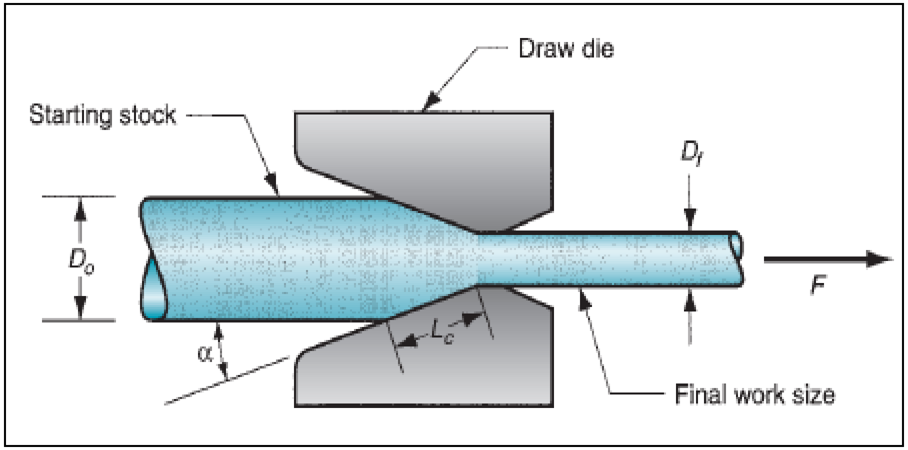
Wire, rod, bar drawing

- In this bulk forming process, a wire, rod, bar are pulled through a die hole reducing their cross-section area.



Wire, rod, bar drawing

Difference between wire drawing and rod drawing:

Initial stock size:

- The basic difference between bar drawing and wire drawing is the stock size that is used for forming. Bar drawing is meant for large diameter bar and rod, while wire drawing is meant for small diameter stock. Wire sizes of the order of 0.03 mm are produced in wire drawing.

Operating stages:

- Bar drawing is generally done as a single stage operation, in which stock is pulled through one die opening. The inlet bars are straight and not in the form of coil, which limits the length of the work that can be drawn. This necessitates a batch type operation.

- In contrast, wire is drawn from coils consisting of several hundred meters of wire and is drawn through a series of dies. The number of dies varies between 4 and 12. This is termed as ‘continuous drawing’ because of the long production runs that are achieved with the wire coils. The segments can be butt-welded to the next to make the operation truly continuous.

Simple analysis of wire drawing

True strain in wire drawing under ideal deformation (no friction and redundant work) is given by,

$$\varepsilon = \ln\left(\frac{A_0}{A_f}\right) = \ln\left(\frac{1}{1-r}\right)$$

Here $r = (A_0 - A_f) / A_0$

Under ideal deformation, the stress required in wire drawing is given by,

$$\sigma_d = \bar{Y}_f \ln\left(\frac{A_0}{A_f}\right)$$

Here $\bar{Y}_f = \frac{K\varepsilon^n}{1+n}$, $\bar{Y}_f$ is the average flow stress corresponding to ε mentioned in above equation.

In order to consider the effect of die angle and friction coefficient on the drawing stress, Schey has proposed another equation as shown below:

$$\sigma_d = \bar{Y}_f \left(1 + \frac{\mu}{\tan\alpha}\right) \phi \ln\left(\frac{A_0}{A_f}\right)$$

Here ϕ is a term that accounts for inhomogeneous deformation which is found by the following eqn. for round cross-section.

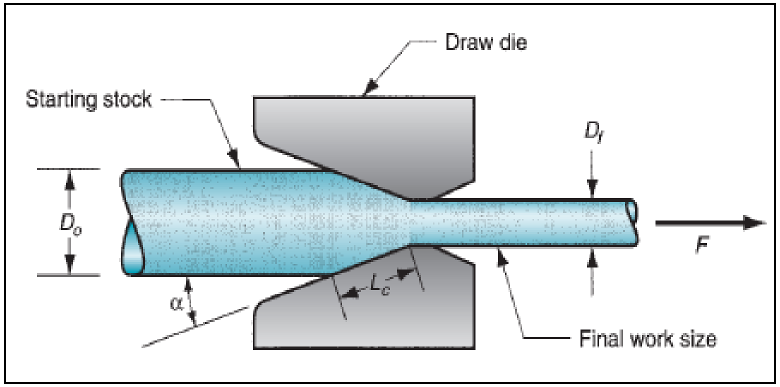
$$\phi = 0.88 + 0.12\frac{D}{L_c}$$

Here D is the average diameter of the workpiece, L_C is the contact length of the work with die given by,

$$D = \frac{D_0 + D_f}{2};\; L_C = \frac{D_0 - D_f}{2\sin\alpha}$$

Finally the drawing force is given by, $F = A_f \sigma_d$

The power required for drawing is given by multiplying drawing force with exit velocity of the workpiece



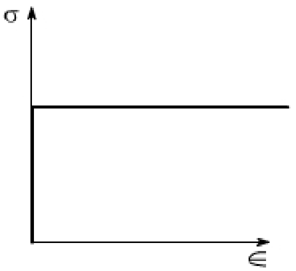
Wire is drawn through a draw die with entrance angle 15°. Starting diameter is 2.5 mm and final diameter 2 mm. The coefficient of friction at the work–die interface is 0.07. The metal has a strength coefficient K = 205 MPa and a strain-hardening exponent n = 0.2. Determine the draw stress and draw force in this operation.

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

Maximum reduction per pass

Increase in reduction, increase the draw stress. If the reduction is large enough, draw stress will exceed the yield strength of the material. Then the wire will just elongate rather than new material being drawn into the die hole. To have a successful wire drawing operation, drawing stress should be less than yield strength of the drawn metal.

Assume a perfectly plastic material (n = 0), no friction and redundant work, then,



$$\sigma_d = \bar{Y}_f \ln\left(\frac{A_0}{A_f}\right) = Y \ln\left(\frac{A_0}{A_f}\right) = Y \ln\left(\frac{1}{1-r}\right) = Y$$

which means that

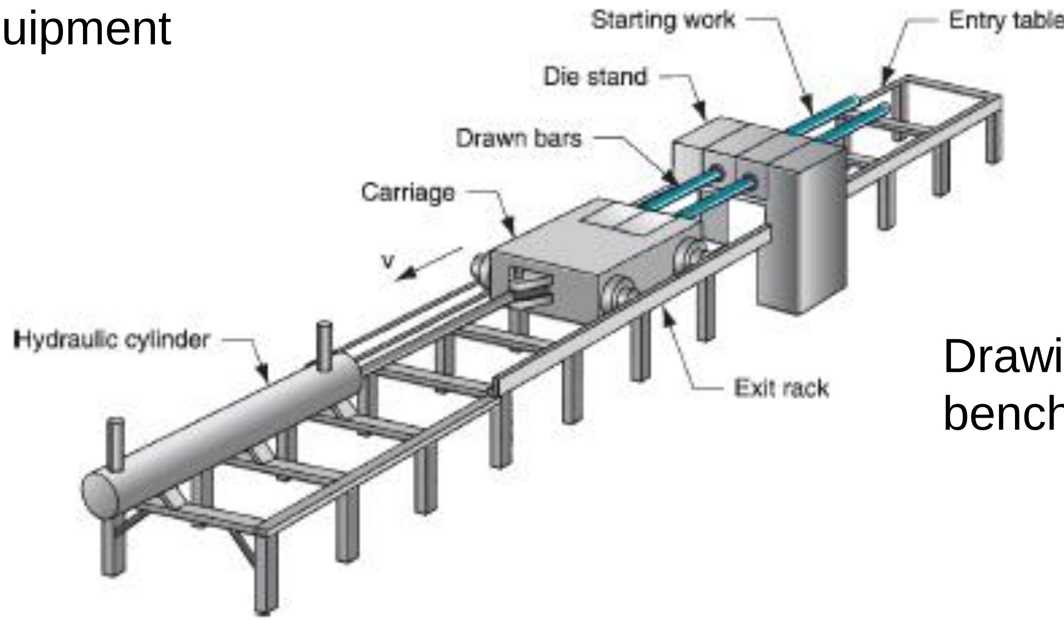
$$\ln\left(\frac{A_0}{A_f}\right) = \ln\left(\frac{1}{1-r}\right) = 1$$

This gives a condition that the maximum possible reduction, r_{max} is

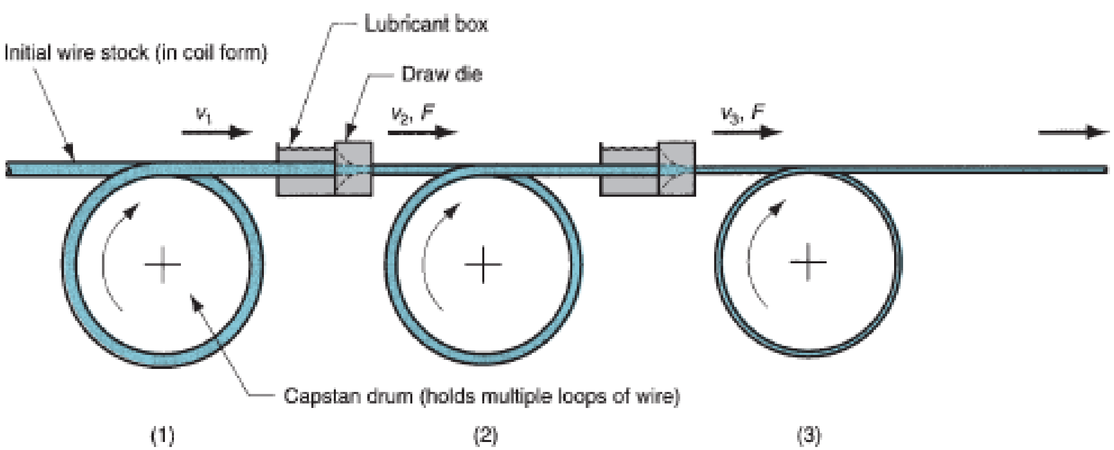
r_{max} **= *0.632*** (theoretical maximum limit)

This analysis ignores the effects of friction and redundant work, which would further reduce the maximum value, and strain hardening, which would increase the maximum reduction because of the stronger wire than the starting metal. **Reductions of 0.5-0.3 per pass seem to be possible in industrial operations.**

Drawing equipment

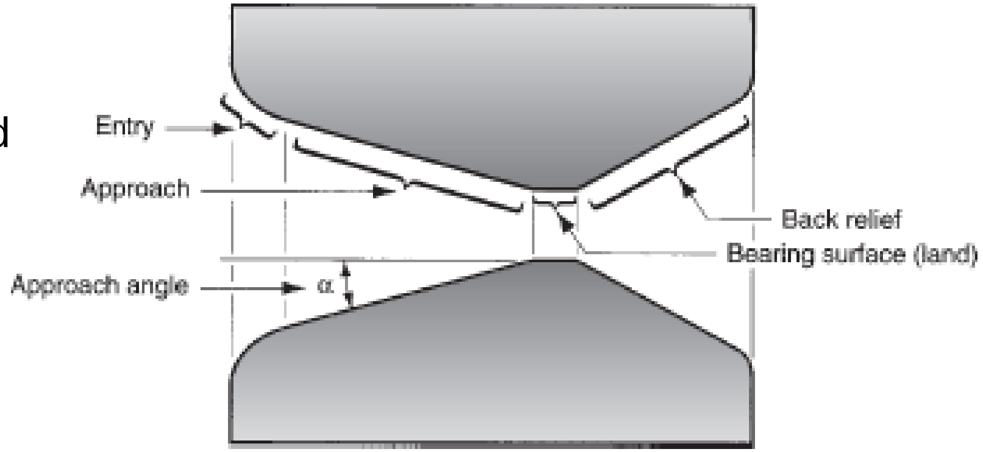


Drawing bar by draw bench



Continuous drawing of wire

Drawing dies



The entry region is generally a bell-shaped mouth that does not contact the work-piece. Its function is to contain and push the lubricant into the die and prevent wearing of work and die surfaces

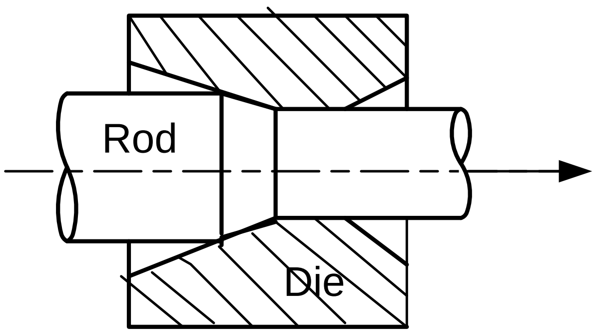
The approach region is where the drawing operation occurs. It is cone-shaped with an angle (half-angle) normally ranging from 6° to 20°.

The bearing surface or land, determines the size of the final drawn work-piece.

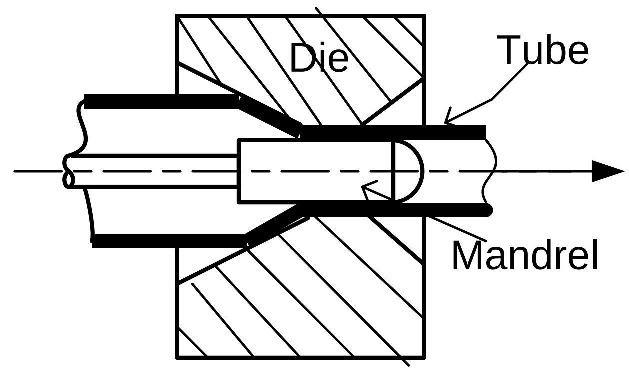
Finally, the back relief is the exit zone. It is provided with a back relief angle (half-angle) of about 25-30°.

Tube drawing

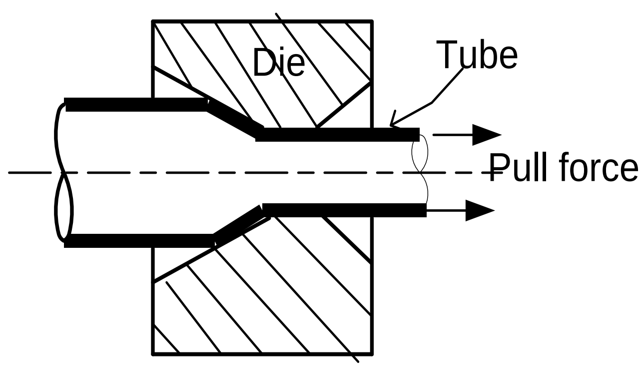
This operation is used to reduce the diameter or wall thickness of the seamless tubes and pipes. Tube drawing can be done either with or without mandrel. **The simplest method uses no mandrel and is used for diameter reduction called as tube sinking.** But inside diameter and wall thickness cannot be controlled. So mandrel is required.



(a) Rod drawing

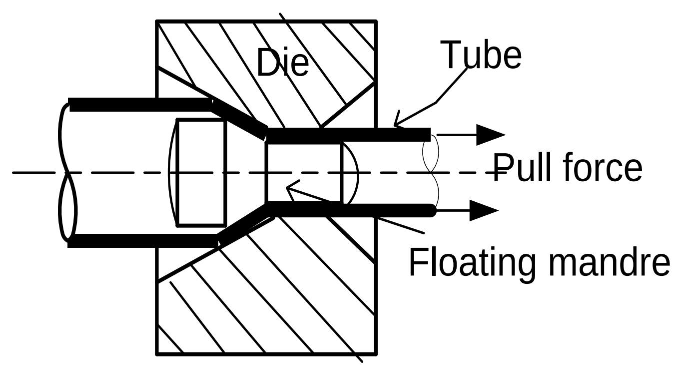


(c) Tube drawing with fixed mandrel



(b) Tube drawing without mandrel

(TUBE SINKING)



(d) Tube drawing with floating mandrel

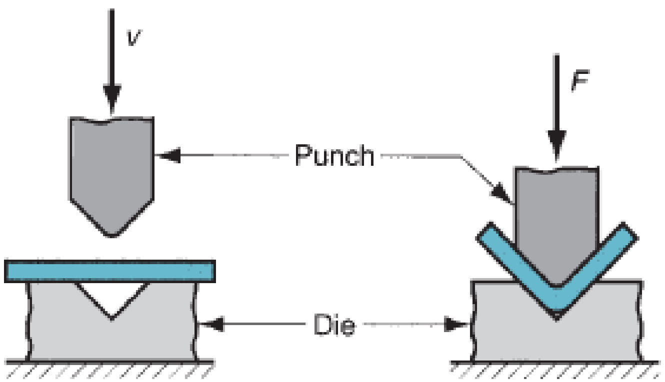
Using a fixed mandrel: In this case, a mandrel is attached to a long support bar to control the inside diameter and wall thickness during the operation. The length of the support bar restricts the length of the tube that can be drawn.

Using a floating plug: As the name suggests the mandrel floats inside the tube and its shape is designed so that it finds a suitable position in the reduction zone of the die. There is no length restriction in this as seen with the fixed mandrel.

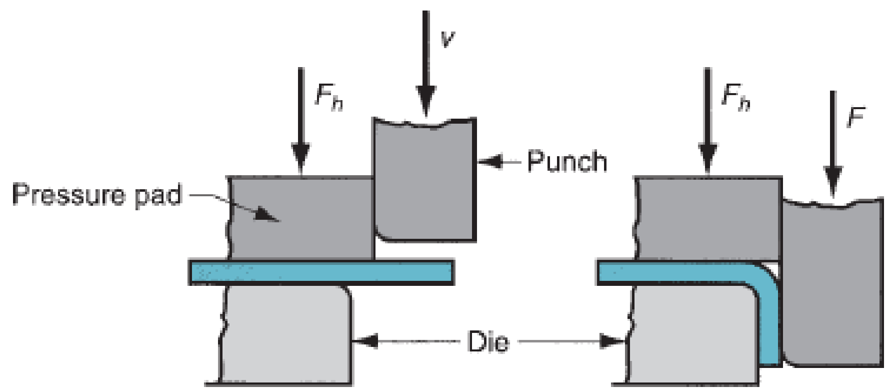
Sheet forming operations

Sheet forming:

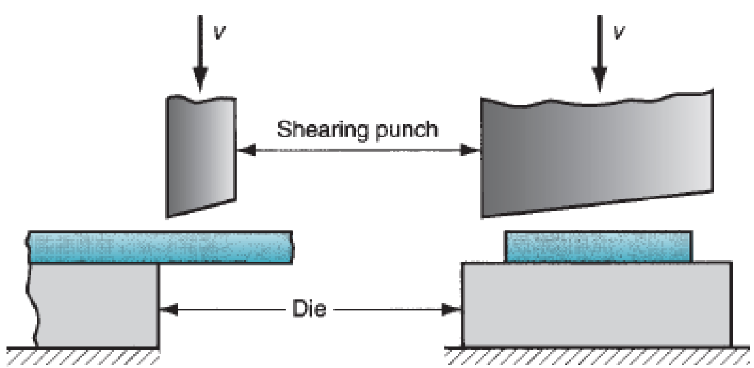
Involves plastic deformation of sheets like deep drawing, cutting, bending, hemming, flanging, curling, stretch forming/stretching, stamping etc.



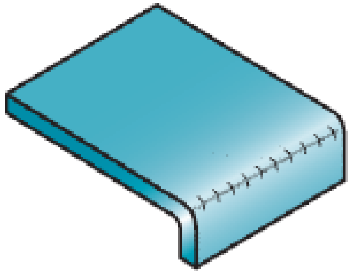
V-bending



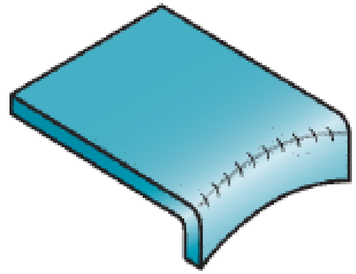
Edge bending



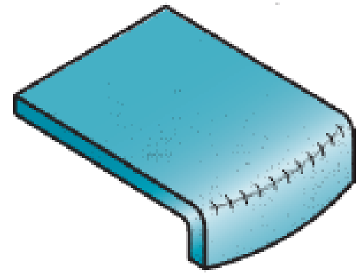
shearing



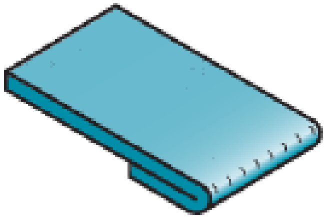
Straight flanging



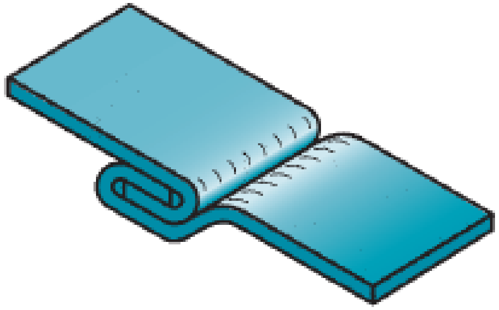
stretch flanging



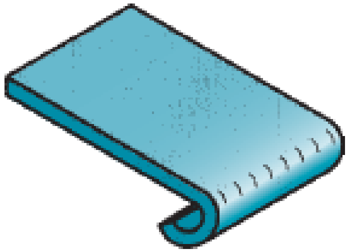
shrink flanging



Hemming



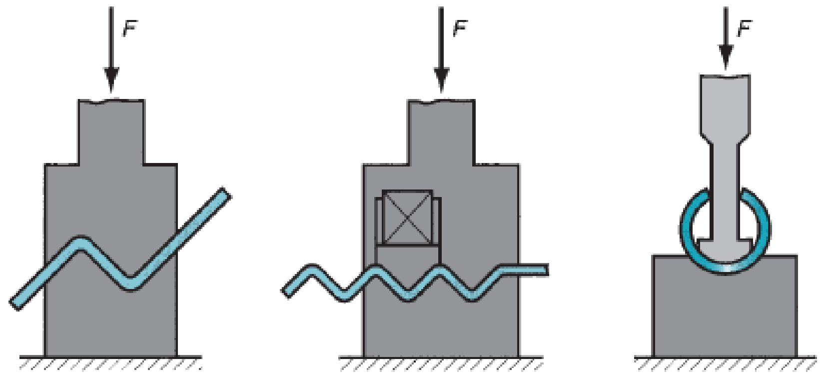
seaming



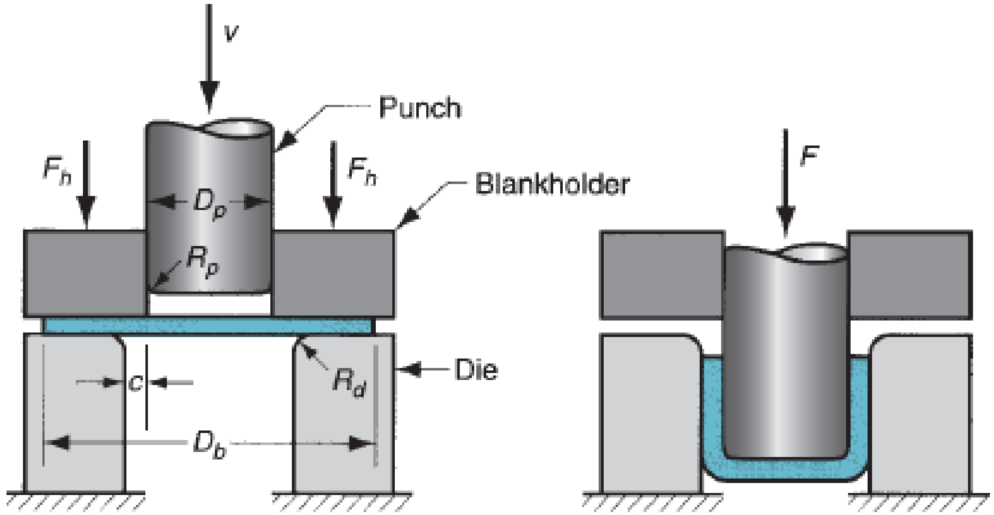
curling

R. Ganesh Narayanan, IITG

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed



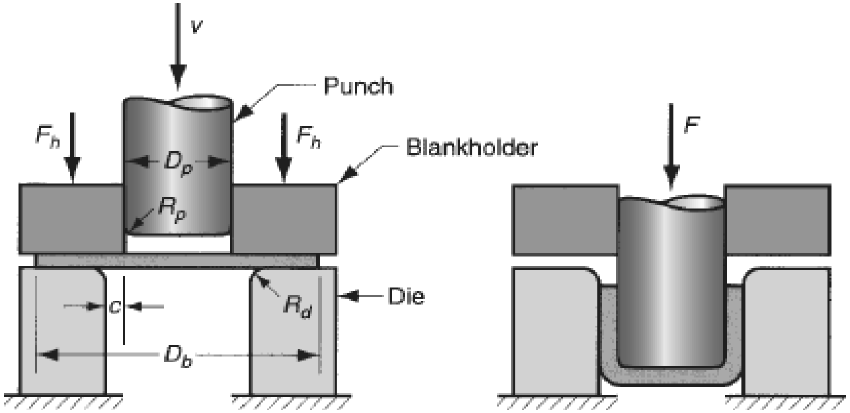
Other bending operations



Cup deep drawing

Cup deep drawing

It is a sheet forming operation, in which the sheet is placed over the die opening and is pushed by punch into the opening. The sheet is held flat on the die surface by using a blank holder.



c – clearance
D_b – blank diameter
D_p – punch diameter
R_d – die corner radius
R_p – punch corner radius
F – drawing force
F_h – holding force

The clearance '*c*' is defined to equal to 10% more than the sheet thickness '*t*'. If the clearance between the die and the punch is less than the sheet thickness, then ironing occurs.

$$c = 1.1t$$

Stages in deep drawing:

(i) As the punch pushes the sheet, it is subjected to a bending operation. Bending of sheet occurs over the punch corner and die corner. The outside perimeter of the blank moves slightly inwards toward the cup center.

(ii) In this stage, the sheet region that was bent over the die corner will be straightened in the clearance region at this stage, so that it will become cup wall region. In order to compensate the presence of sheet in cup wall, more metal will be pulled from the sheet edge, i.e., more metal moves into the die opening.

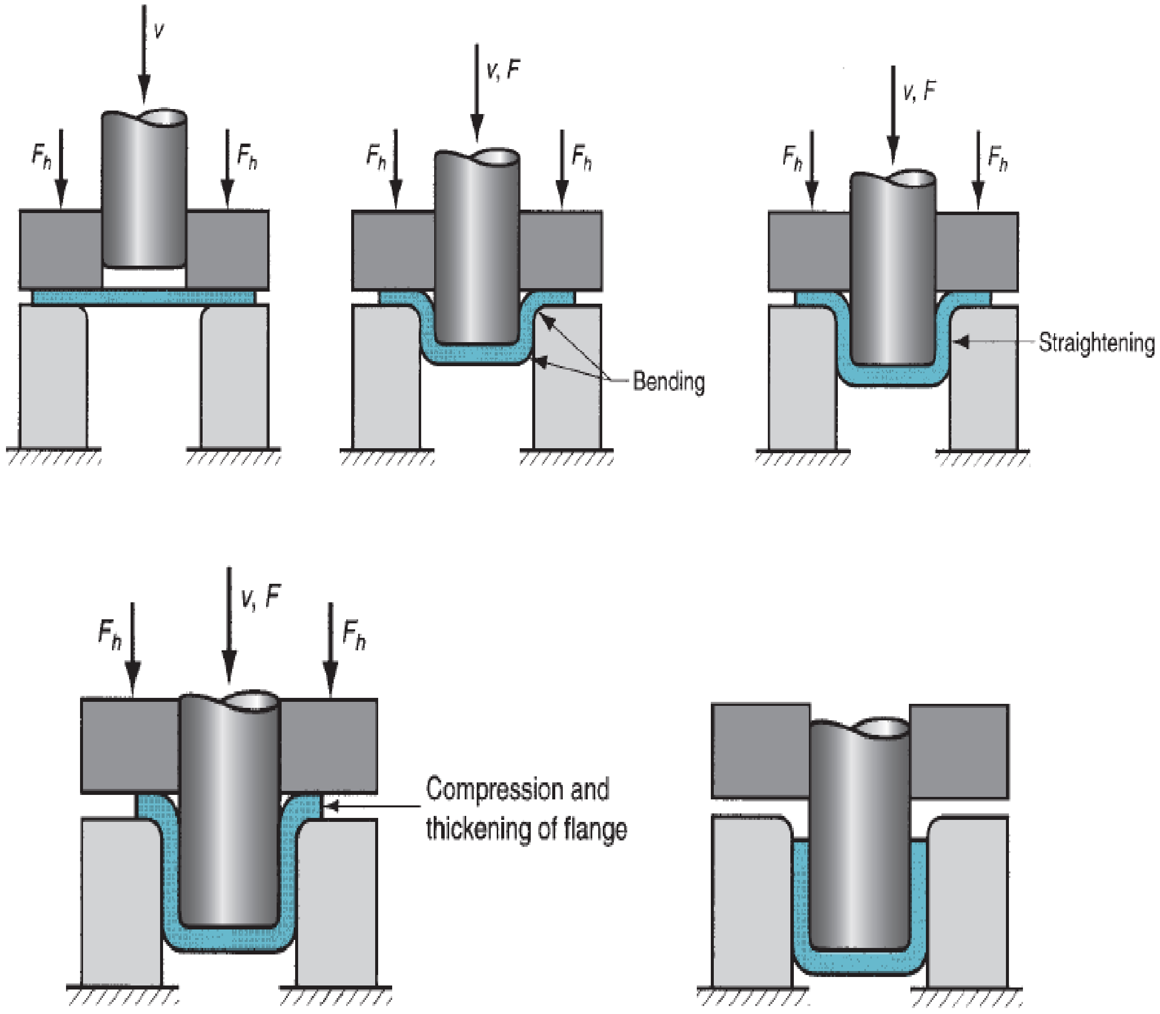
(iii) Friction between the sheet and the die, blank holder surfaces restricts the movement of sheet into the die opening. The blank holding force also influences the movement. Lubricants or drawing compounds are generally used to reduce friction forces.

(iv) Other than friction, compression occurs at the edge of the sheet. Since the perimeter is reduced, the sheet is squeezed into the die opening. Because volume remains constant, with reduction in perimeter, thickening occurs at the edge.

In thin sheets, this is reflected in the form of wrinkling. This also occurs in case of low blank holding force. If BHF very small, wrinkling occurs. If it is high, it prevents the sheet from flowing properly toward the die hole, resulting in stretching and tearing of sheet.

(v) The final cup part will have some thinning in side wall.

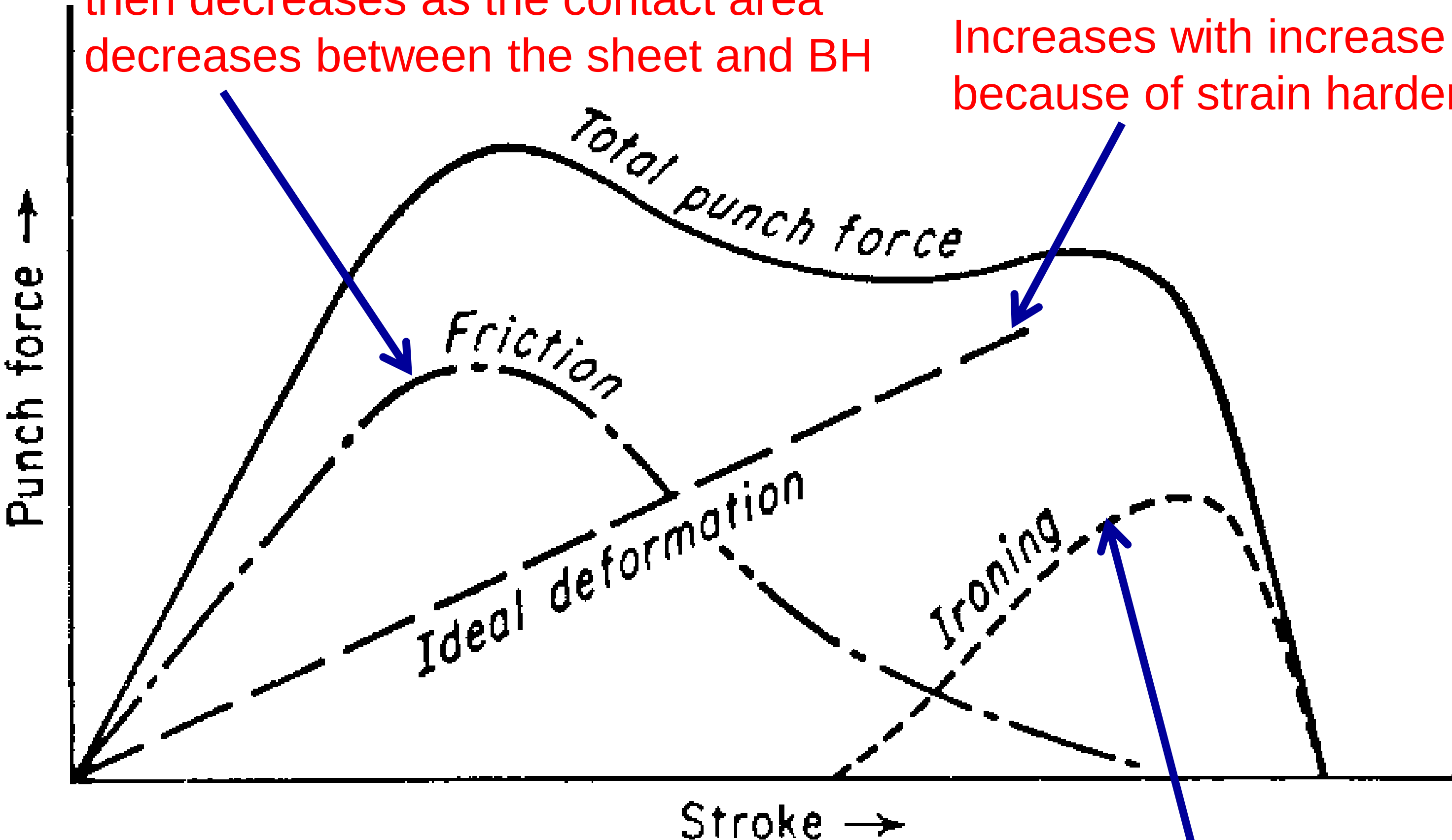
M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed



Stages in cup deep drawing

Friction force reaches peak early and then decreases as the contact area decreases between the sheet and BH

Increases with increase in strain because of strain hardening



Punch force-stroke for cup deep drawing: contribution from three important factors

Ironing occurs late in the process once the cup wall has reached the maximum thickness

G.E.Dieter, *Mechanical Metallurgy*

Quantification of cup drawability

Drawing ratio: ratio of blank diameter, D_b, to punch diameter, $D_{p.}$ The greater the ratio, the more severe the drawing operation.

$$DR = \frac{D_b}{D_P}$$

The limiting value for a given operation depends on punch and die corner radii, friction conditions, draw depth, and quality of the sheet metal like ductility, degree of directionality of strength properties in the metal.

Reduction, R, is defined as, $$R = \frac{D_b - D_P}{D_b}$$

Limiting values: $DR \leq 2$; $R \leq 0.5$

Thickness to diameter ratio, $t/D_b > 1\%$;

As the ratio decreases, tendency for wrinkling increases.

The maximum drawing force, F , can be estimated approximately by the following equation .

$$F = \pi D_p t \sigma_{UTS} \left(\frac{D_b}{D_p} - 0.7 \right)$$

Correction factor for friction

The holding force, F_h, is given by,

$$F_h = 0.015 \sigma_{ys} \pi \left\{ D_b^{\,2} - \left(D_p + 2.2t + 2R_d \right)^2 \right\}$$

$$F_h = \frac{F}{3}$$ (approx. holding force is one-third of drawing force)

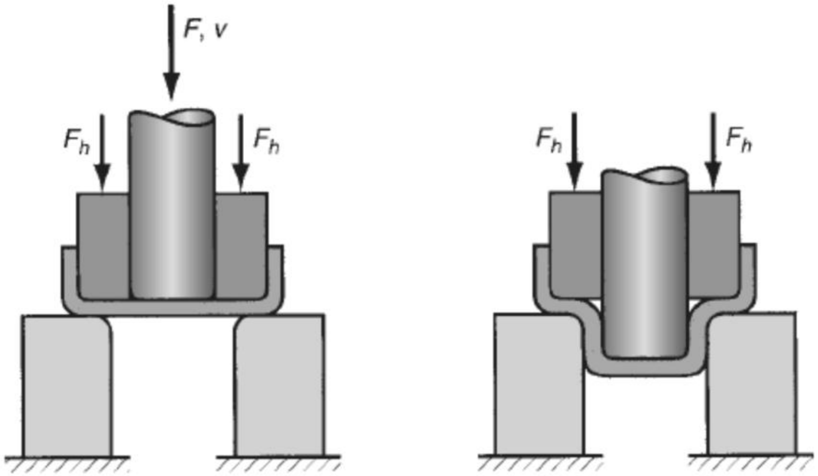
M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

A cup drawing operation is performed in which the inside diameter = 80 mm and the height = 50 mm. The stock thickness = 3 mm, and the starting blank diameter = 150 mm. Punch and die radii = 4 mm. Tensile strength = 400 MPa and a yield strength = 180 MPa for this sheet metal. Determine: (a) drawing ratio, (b) reduction, (c) drawing force, and (d) blankholder force.

Redrawing

In many cases, the shape change involved in making that part will be severe (drawing ratio is very high). In such cases, complete forming of the part requires more than one deep drawing step.

Redrawing refers to any further drawing steps that is required to complete the drawing operation.

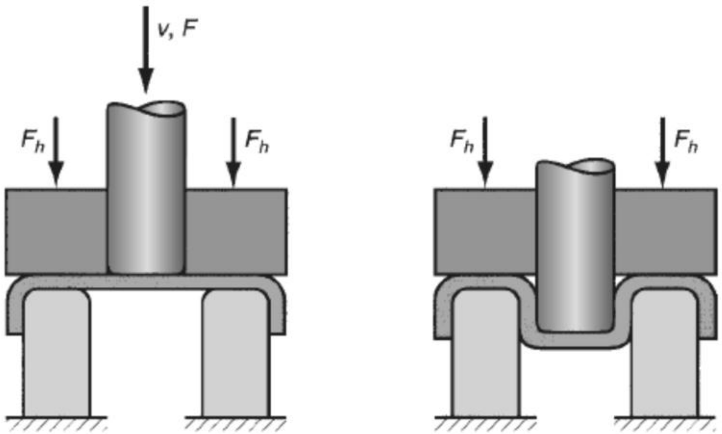


Redrawing

Guidelines for successful redrawing:

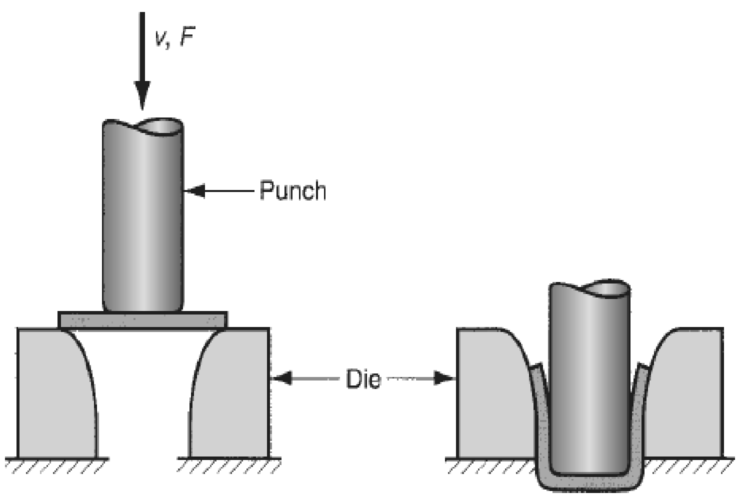
First draw: Maximum reduction of the starting blank - 40% to 45%
Second draw: 30%
Third draw : 16%

Reverse redrawing



In reverse redrawing, the sheet part will face down and drawing is completed in the direction of initial bend.

Drawing without blank holder



The main function of BH is to reduce wrinkling. The tendency of wrinkling decreases with increase in thickness to blank diameter ratio (t/D_b). For a large t/D_b ratio, drawing without blank holder is possible.

The die used must have the funnel or cone shape to permit the material to be drawn properly into the die cavity.

Limiting value for drawing without BH:

$$D_b - D_p = 5t$$

Plastic anisotropy

The main cause of anisotropy of plastic properties is the preferred orientation of grains, i.e., tendency for grains to have certain orientations. This is cause mainly by mechanical forming of metals.

A useful parameter to quantify anisotropy is *R*, the plastic strain ratio, which is the ratio of true plastic strain in width direction to that in thickness direction. Higher R, large resistance to thinning.

$$R = \frac{\varepsilon_w}{\varepsilon_t}$$

For isotropic materials, *R* = 1; for anisotropic materials: *R* > 1 or *R* < 1

In many sheet forming operations like deep drawing, the materials exhibit some anisotropy in the sheet plane. So averaging is done to find a value quantifying all the variations in the sheet surface as given by the following equation. But this is practically impossible.

$$\overline{R} = \int_{\theta=0}^{\theta=360^\circ} R_\theta \, d\theta$$

(Average plastic strain ratio)

Usually the following equation is used by considering orthotropy is accurate.

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

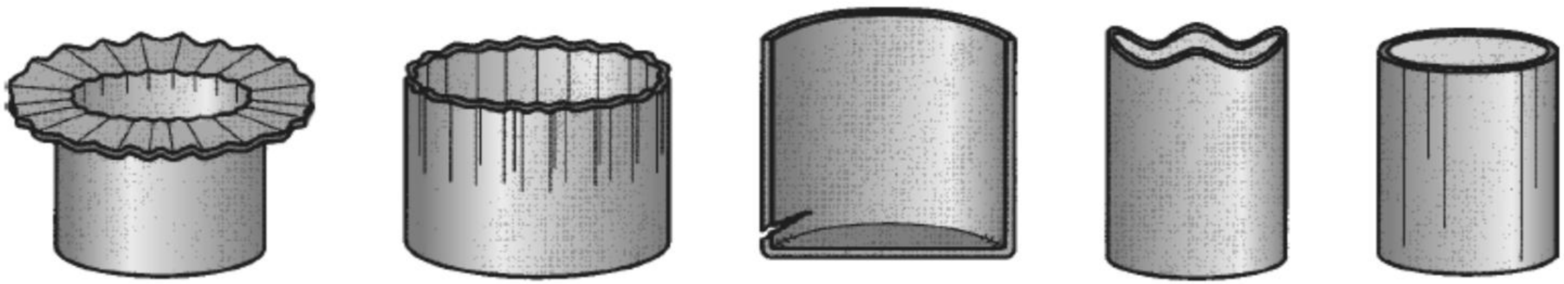
(normal anisotropy)

Another parameter that takes care of planar anisotropy is ΔR given by,

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

This is a measure of how different the 45° directions are from the symmetry axes.

Defects in deep drawing



wrinkling in flange and cup wall **tearing** **earing** **surface scratches**

Wrinkling in flange and cup wall: This is like ups and downs or waviness that is developed on the flange. If the flange is drawn into the die hole, it will be retained in cup wall region.

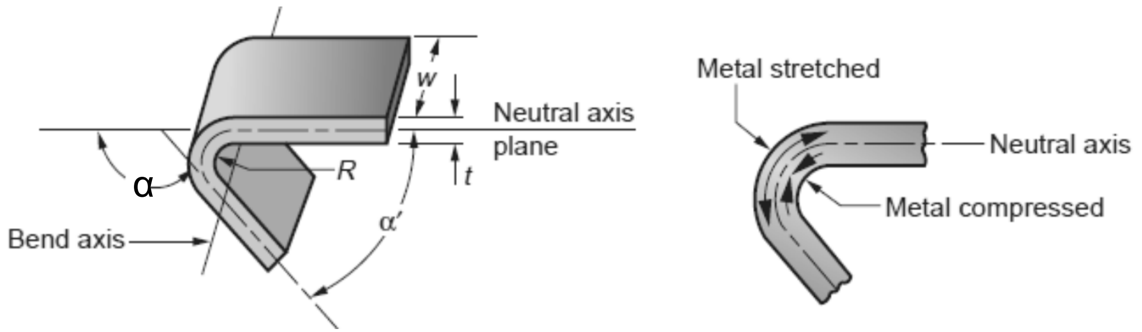
Tearing: It is a crack in the cup, near the base, happening due to high tensile stresses causing thinning and failure of the metal at this place. This can also occur due to sharp die corner.

Earing: The height of the walls of drawn cups have peaks and valleys called as earing. There may be more than four ears. Earing results from planar anisotropy (ΔR), and ear height and angular position correlate well with the angular variation of R.

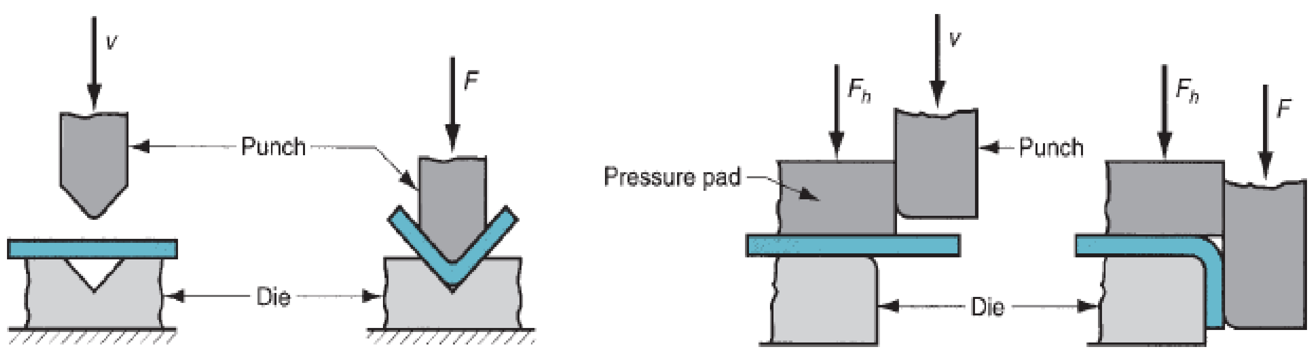
Surface scratches: Usage of rough punch, dies and poor lubrication cause scratches in a drawn cup.

Sheet bending

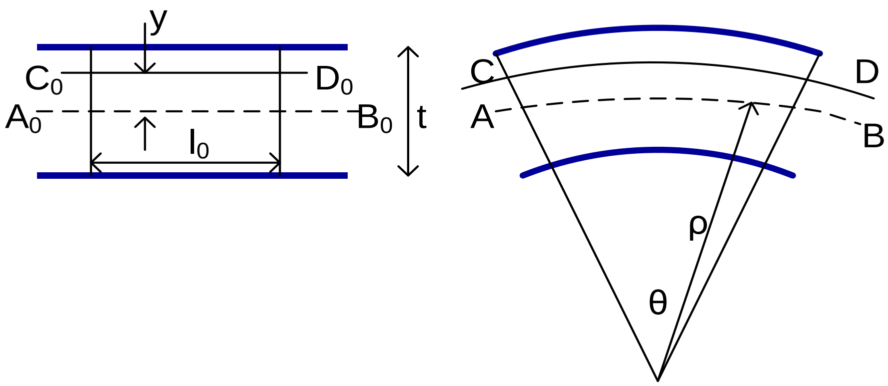
Sheet bending is defined as the straining of the metal around a straight axis as shown in figure. During bending operation, the metal on the inner side of the neutral plane is compressed, and the metal on the outer side of the neutral plane is stretched. Bending causes no change in the thickness of the sheet metal.



In V-bending, the sheet metal is bent between a V-shaped punch and die set up. The included angles range from very obtuse to very acute values.
In edge bending, cantilever loading of the sheet is seen. A pressure pad is used to apply a force to hold the sheet against the die, while the punch forces the sheet to yield and bend over the edge of the die.



Deformation during bending



For our analysis, it may be assumed that a plane normal section in the sheet will remain plane and normal and converge on the center of curvature as shown in Figure. The line A_0B_0 at the middle surface may change its length to AB, if the sheet is under stretching during bending. The original length l_o becomes, $l_s = \rho\theta$. A line C_0D_0 at a distance *y* from the middle surface will deform to a length,

$$l = \theta(\rho + y) = \rho\theta(1 + \frac{y}{\rho}) = l_s(1 + \frac{y}{\rho})$$

where ρ is the radius of curvature.

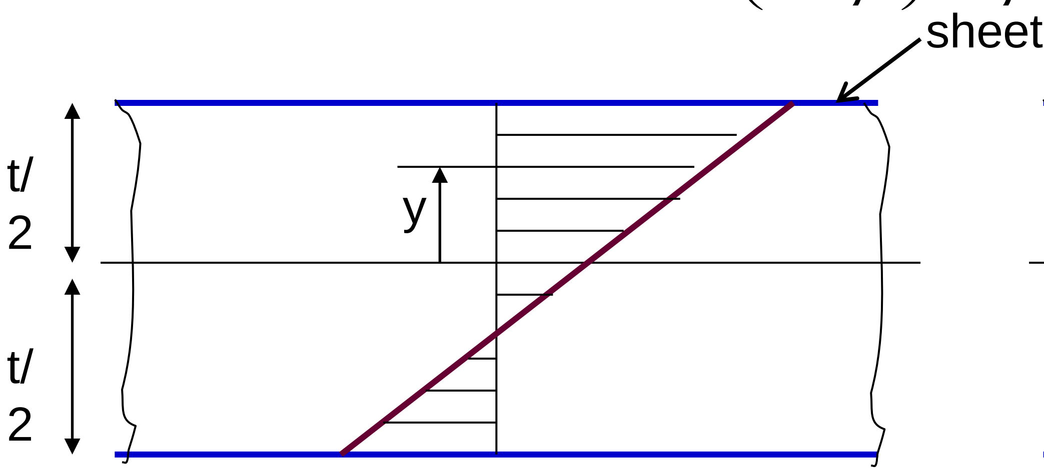
The axial strain of the fiber CD is,

$$\varepsilon_1 = \ln\frac{l}{l_0} = \ln\frac{l_s}{l_0} + \ln\left(1 + \frac{y}{\rho}\right) = \varepsilon_a + \varepsilon_b \qquad (1)$$

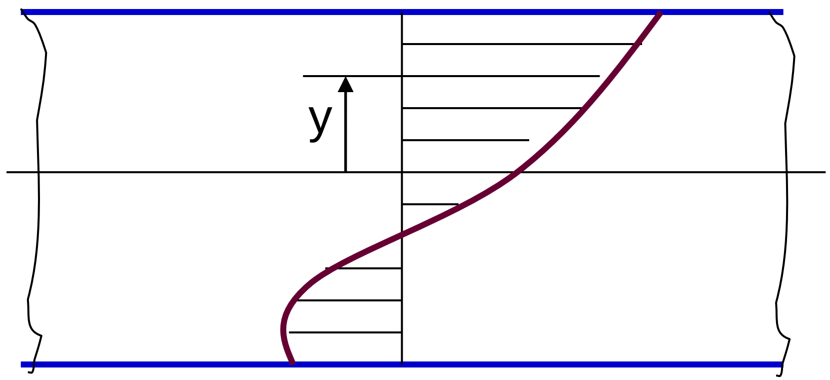
Marciniak, Duncan, Hu, *Mechanics of sheet metal forming* where 'ε_a' and 'ε_b' are the strains at the middle surface and bending strain respectively.

In the case of bending with radius of curvature larger compared to the thickness, the bending strain is approximated as,

$$\varepsilon_b = \ln\left(1 + \frac{y}{\rho}\right) \approx \frac{y}{\rho}$$



Strain distribution in bending



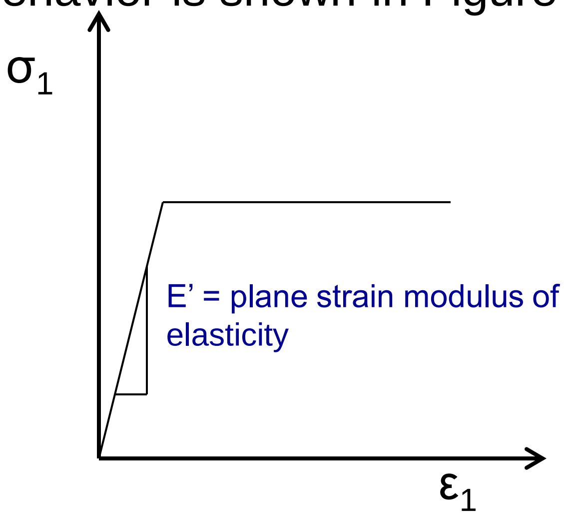
Typical stress distribution in bending

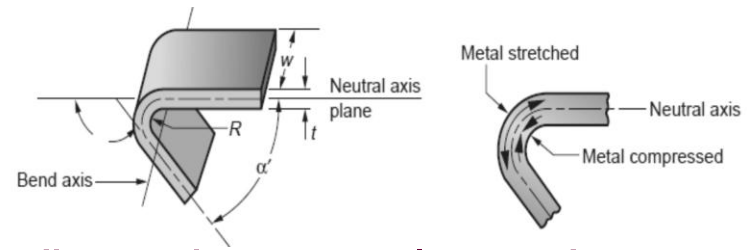
Choice of material model

For the strain distribution given by equation (1) for bending, the stress distribution on a section can be found out by knowing a stress-strain law.

Generally elastic-plastic strain hardening behavior is seen in sheet bending. But there are other assumptions also.

Elastic, perfectly plastic model: Strain hardening may not be important for a bend ratio (ρ/t) (radius of curvature/thickness) of about 50. For this case the stress-strain behavior is shown in Figure below.





Bending can be seen as plane strain deformation as strain along bend can be zero

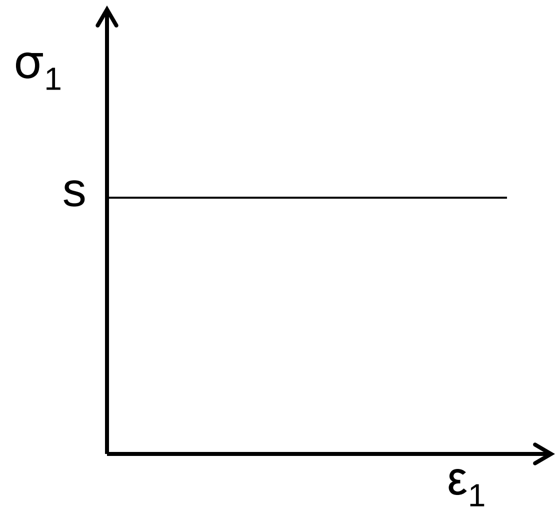
For elastic perfectly plastic model, for stress less than plane strain yield stress, S,

$\boldsymbol{\sigma_1 = E' \varepsilon_1}$ where $E' = E/1-\gamma^2$

For strains greater than yield strains, $\boldsymbol{\sigma_1 = S}$ *where* $S = \sigma_f\,(2/\sqrt{3})$

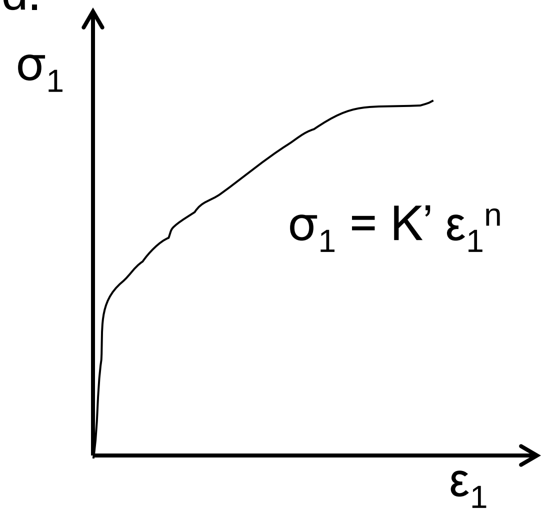
Rigid, perfectly plastic model: For smaller radius bends, where elastic springback is not considered, the elastic strains and strain hardening are neglected. So,

$$\sigma_1 = S$$



Strain hardening model: When the strains are large, elastic strains can be neglected, and the power hardening law can be followed.

$$\sigma_1 = K' \varepsilon_1^n$$



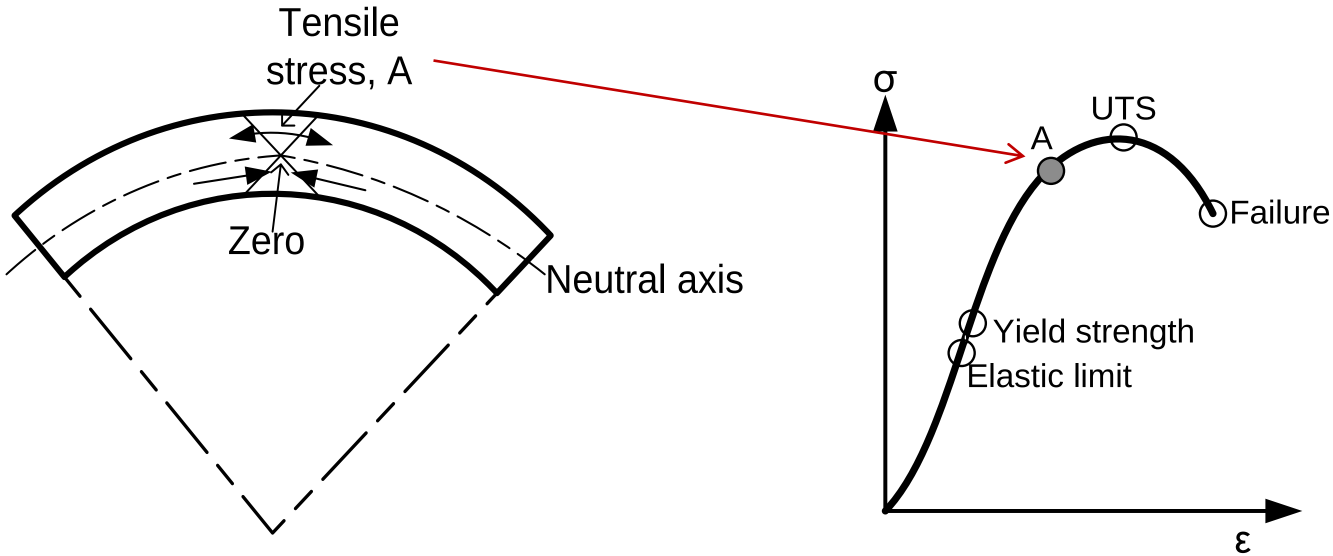
Spring back

•*Spring back* occurs because of the variation in bending stresses across the thickness, i.e., from inner surface to neutral axis to outer surface. The tensile stresses decrease and become zero at the neutral axis.

•Since the tensile stresses above neutral axis cause plastic deformation, the stress at any point (say '*A*') in the tensile stress zone should be less than the ultimate tensile strength in a typical tensile stress-strain behavior. The outer surface will crack, if the tensile stress is greater than ultimate stress during bending.

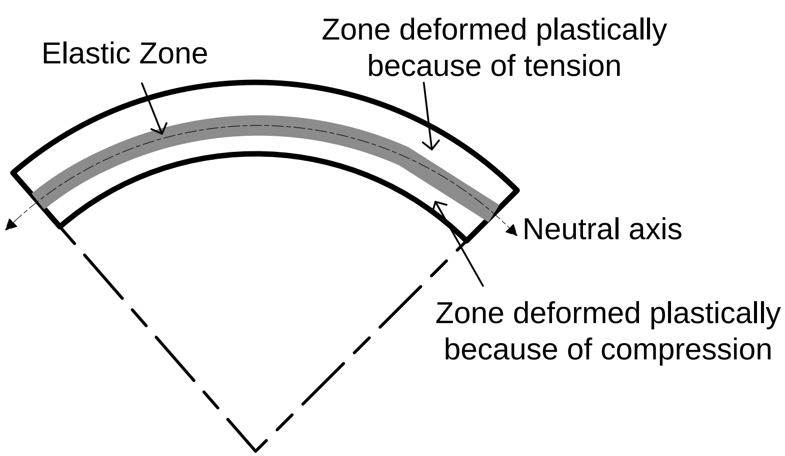
•The metal region closer to the neutral axis has been stressed to values below the elastic limit. This elastic deformation zone is a narrow band on both sides of the neutral axis, as shown in Fig. The metal region farther away from the axis has undergone plastic deformation, and obviously is beyond the yield strength.

•Upon load removal after first bending, the elastic band tries to return to the original flat condition but cannot, due to the restriction given by the plastic deformed regions. Some return occurs as the elastic and plastic zones reach an equilibrium condition and this return is named as *spring back*.

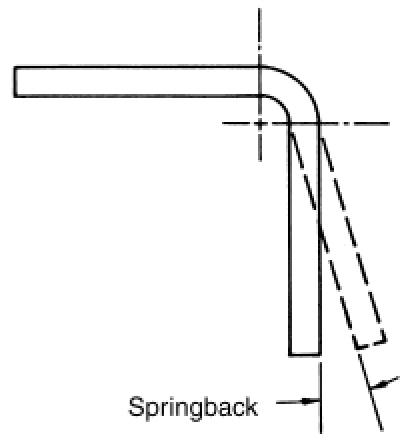


Changing stress patterns in a bend

ASM handbook, sheet metal forming



Elastic and plastic deformation zones during bending

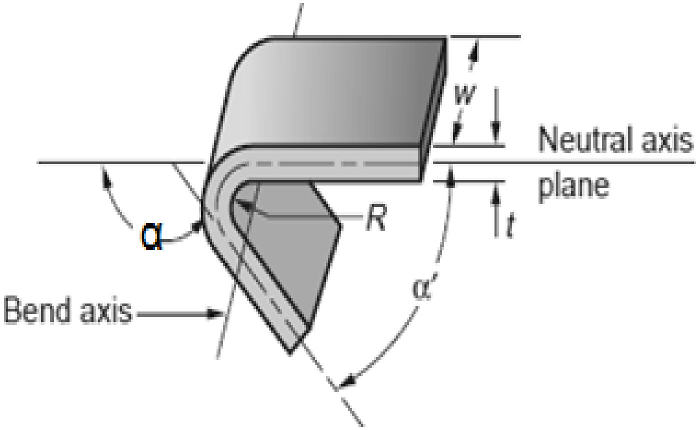


Springback

- Sprinback can be minimized by overbending, bottoming and stretch forming.
- In overbending, the punch angle and radius are made smaller than the specified angle on the final part so that the sheet metal springs back to the desired value.
- Bottoming involves squeezing the part at the end of the stroke, thus plastically deforming it in the bend region.

Spring back is defined by the equation:

$$SB = \frac{\alpha^{'} - \alpha_{tool}}{\alpha_{tool}}$$

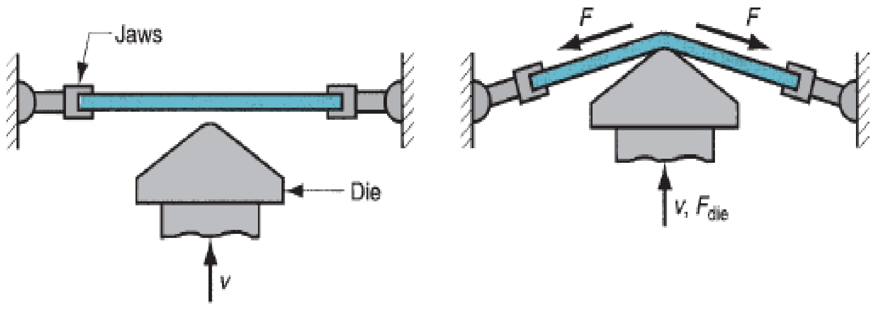


Stretching/stretch forming

- Stretch forming is a sheet metal forming process in which the sheet metal is intentionally stretched and simultaneously bent to have the shape change.

-The sheet is held by jaws or drawbeads at both the ends and then stretched by punch, such that the sheet is stressed above yield strength.

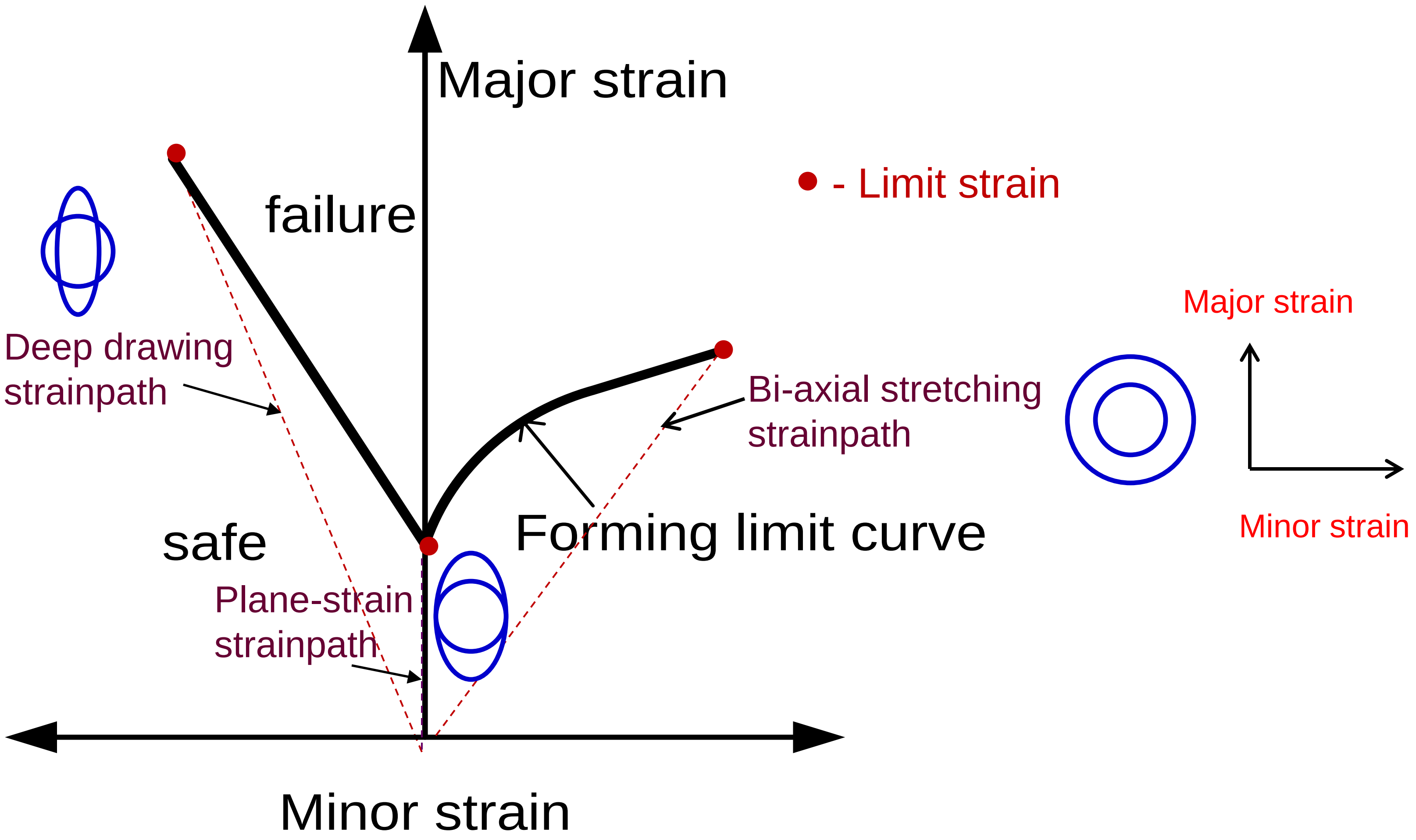
- When the tension is released, the metal has been plastically deformed. The combined effect of stretching and bending results in relatively less springback in the part.



Stretching/stretch forming

Photo from public resource

Forming limit diagram (FLD)

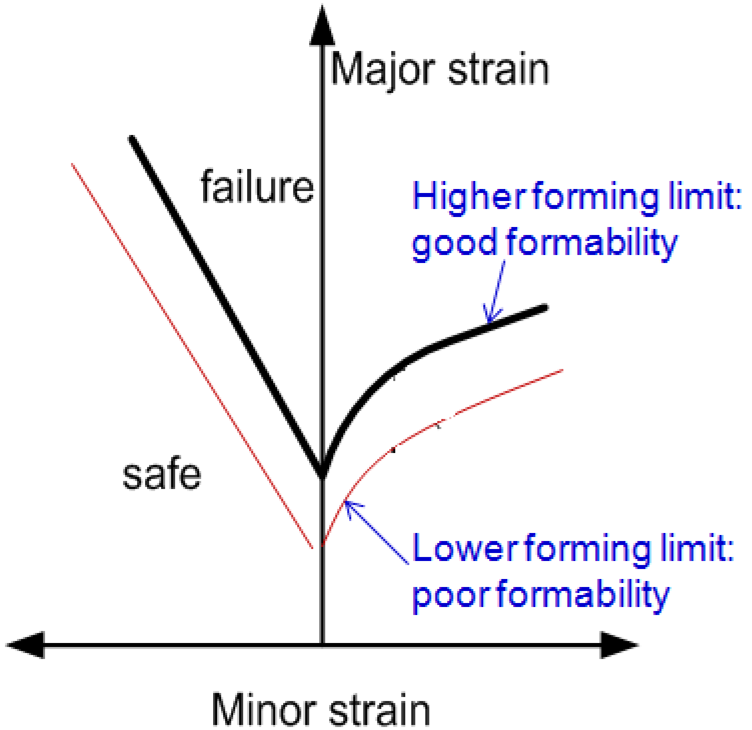


From tensile test we get only ductility, work hardening exponent, but it is in a uniaxial tension without friction, which cannot truly represent material behaviours obtained from actual sheet forming operations.

In sheet forming, mainly in stretching, FLD gives quantification about formability of sheet material. It tells about quality of the material.

In this diagram, *forming limit curve* (*FLC*), plotted between major strain (in Y-axis) and minor strain (in X-axis), is the index that says the amount of safe strains that can be incorporated into the sheet metal.

The FLC is the locus of all the limit strains in different strain paths (like deep drawing, biaxial stretching, plane strain) of the sheet material. The plane-strain condition possesses the least forming limit, when compared to deep drawing and stretching strain paths.



A sheet material with higher forming limit is considered good.