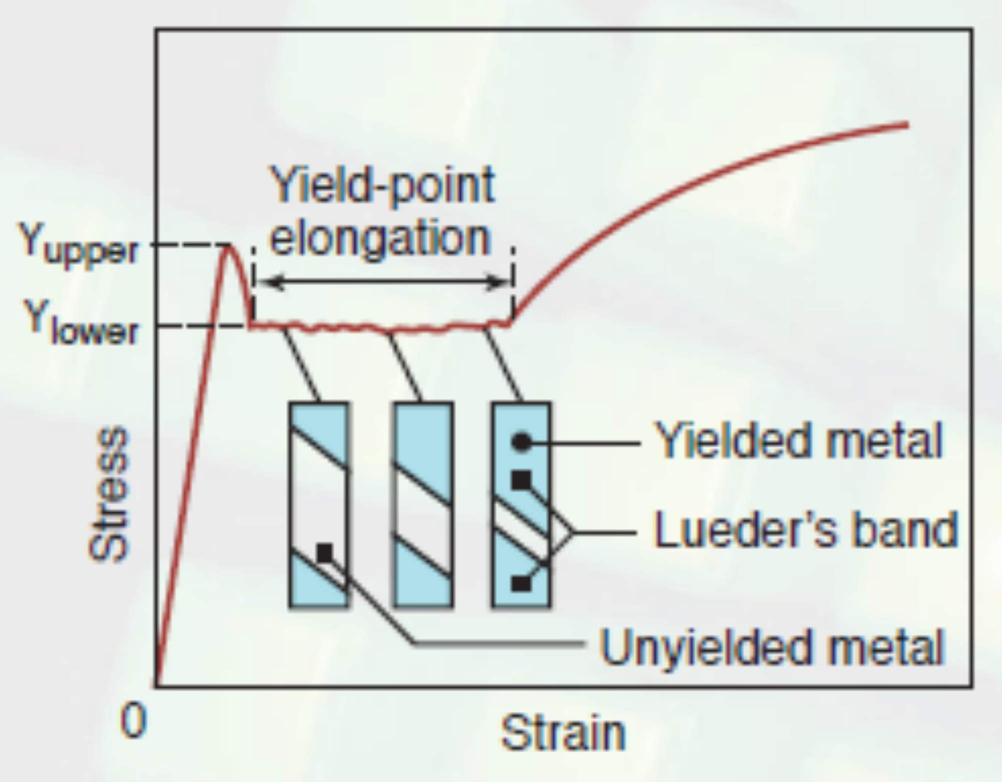


Bulk deformation elastic region is ignored



Sheet deformation: region near elastic region is an important consideration

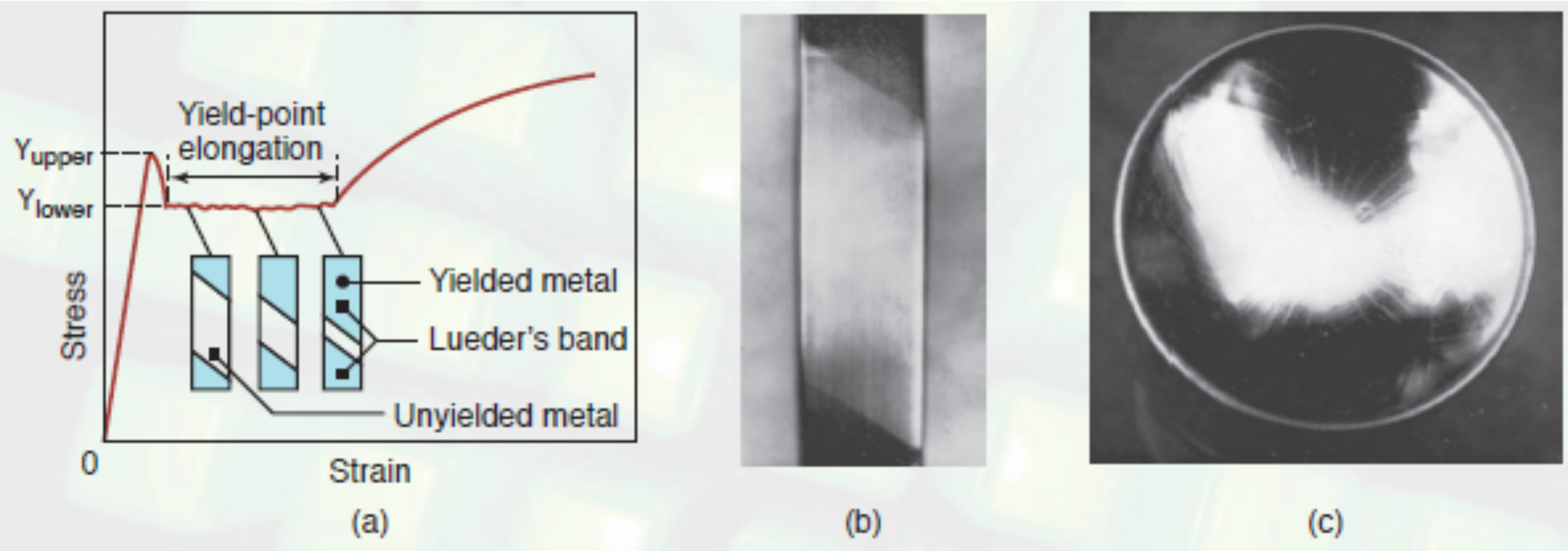
Yield point elongation: low carbon steel



(a)

Strain rate (↑) and grain size (↓) of the sheet metal

Effect of being near elastic region: yield point elongation/Lueders bands



To avoid this problem, temper rolling is carried out – where sheet thickness is reduced (0.5-1.5%) by cold rolling

Sheet metal working terminology

1. "Punch-and-die"
   - Tooling to perform cutting, bending, and drawing
2. "Stamping press"
   - Machine tool that performs most sheet metal operations
3. "Stampings"
   - Sheet metal products

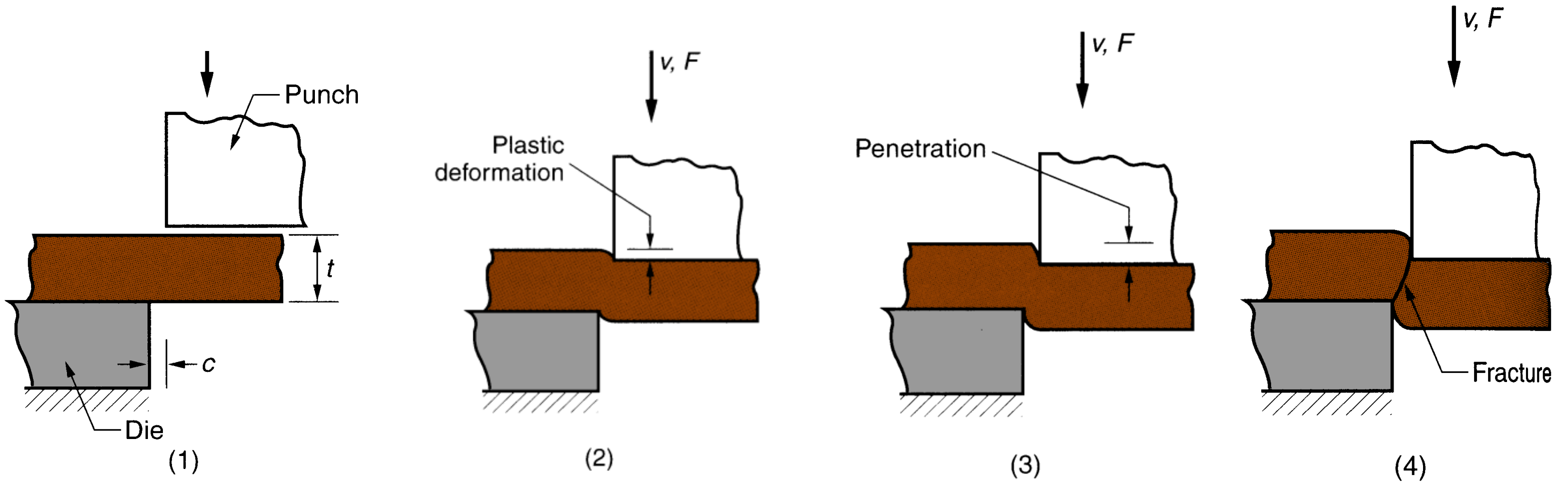
Major categories of sheet metal processes

1. Cutting
   - Shearing to separate large sheets; or cut part perimeters or make holes in sheets

2. Bending
   - Straining sheet around a straight axis

3. Drawing
   - Forming of sheet into convex or concave shapes

Cutting



Shearing between two sharp cutting edges

Shearing, Blanking and Punching

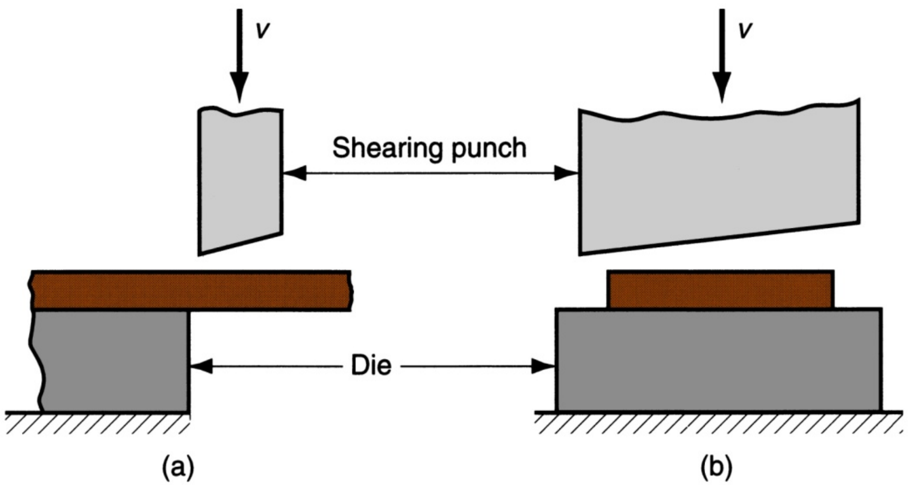
Three principal operations in pressworking that cut sheet metal:

- Shearing
- Blanking
- Punching

Shearing

Sheet metal cutting operation along a straight line between two cutting edges

- Typically used to cut large sheets into smaller sections for subsequent operations



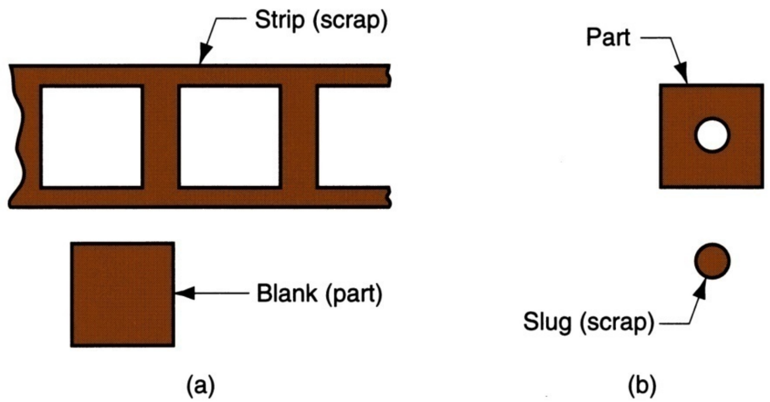
Blanking and punching

Blanking - sheet metal cutting to separate piece from surrounding stock

- Cut piece is the desired part, called a *blank*

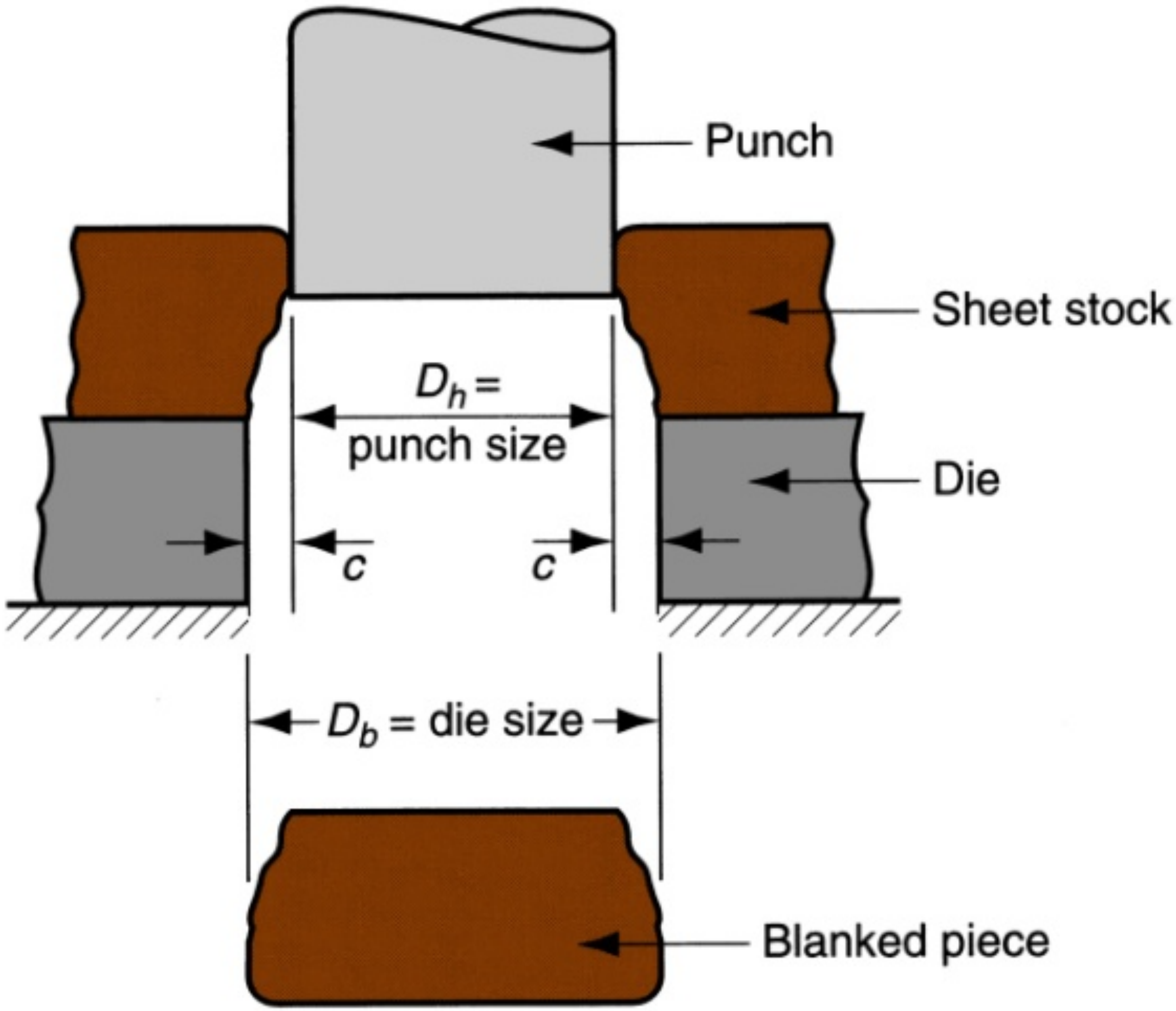
Punching - sheet metal cutting similar to blanking except cut piece is scrap, called a *slug*

- Remaining stock is the desired part



(a) Blanking and (b) punching

Clearance in sheet metal cutting



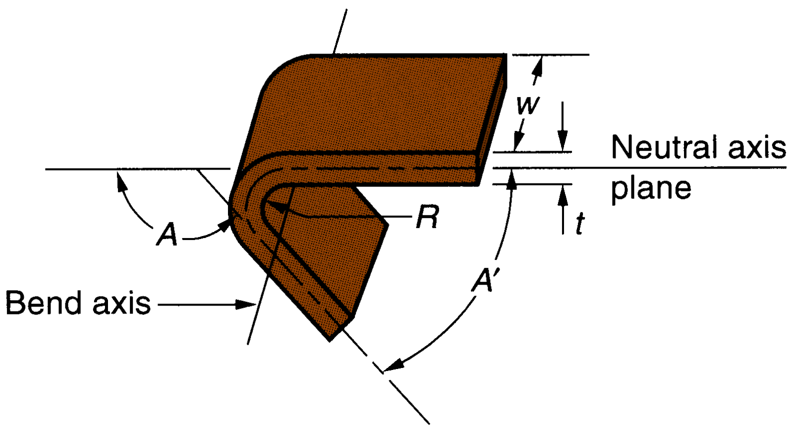
Clearance in sheet metal cutting

Distance between the punch and die

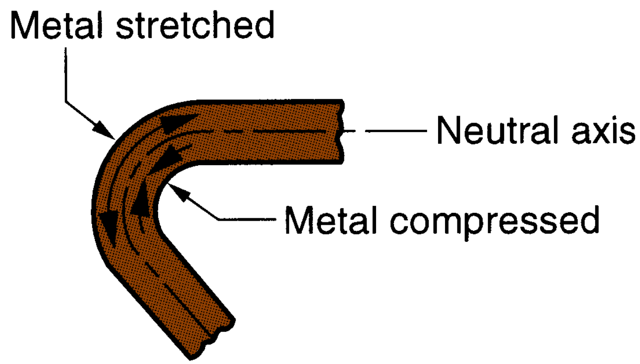
- Typical values range between 4% and 8% of stock thickness
  - If too small, fracture lines pass each other, causing double burnishing and larger force
  - If too large, metal is pinched between cutting edges and excessive burr results

Bending

Straining sheet metal around a straight axis to take a permanent bend



(a)



(b)

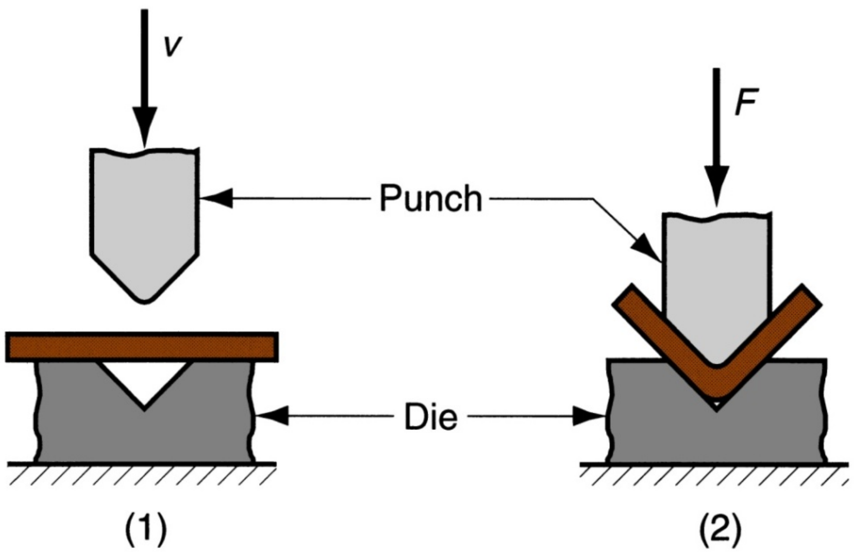
(a) Bending of sheet metal

(b) both compression and tensile elongation of the metal occur in bending

V-bending

V-bending: Performed with a V-shaped die

- For low production
- Performed on a *press brake*
- V-dies are simple and inexpensive

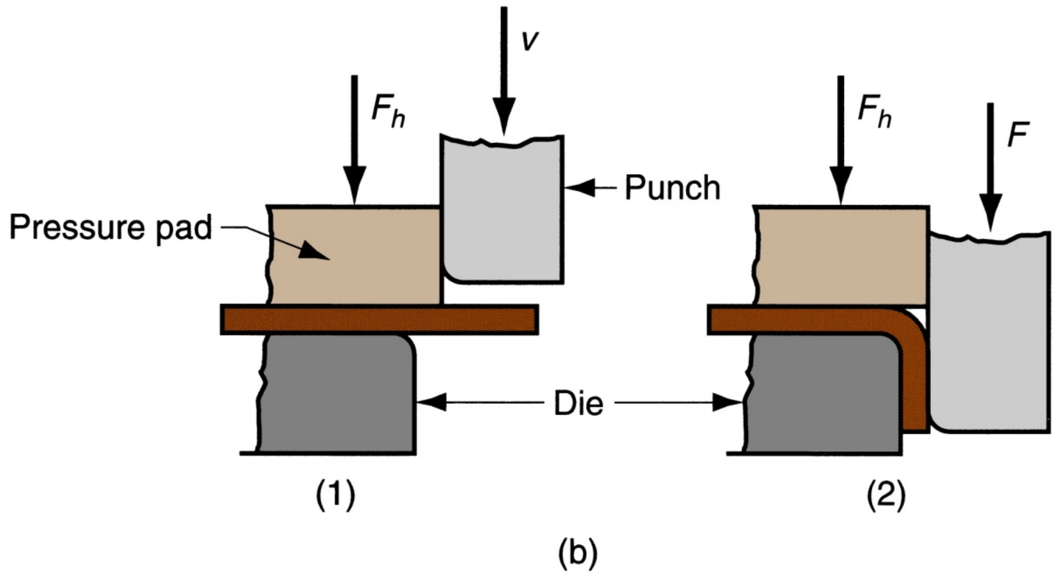


(a)

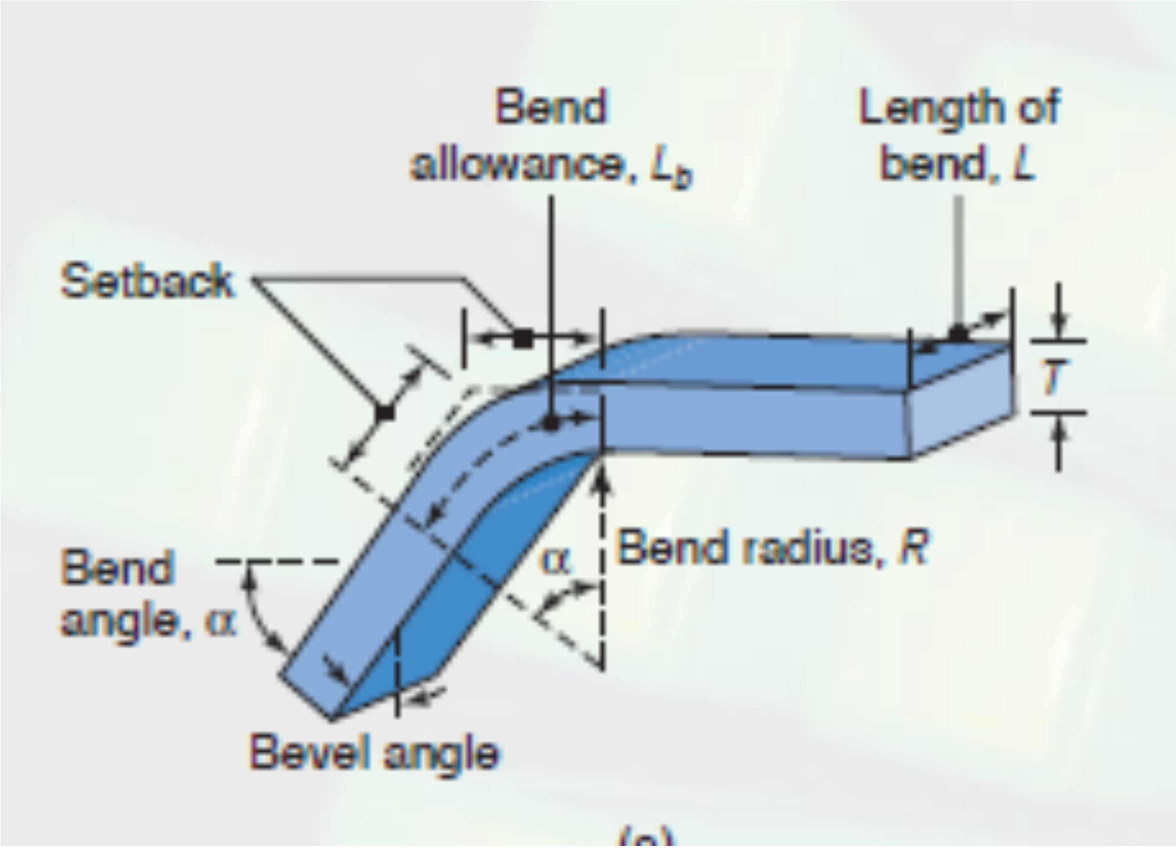
Edge bending

Edge-bending: Performed with a wiping die

- For high production
- Pressure pad required
- Dies are more complicated and costly



Calculation of length: Bending

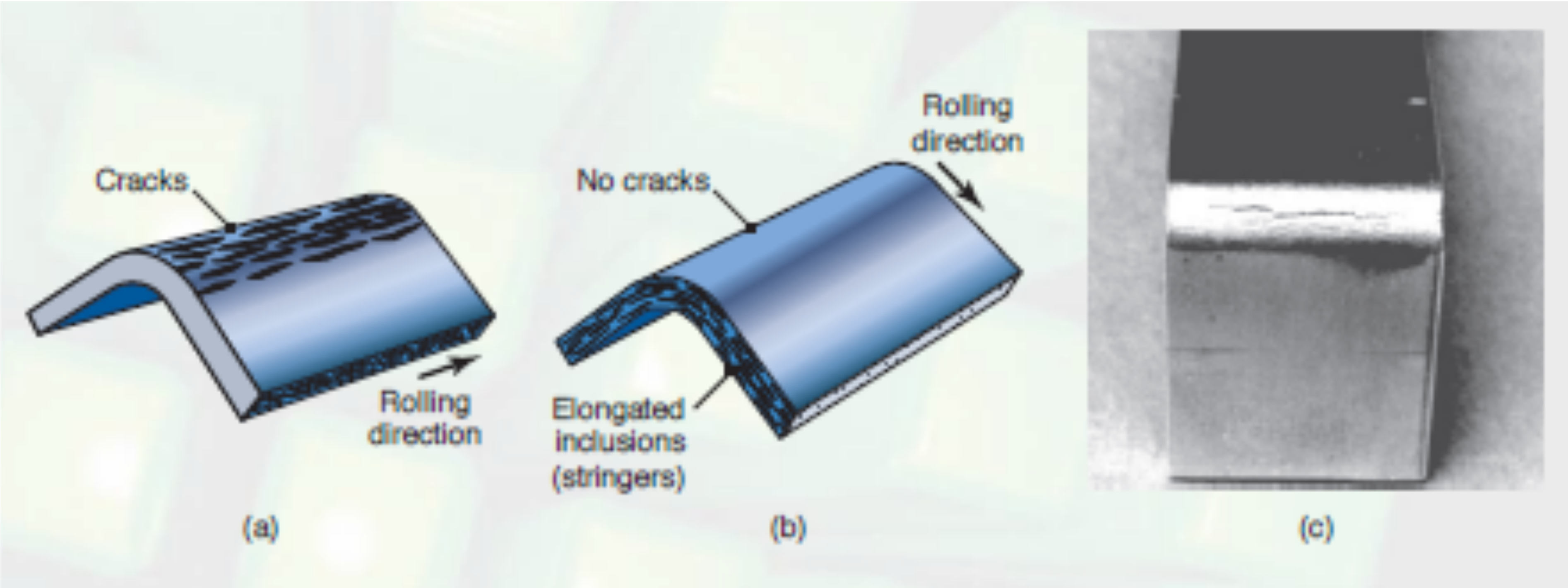


$$L_b = \alpha(R + kt)$$

k = 0.33 for R<2t

k = 0.5 for R>2t

Minimum bending radius



The radius R at which cracks appear at the outer surface of the bend is called minimum bending radius

Strain while bending?

$$e = \frac{1}{(2R/t+1)}$$

Minimum bending radius

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

Minimum bending radius

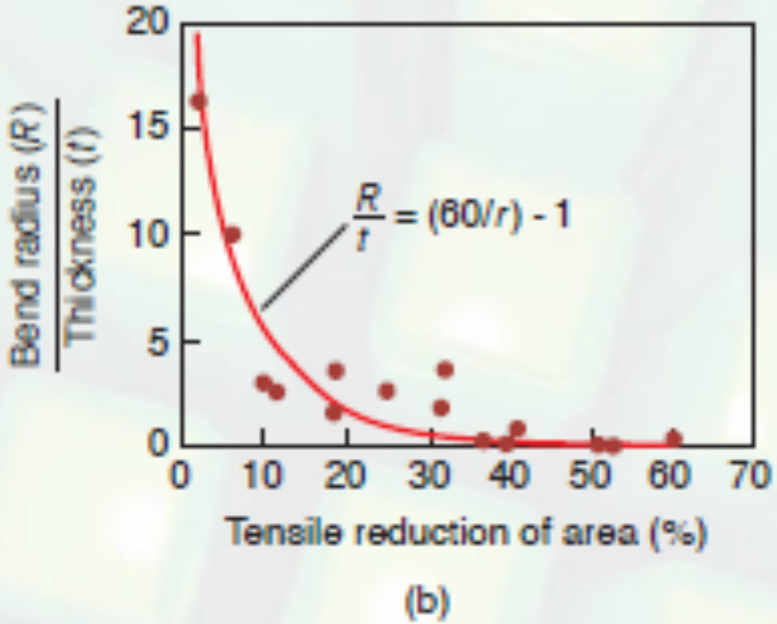
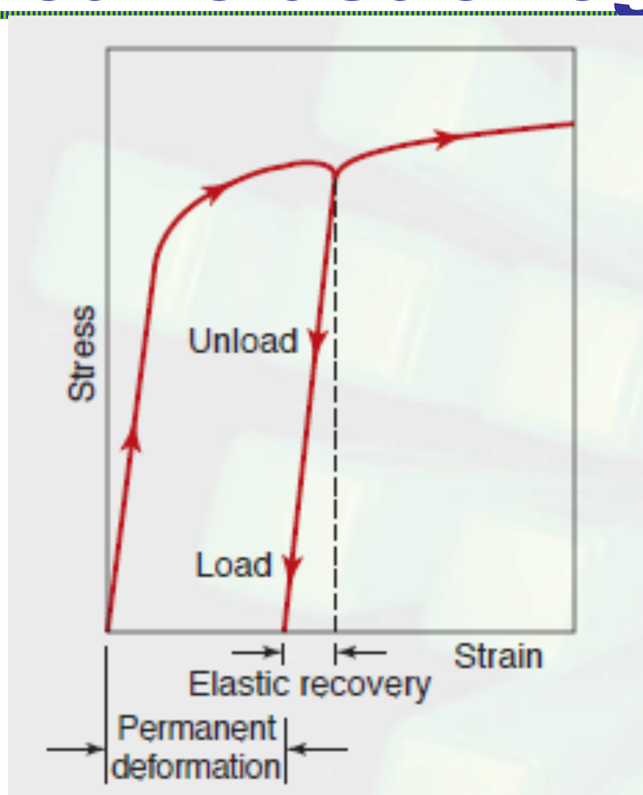


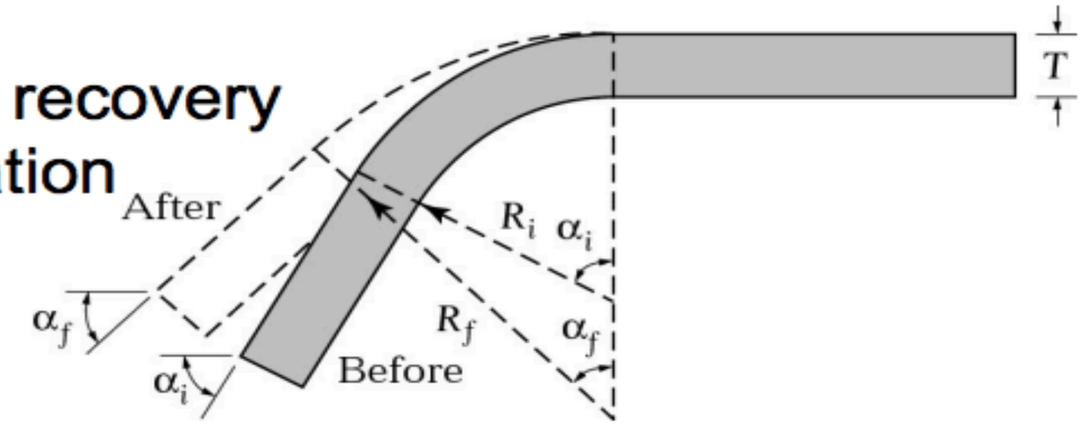
FIGURE 7.5 (a) Bending terminology. Note that the bend radius is measured to the inner surface of the bend, and that the length of the bend is the width of the sheet. (b) Relationship between the ratio of bend-radius to sheet-thickness and tensile reduction of area for a variety of materials. Note that sheet metal with a reduction of area of about 50% can be bent and flattened over itself without cracking, similar to folding paper. *Source:* After J. Datsko and C.T. Yang.

Effect of being near elastic region: Springback



- Springback is the elastic recovery following plastic deformation during bending

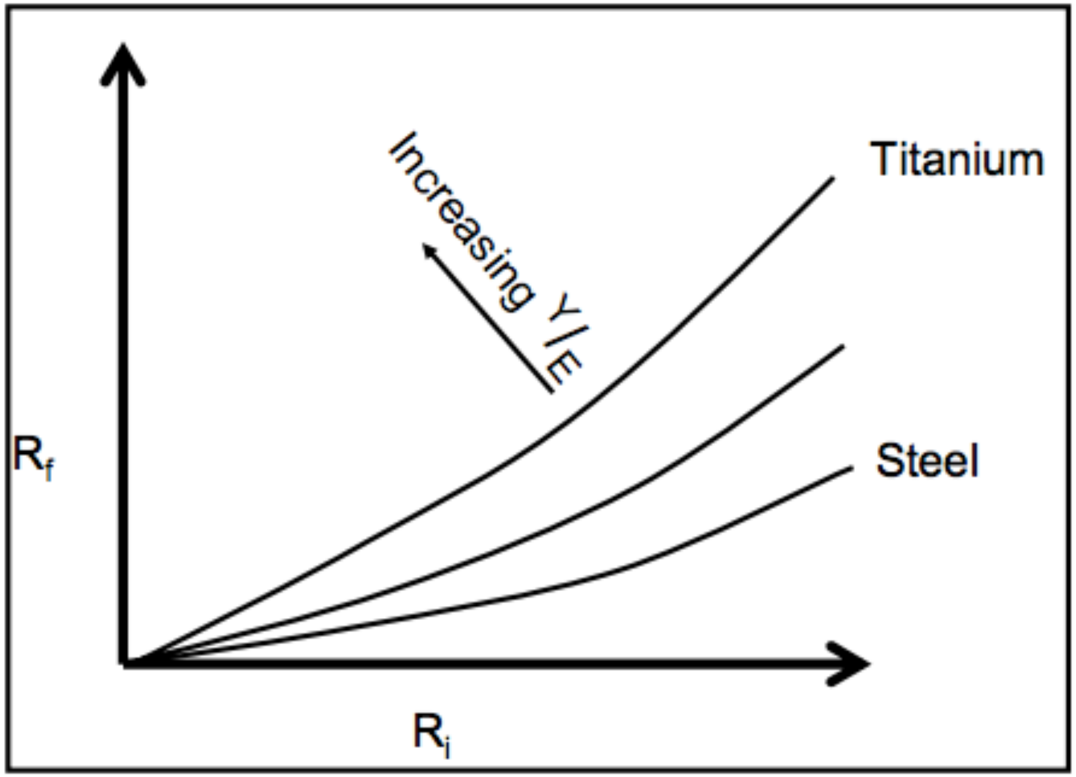
$$\frac{R_i}{R_f} = 4\left(\frac{R_i Y}{ET}\right)^3 - 3\left(\frac{R_i Y}{ET}\right) + 1$$



Springback

Elastic recovery of material leads to spring back

- **Y = Yield stress** **E = Young's Modulus** **t = thickness**
- $$\frac{R_i}{R_f} = 4\cdot\left(\frac{R_i}{t}\cdot\frac{Y}{E}\right)^3 - 3\cdot\left(\frac{R_i}{t}\cdot\frac{Y}{E}\right) + 1 \longrightarrow \frac{1}{R_i} - \frac{1}{R_f} = \frac{3}{t}\cdot\left(\frac{Y}{E}\right) - \frac{4R_i^2}{t^3}\cdot\left(\frac{Y}{E}\right)^3$$
- **With increase in R_i / t or Y OR decrease in E spring back increases**



Springback

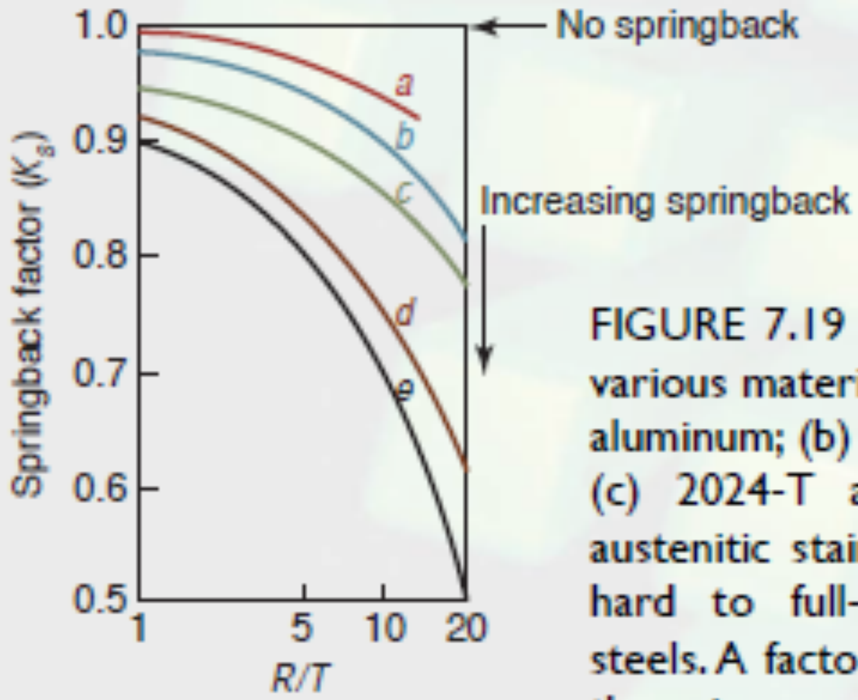


FIGURE 7.19 Springback factor, K_s, for various materials: (a) 2024-0 and 7075-0 aluminum; (b) austenitic stainless steels; (c) 2024-T aluminum; (d) 1/4-hard austenitic stainless steels; and (e) 1/2-hard to full-hard austenitic stainless steels. A factor of $K_s = 1$ indicates that there is no springback. *Source:* After G. Sachs.

Springback factor:

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

Sheet metal: Anisotropy effect

Directionality

Rolling

Sheet metal working

Anisotropy

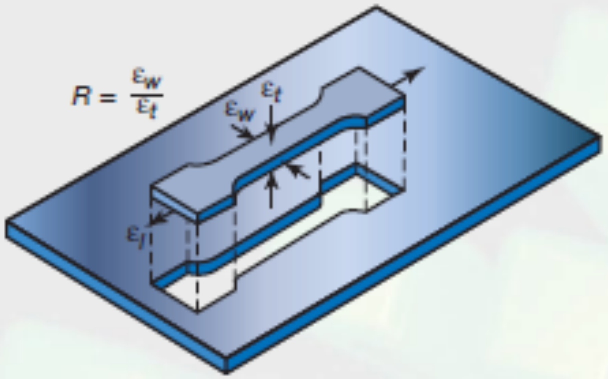


FIGURE 7.54 Definition of the normal anisotropy, R, in terms of width and thickness strains in a tensile-test specimen cut from a rolled sheet. Note that the specimen can be cut in different directions with respect to the length, or rolling direction, of the sheet.

Material	R
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

TABLE 7.3 Typical range of the average normal anisotropy ratio, $\overline{R}$, for various sheet metals.

Normal anisotropy:

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

Average anisotropy:

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

Planar anisotropy:

$$\Delta R = \frac{R_0 - 2R_{45} + R_{90}}{2}$$

Sheet metal: Anisotropy effect

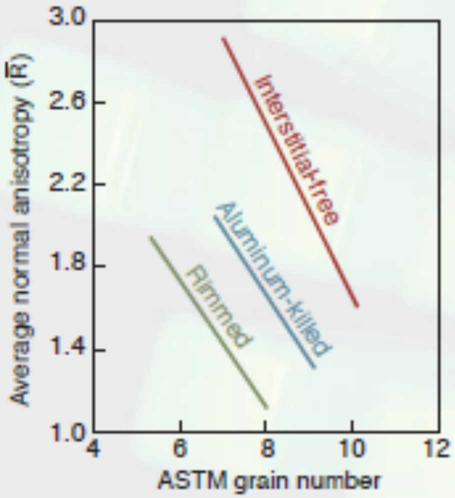


FIGURE 7.55 Effect of grain size on the average normal anisotropy for various low-carbon steels. *Source:* After D.J. Blickwede.

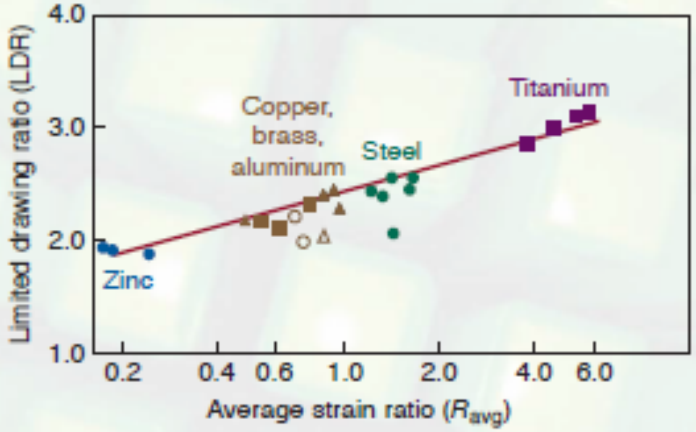


FIGURE 7.56 Effect of average normal anisotropy, $\bar{R}$ on limiting drawing ratio (LDR) for a variety of sheet metals. *Source:* After M. Atkinson.

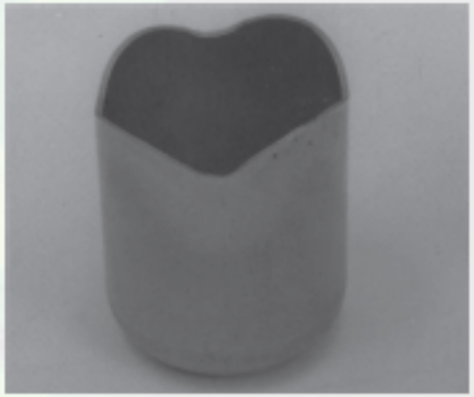


FIGURE 7.57 Typical earing in a drawn steel cup, caused by the planar anisotropy of the sheet metal.

Negative springback

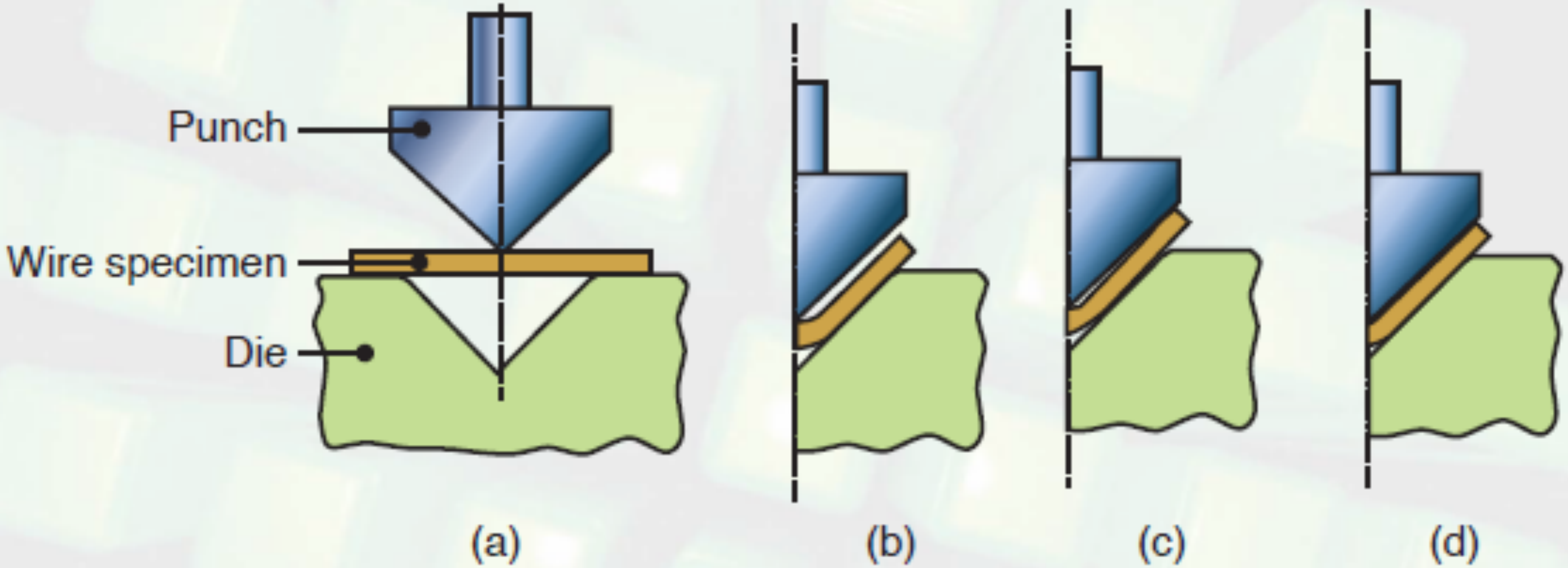


FIGURE 7.20 Schematic illustration of the stages in bending round wire in a V-die. This type of bending can lead to negative springback, which does not occur in air bending (shown in Fig. 7.24a). *Source:* After K.S. Turke and S. Kalpakjian.

Die bending operation

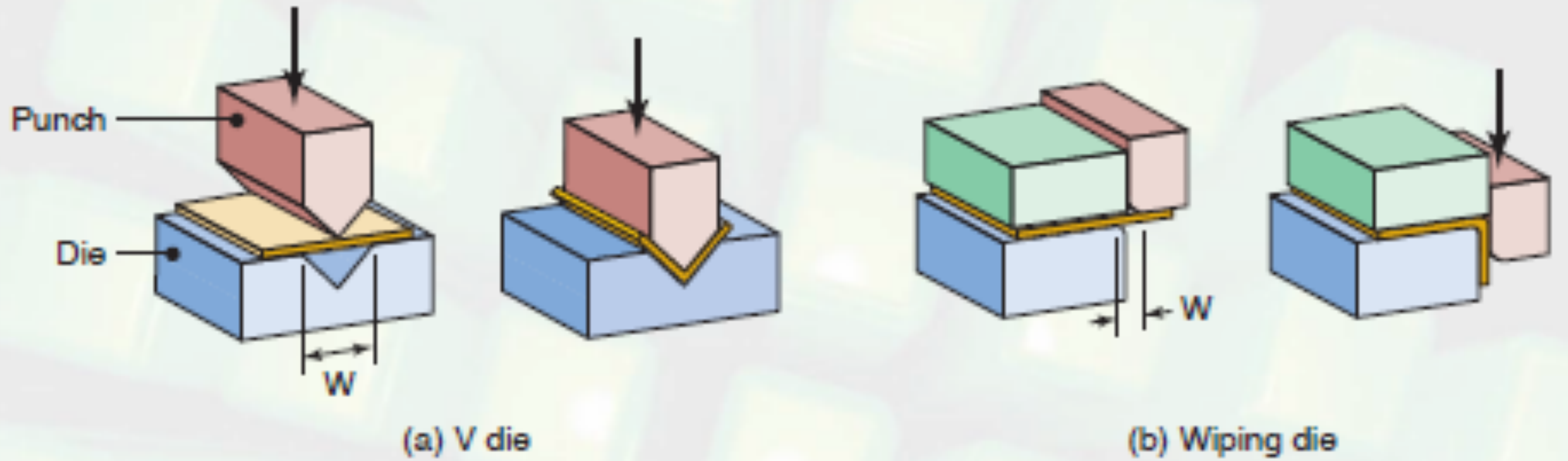


FIGURE 7.22 Common die-bending operations, showing the die-opening dimension W, used in calculating bending forces, as shown in Eq. (7.11).

Bending force:

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

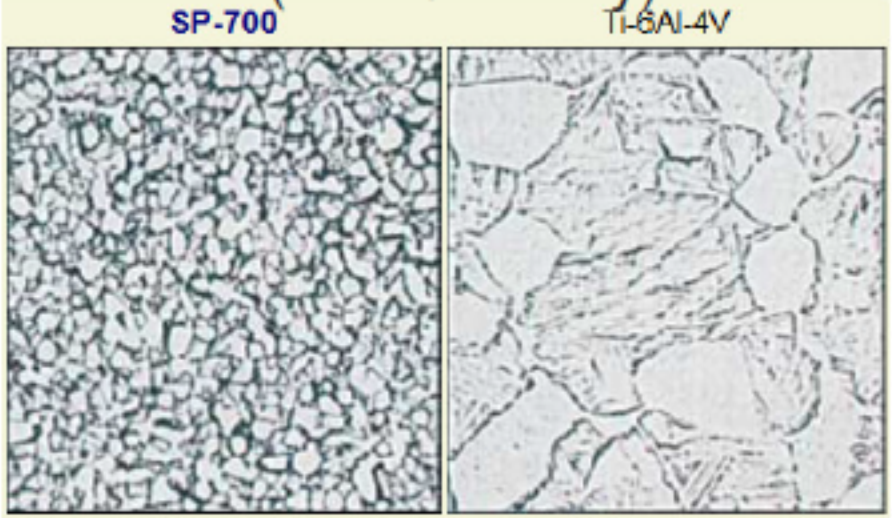
How to apply the force?

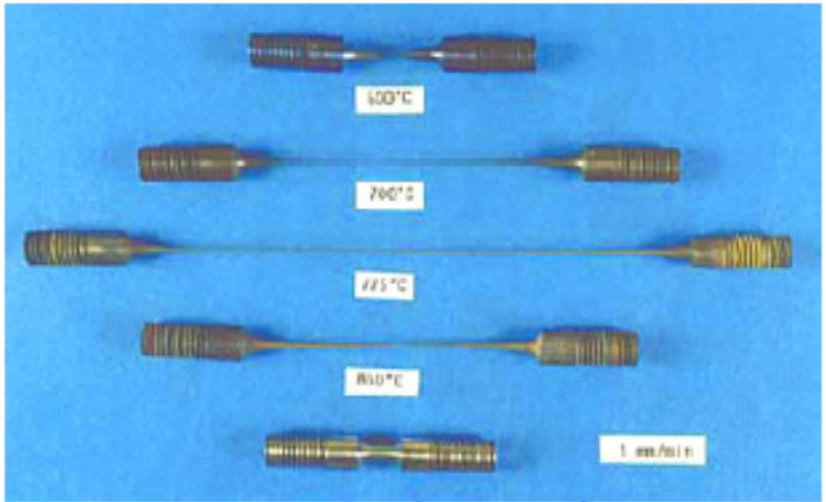
- Mechanically – push by making mechanical contact
– Using a shaped die
– Using a localized tool traversed incrementally (without mold/die)
- Using fluid pressure (with a mold/die)
- Using explosive detonated pressure waves in fluids (with a mold/die)
- Using electro-hydraulic forces (using a mold/die)
- Using magnetic pulses (using a mold/die)
- Internal forces - by inducing compressive stresses on one side of the part

Super plasticity

- Under some conditions (temp, low strain-rates, microstructure) – some materials can stretch to very long lengths without necking
- Ti alloys: 1173 K, Al-alloys: 773 K
- Strain-rates: 10^{-4} to 10^{-2} s^{-1}

(titanium alloy)

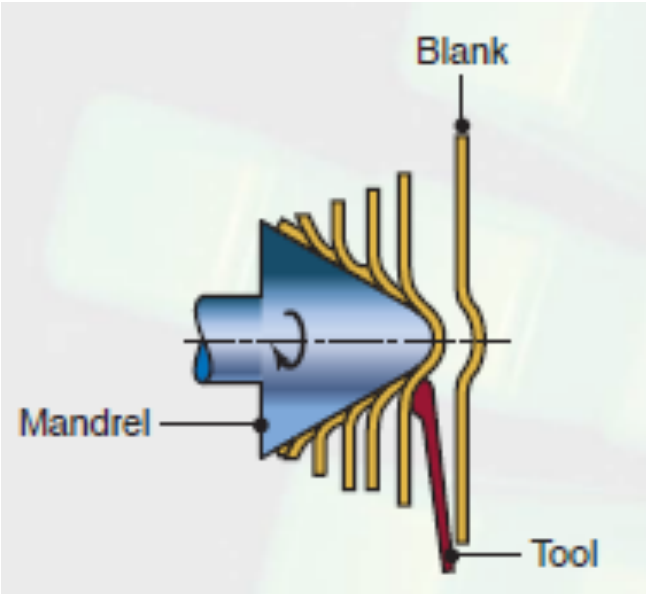




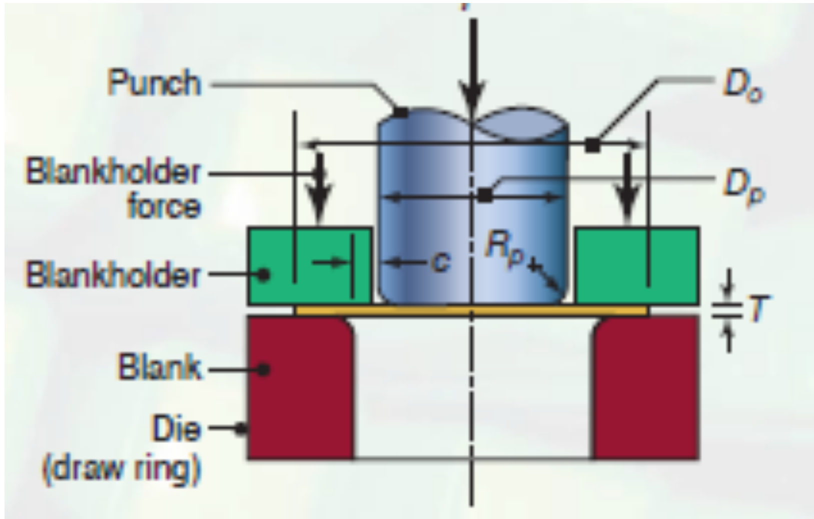
2000% elongation

Spinning and deep drawing

Spinning



Deep drawing



Spinning: Folding over a die constant t

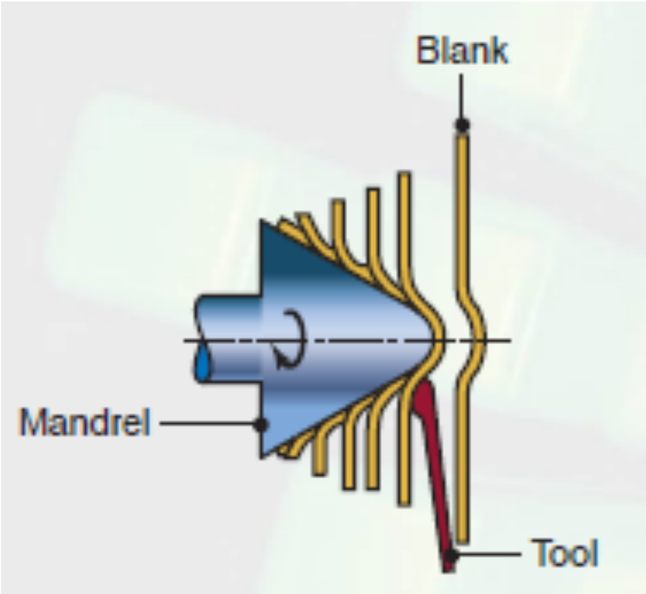
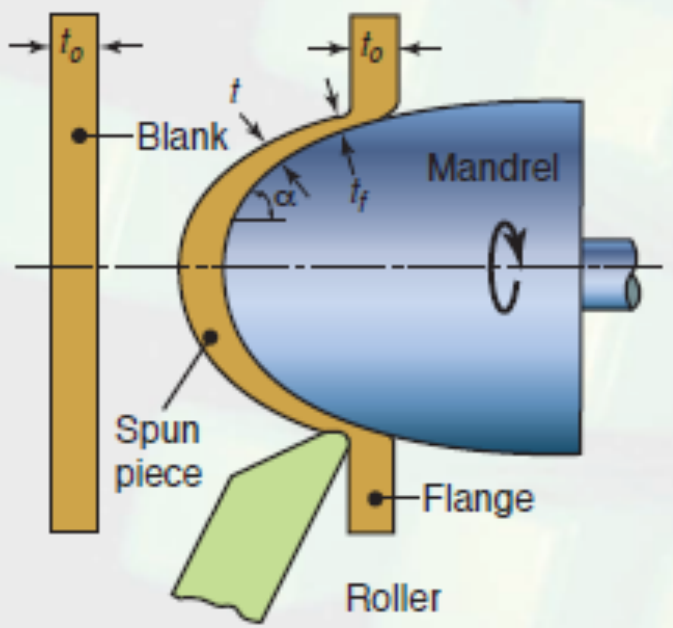
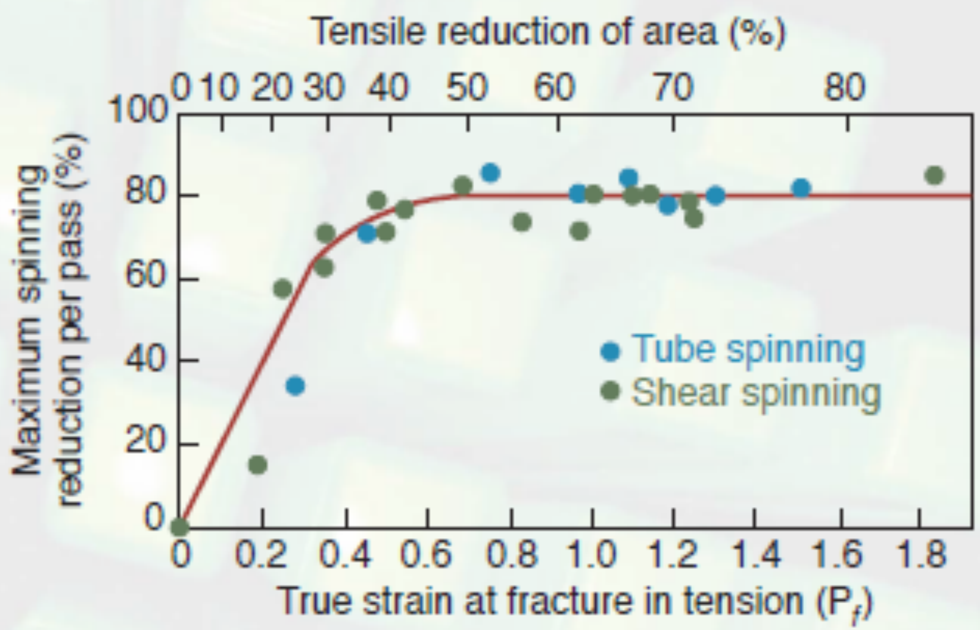


FIGURE 7.37 Typical shapes produced by the conventional spinning process. Circular marks on the external surfaces of components usually indicate that the parts have been made by spinning, such as aluminum kitchen utensils and light reflectors.

Spinnability test





Maximum spinning reduction per pass $\dfrac{t_o - t_f}{t_o} \times 100\%$

Deep drawing

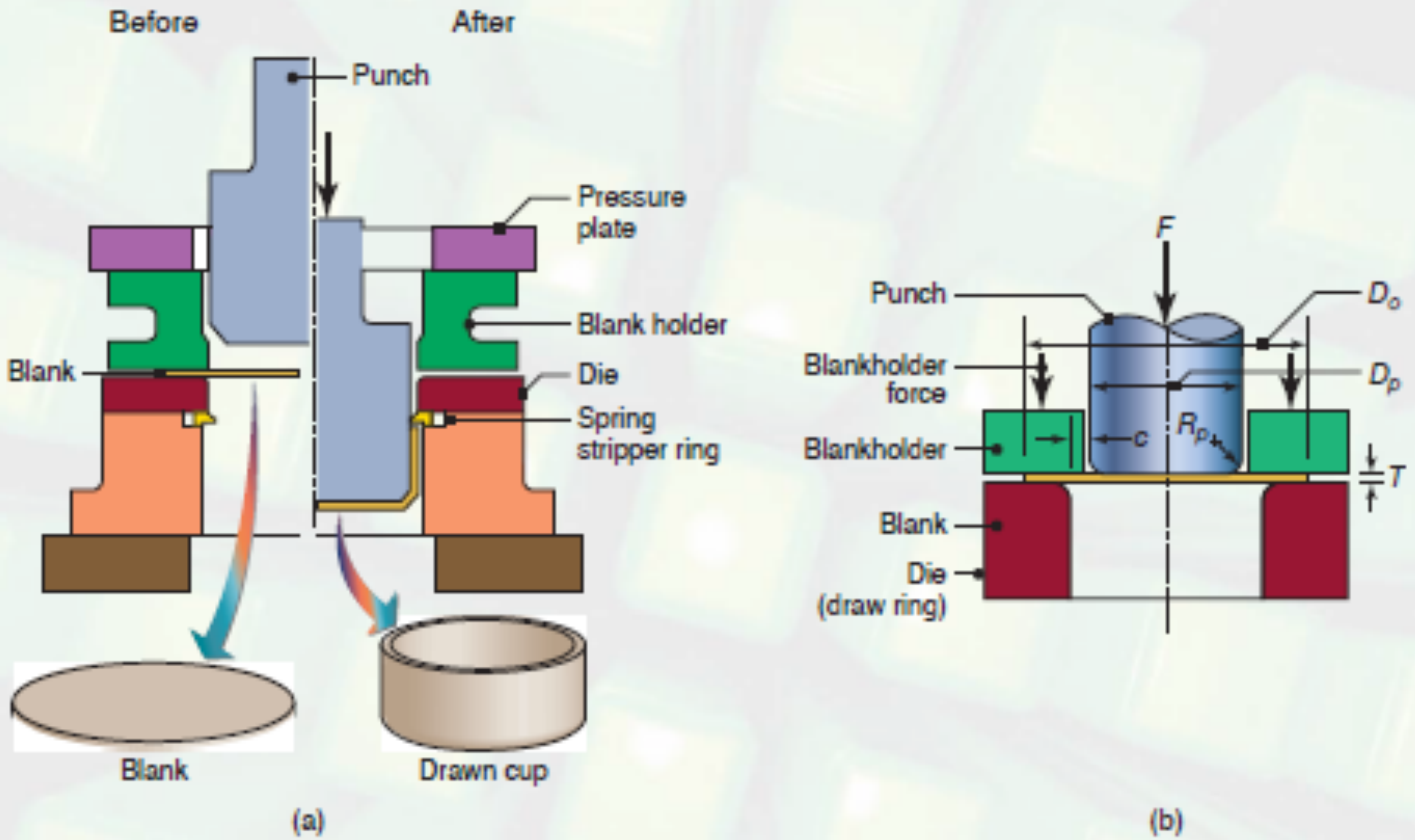


FIGURE 7.49 (a) Schematic illustration of the deep drawing process on a circular sheet-metal blank. The stripper ring facilitates the removal of the formed cup from the punch. (b) Variables in deep drawing of a cylindrical cup. Note that only the punch force in this illustration is a dependent variable; all others are independent variables, including the blankholder force.

Deformation in Flange and Wall

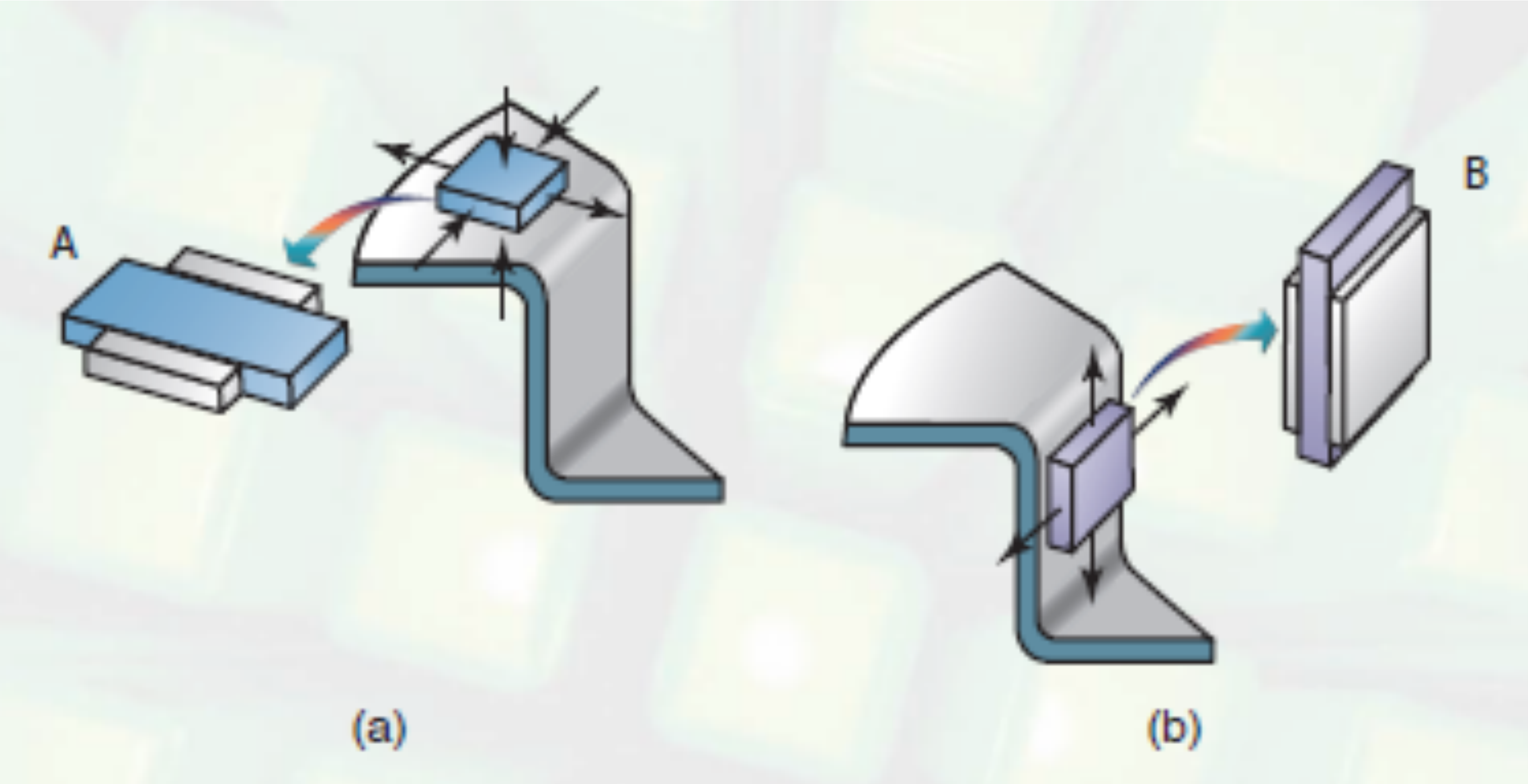


FIGURE: Deformation of elements in (a) the flange and (b) the cup wall in deep drawing of a cylindrical cup.

Pure drawing vs. pure stretching

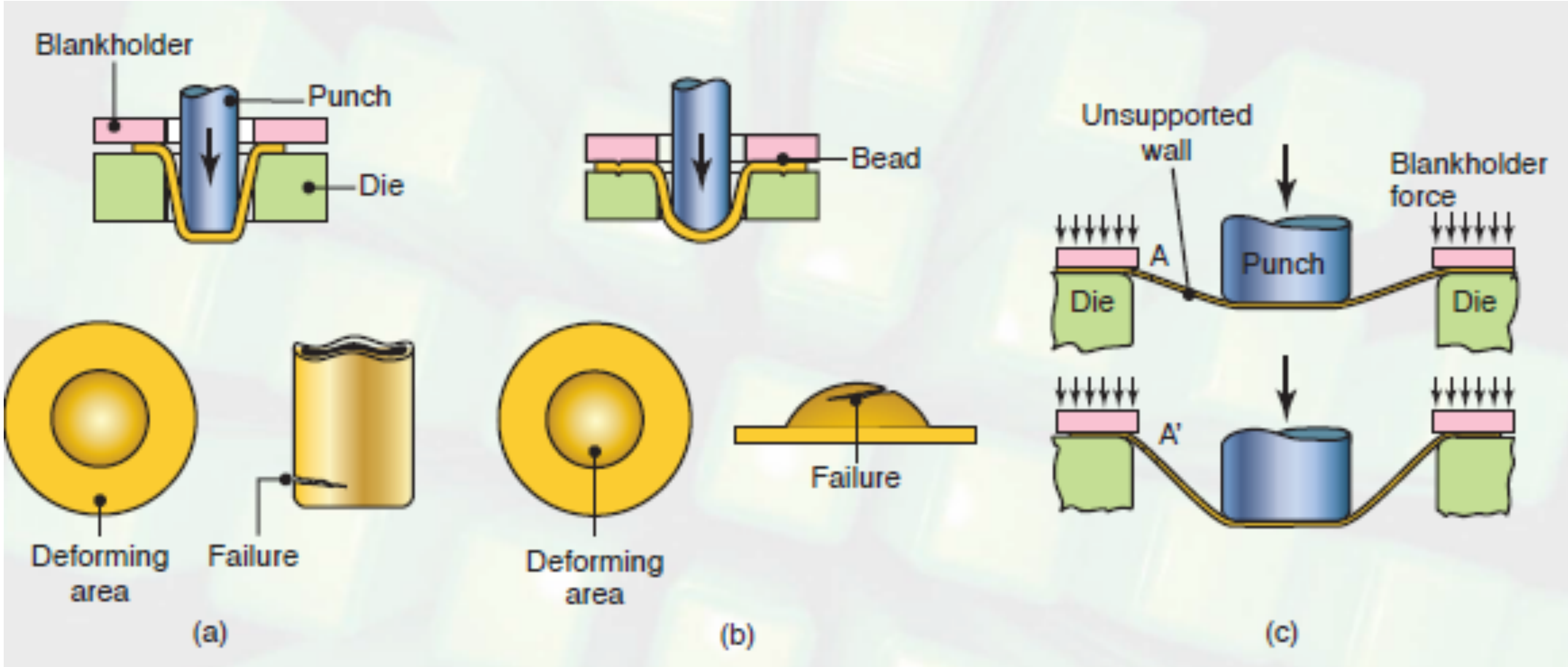


FIGURE 7.51 Examples of (a) pure drawing and (b) pure stretching; the bead prevents the sheet metal from flowing freely into the die cavity. (c) Unsupported wall and possibility of wrinkling of a sheet in drawing. Source: After W.F. Hosford and R.M. Caddell.

Draw Beads & Metal Flow

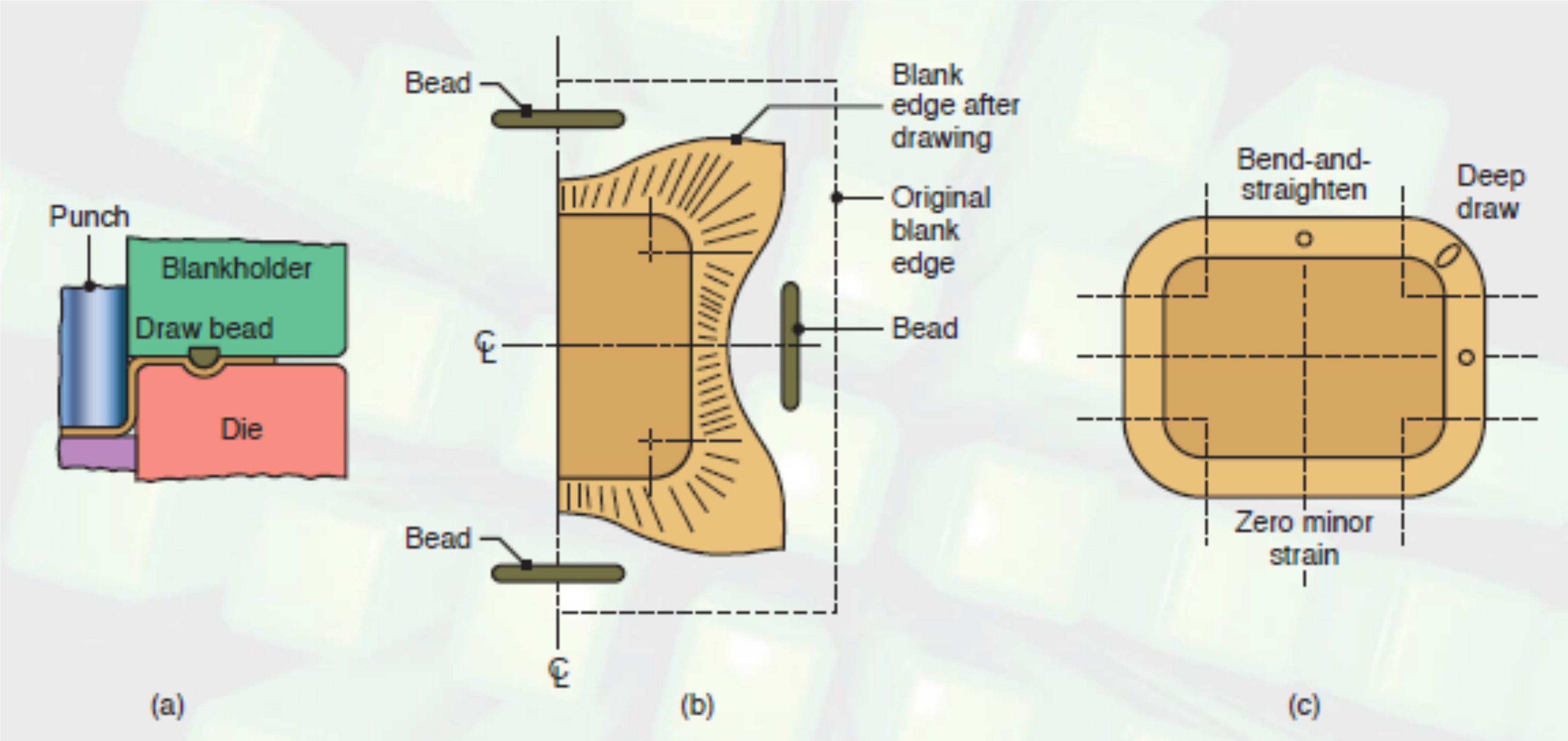


FIGURE: (a) Schematic illustration of a draw bead. (b) Metal flow during drawing of a box-shaped part, using beads to control the movement of the material. (c) Deformation of circular grids in drawing. (See Section 7.7.)

Ironing

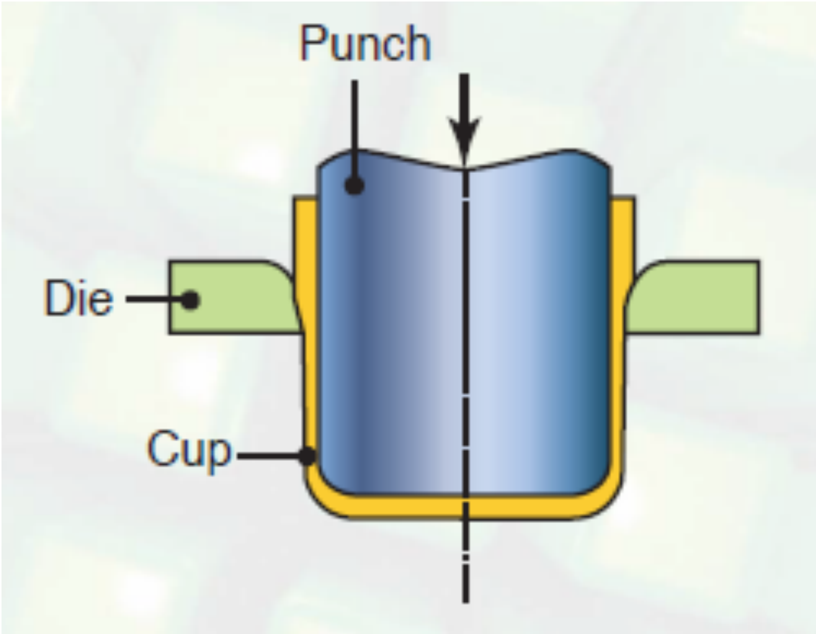
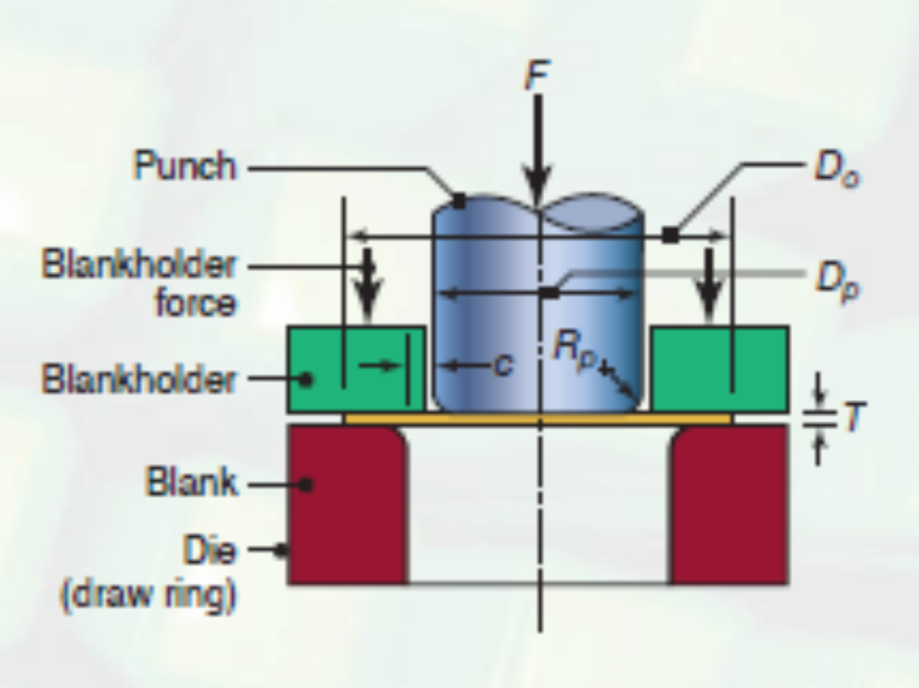


FIGURE 7.53 Schematic illustration of the ironing process. Note that the cup wall is thinner than its bottom. All beverage cans without seams (known as two-piece cans) are ironed, generally in three steps, after being deep drawn into a cup. Cans with separate tops and bottoms are known as three-piece cans.

Limiting drawing ratio



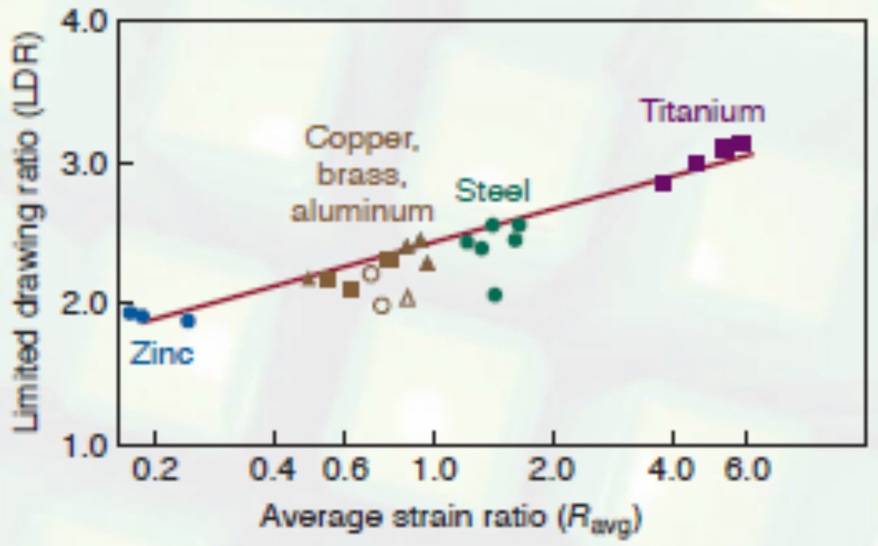


FIGURE 7.56 Effect of average normal anisotropy, $\bar{R}$ on limiting drawing ratio (LDR) for a variety of sheet metals. *Source:* After M.Atkinson.

$$LDR = \frac{D_o}{D_p}$$

Example

Estimate the limiting drawing ratio (LDR) that you would expect from a sheet metal that, when stretched by 23% in length, decreases in thickness by 10%.

Max punch force in drawing

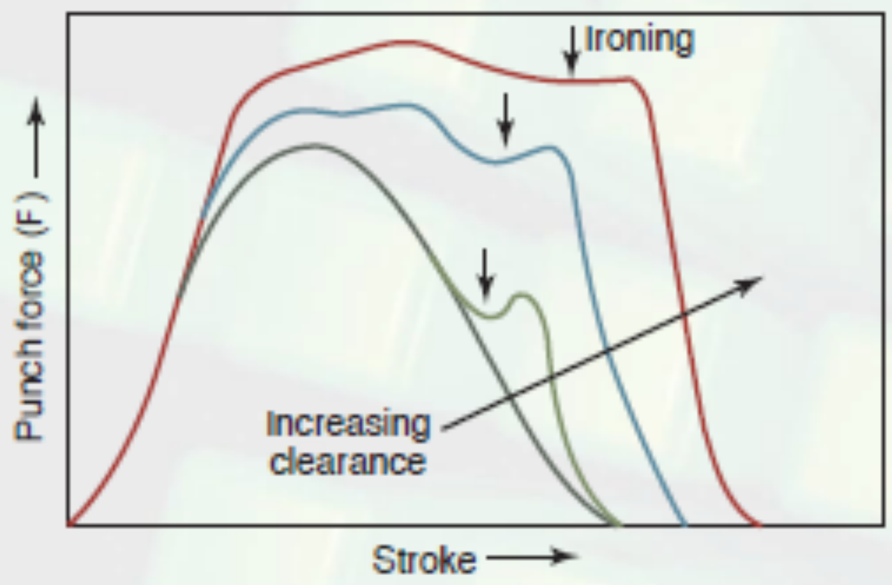


FIGURE 7.58 Schematic illustration of the variation of punch force with stroke in deep drawing. Arrows indicate the initiation of ironing. Note that ironing does not begin until after the punch has traveled a certain distance and the cup is partially formed.

Maximum punch force:

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

Effect of clearance, die/punch corner radii

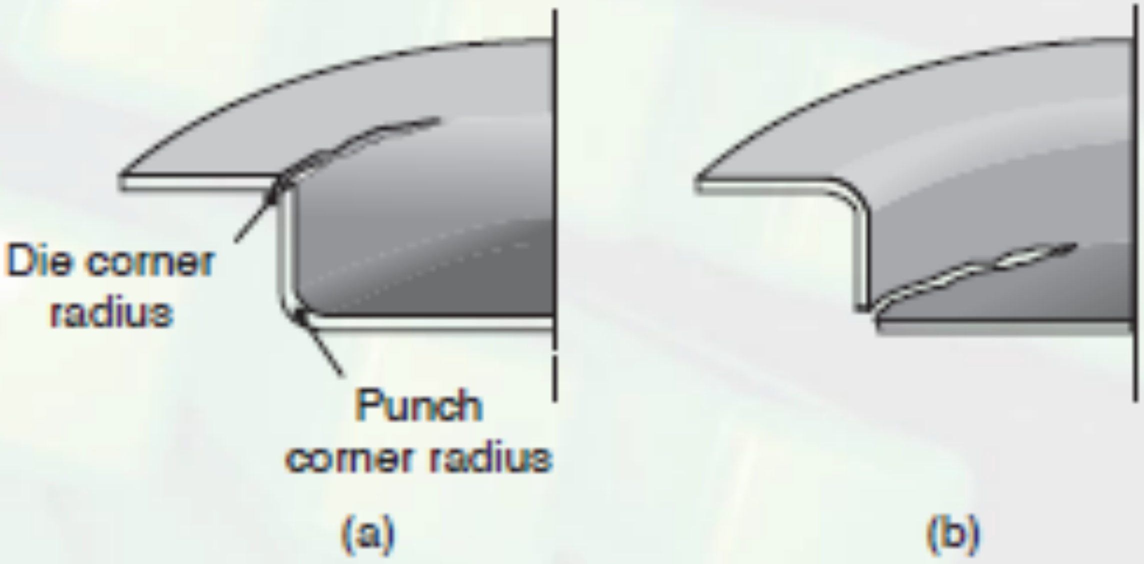


FIGURE 7.59 Effect of die and punch corner radii on fracture in deep drawing of a cylindrical cup. (a) Die corner radius too small; typically, it should be 5 to 10 times the sheet thickness. (b) Punch corner radius too small. Because friction between the cup and the punch aids in the drawing operation, excessive lubrication of the punch is detrimental to drawability.

Redrawing

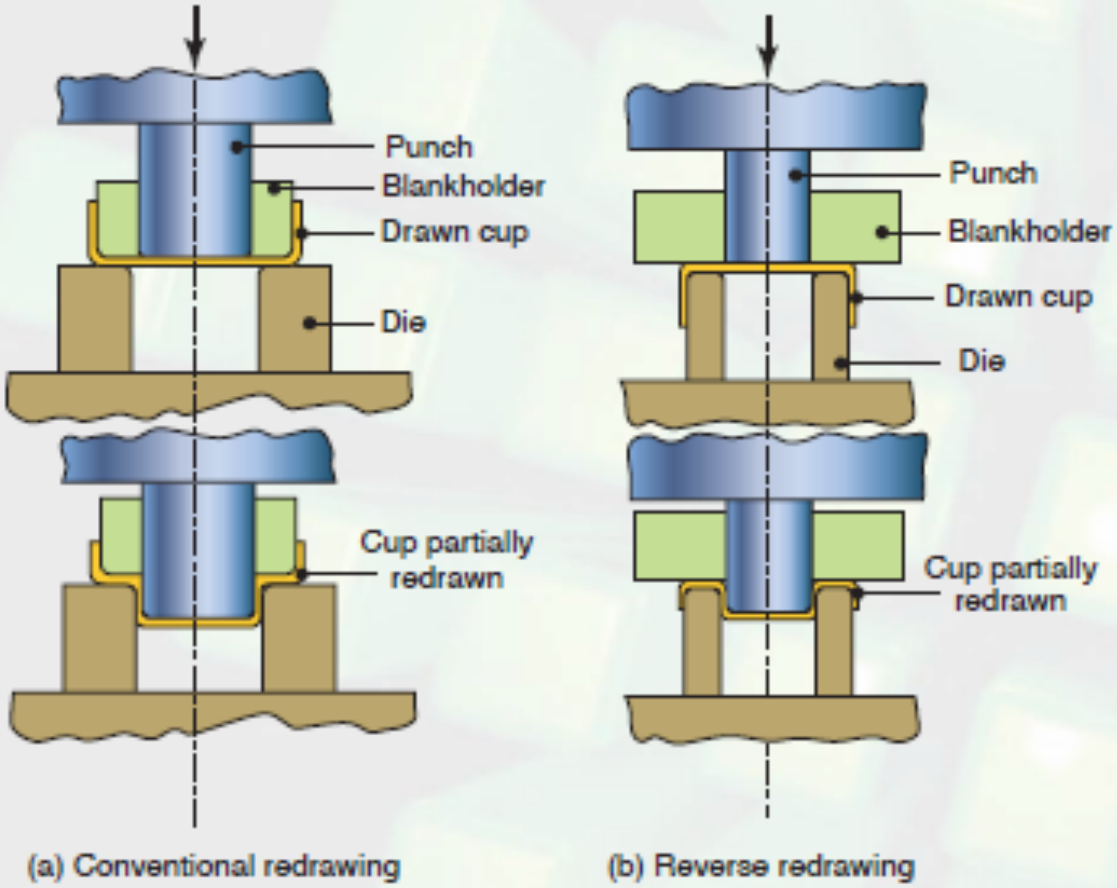


FIGURE 7.60 Reducing the diameter of drawn cups by redrawing operations: (a) conventional redrawing, and (b) reverse redrawing. Small-diameter deep containers may undergo several redrawing operations.

Drawing without a blank holder

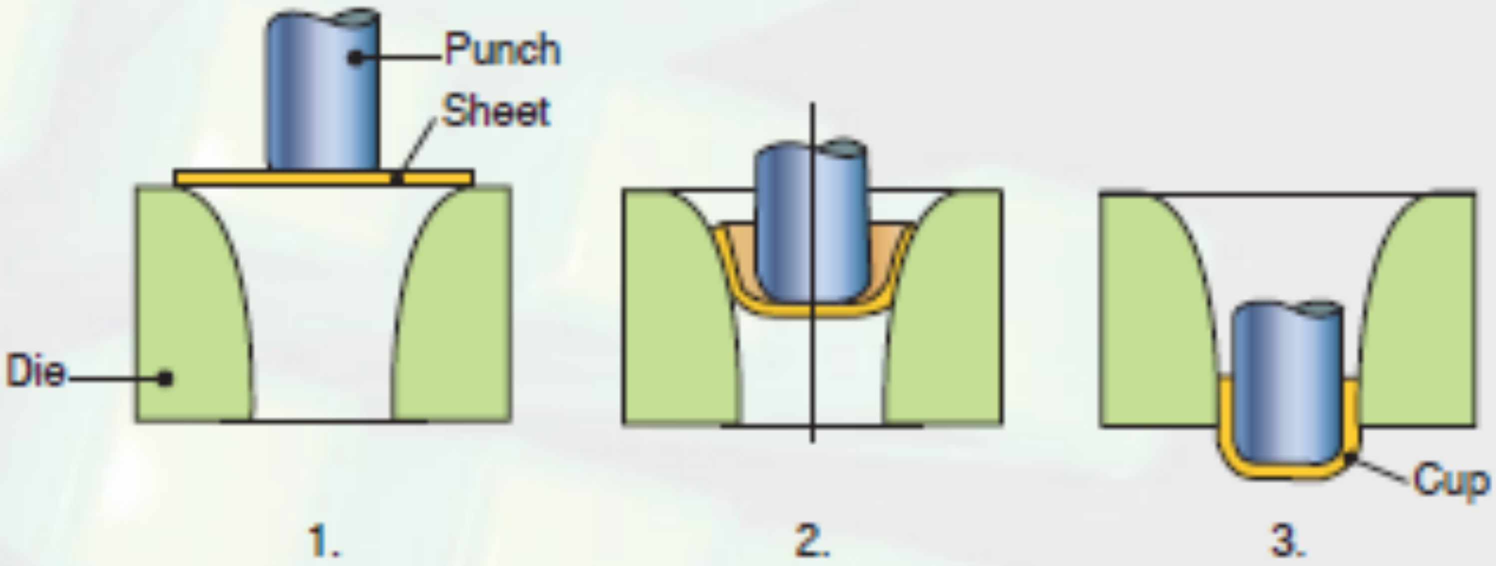
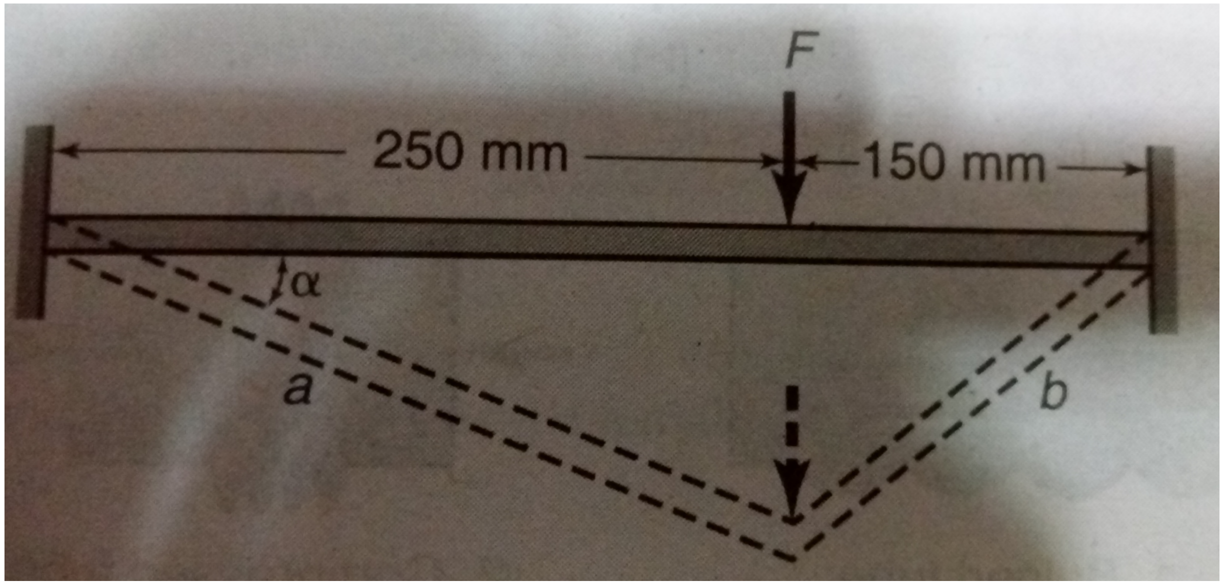


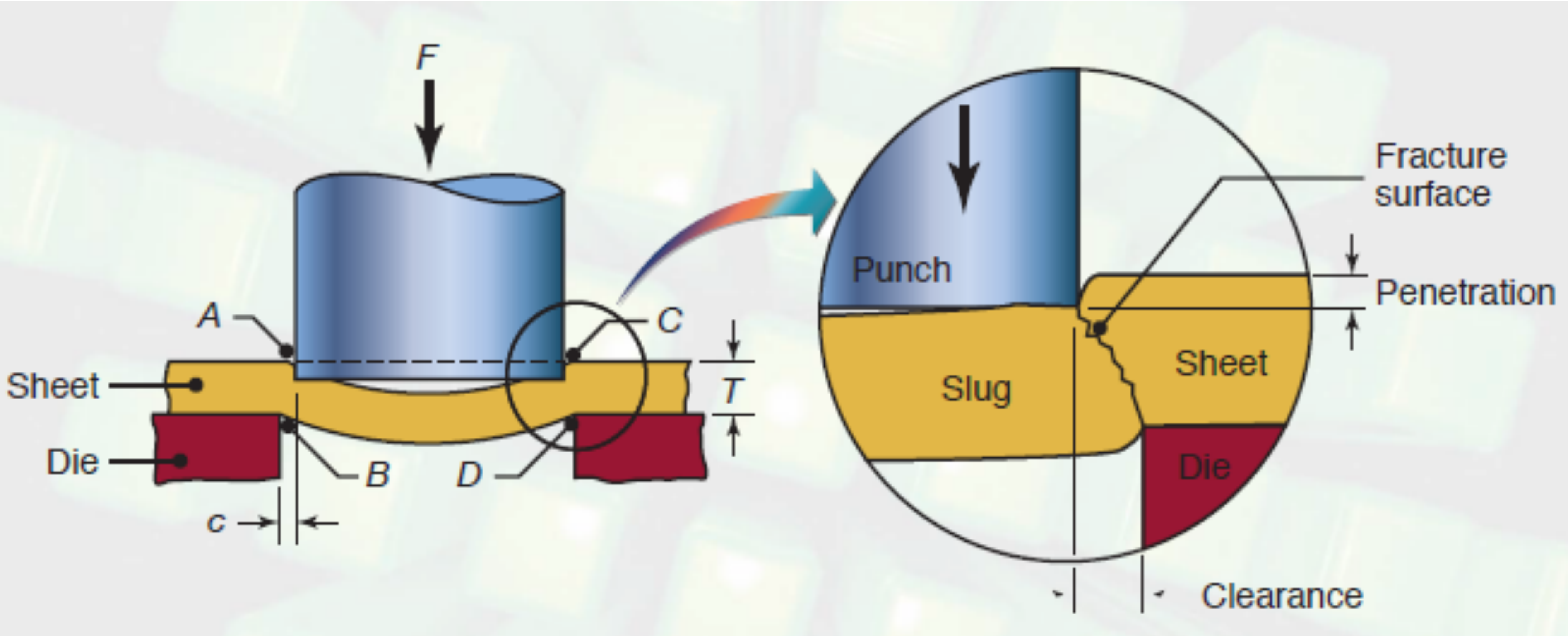
FIGURE 7.61 Stages in deep drawing without a blankholder, using a *tractrix* die profile. The tractrix is a special curve, the construction for which can be found in texts on analytical geometry or in handbooks.

Example

A 400 mm long sheet with a cross sectional area of 300 mm^2 is stretched with a force F, until α = 20 degree. The material has a strength constant of 700 MPa and strain hardening exponent of 0.3. (a) Find the total work done ignoring end effects and bending. (b) What is α_{max} before necking begins?



Deforming sheets enough to cause fracture and break



Its almost exactly like punching a hole
in a paper using a paper-punch

Hole and slug

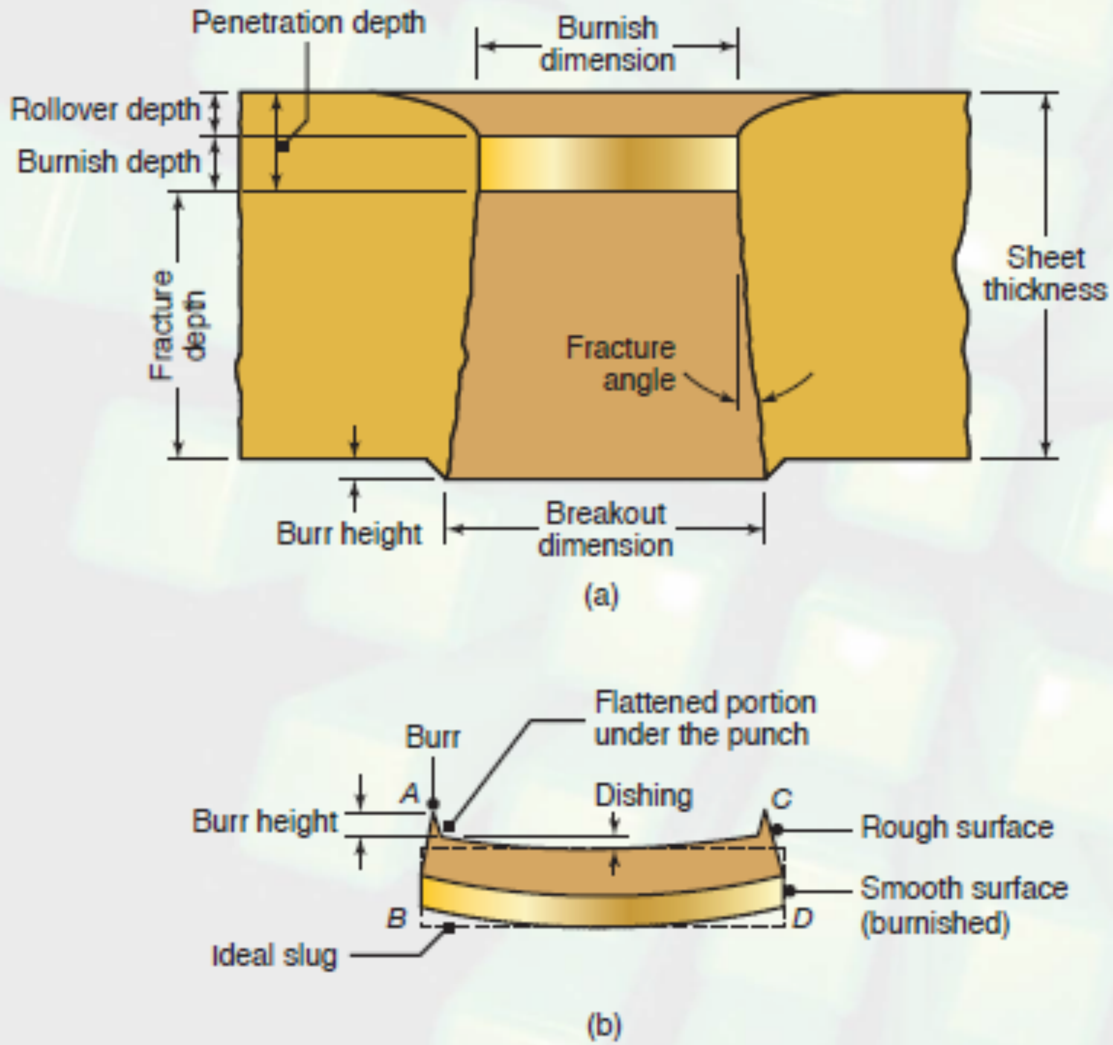


FIGURE 7.5 Characteristic features of (a) a punched hole and (b) the punched slug. Note that the slug has a different scale than the hole.

Shearing mechanics

FIGURE 7.6 a) Effect of clearance, c, on the deformation zone in shearing. Note that, as clearance increases, the material tends to be pulled into the die, rather than being sheared. (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.

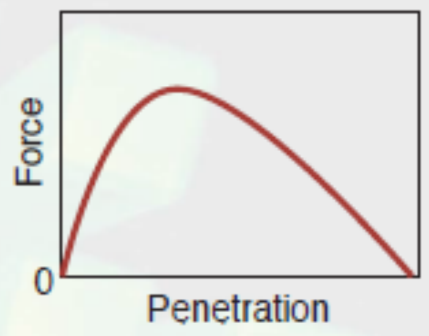


FIGURE 7.7 Typical punch force vs. penetration curve in shearing. The area under the curve is the work done in shearing. The shape of the curve depends on processing parameters and material properties.