# Sheet Metal Working

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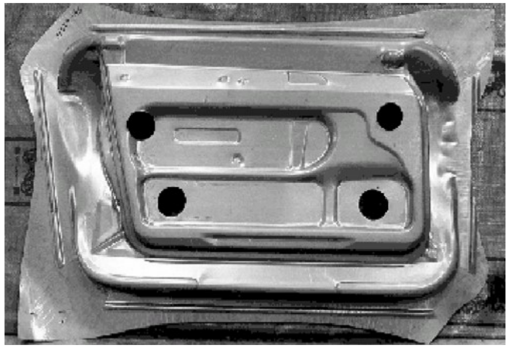
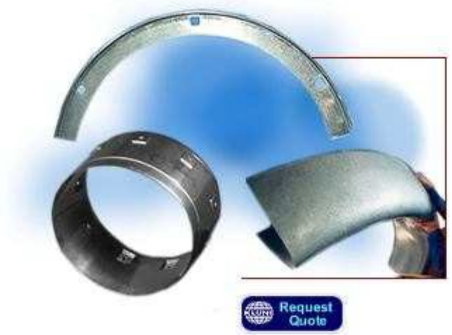
# Introduction

- Sheet metal forming is a process that materials undergo permanent deformation by cold forming to produce a variety of complex three dimensional shapes.
- The process is carried out in the plane of sheet by tensile forces with high ratio of surface area to thickness.
- High rate of production and formability is determined by its mechanical properties.
- Friction conditions at the tool-metal interface are very important and controlled by press conditions, lubrication, tool material, surface condition and strip surface condition.





# Bulk forming Vs. Sheet Forming

- Bulk forming
  - Rolling, extrusion, forging, drawing
  - Mostly compressive stress
  - process changes in thickness or dimensions of workpiece
  - Workpiece subjected to triaxial stresses
- Sheet forming
  - Carried only in plane sheet
  - Tensile force is applied
  - Compressive forces leads to buckling, folding and wrinkling of the sheet
  - Thickness is maintained to avoid necking and failure
  - High ratio to surface area to thickness
  - Workpiece subjected to biaxial stresses

# Classification of sheet metal parts

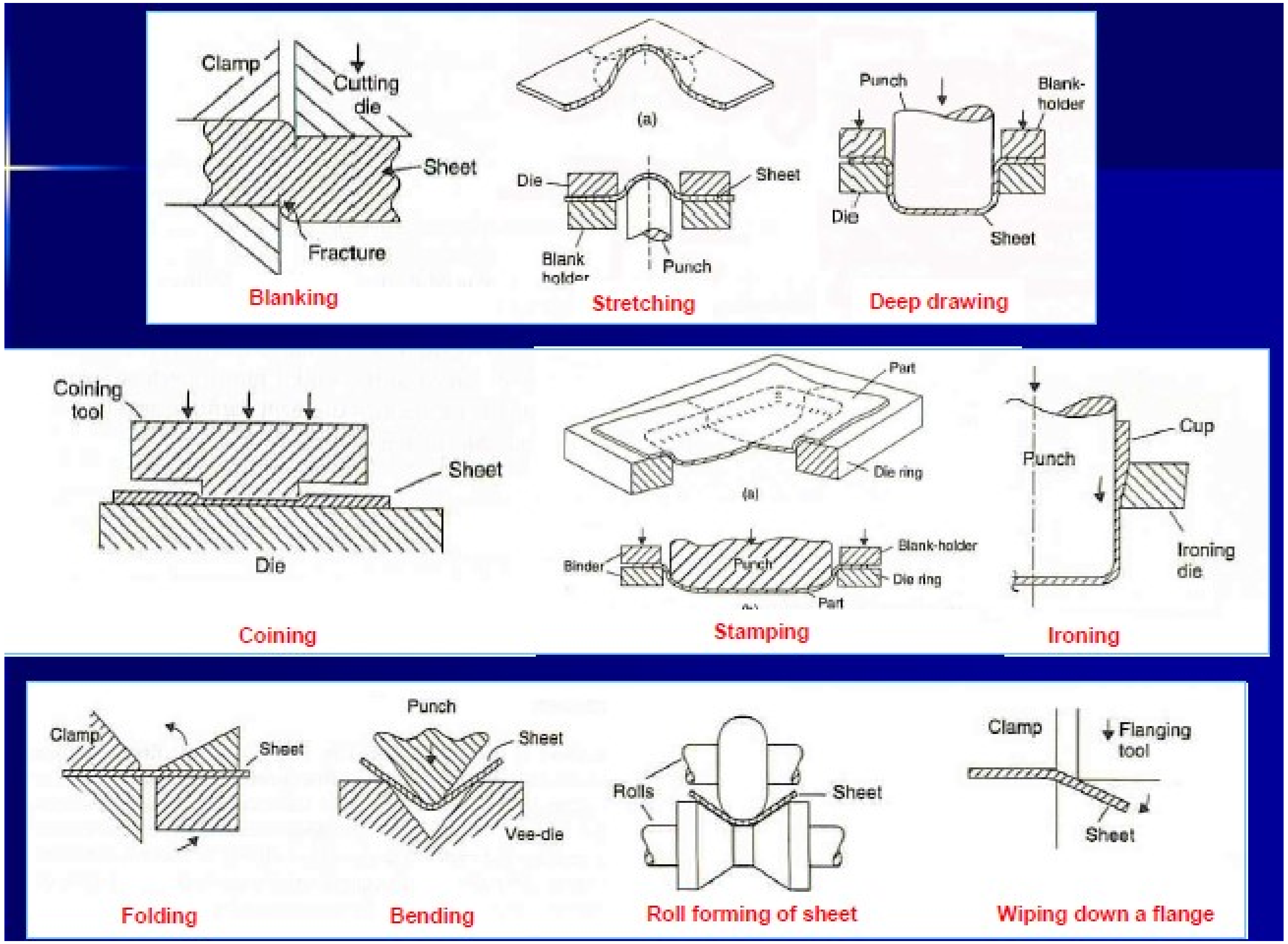
(based on contour)

1) Singly curved parts
2) Contoured flanged parts, i.e., parts with stretch flanges and shrink flanges.
3) Curved sections.
4) Deep-recessed parts, i.e., cups and boxes with either vertical or sloping walls.
5) Shallow-recessed parts, i.e., dish shaped, beaded, embossed and corrugated parts.


Figure: (a) Singly curve (b) Stretch flange (c) Shrink flange (d) Curved section (e) Deep drawn cup (f) Beaded section

# Classification of sheet metal forming

(based on operations)



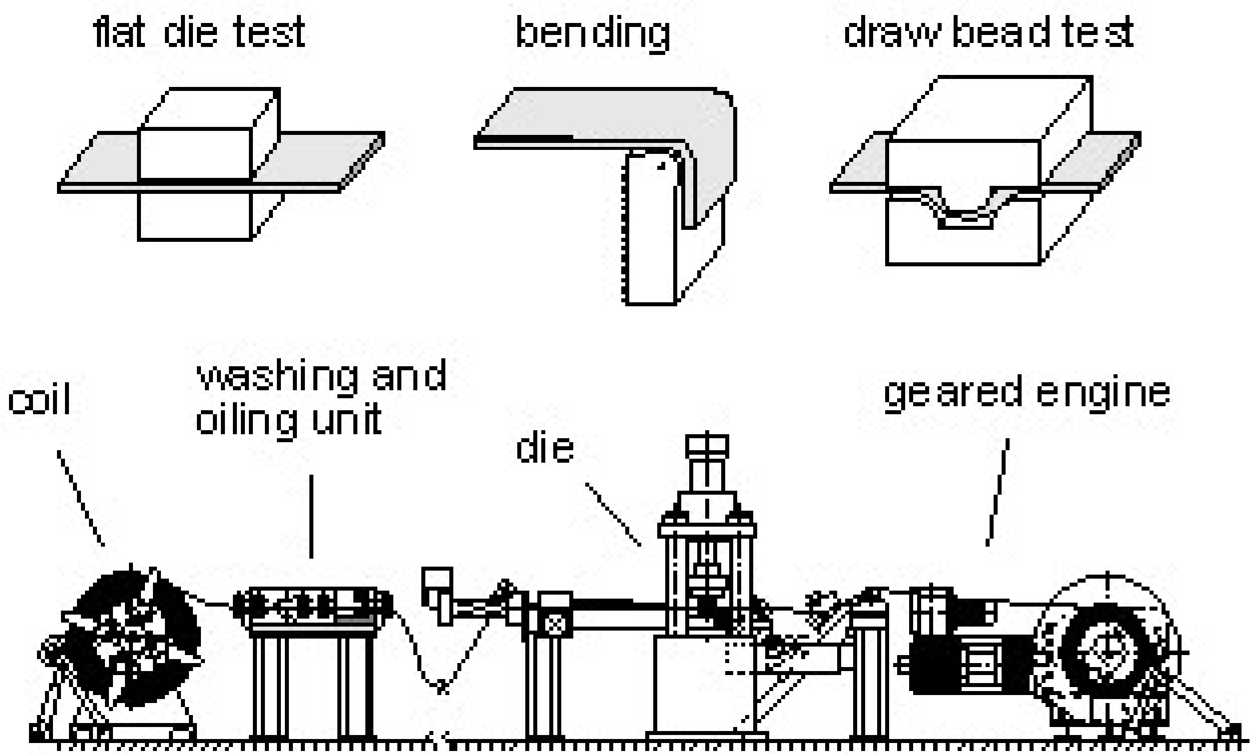
# Forming Equipments

Forming equipments include

1) Forming presses

2) Dies

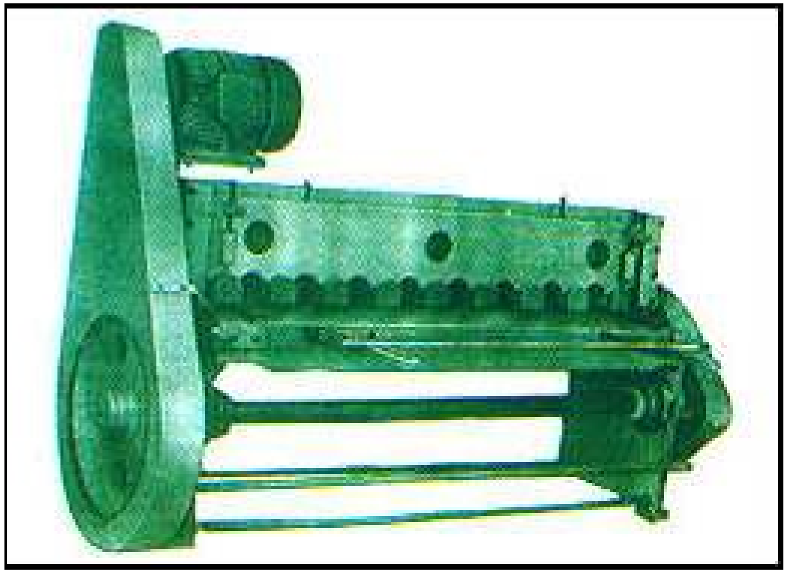
3) Tools



# Forming machines

1) Mechanical presses

- energy stored in a flywheel is transferred to the movable slide on the down stroke of the press.
- quick - acting , short stroke.



2) Hydraulic presses

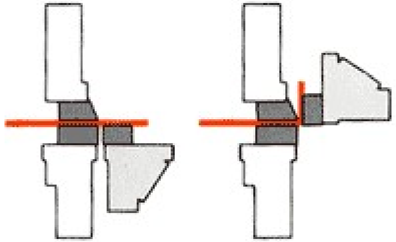
- slower - acting, longer stroke.

# Action of presses

(according to number of slides, which can be operated  independently of each other.)

1) Single - action press

- one slide
- vertical direction



2) Double - action press

- two slides
- the second action is used to operated the hold-down, which prevents wrinkling in deep drawing.

3) Triple - action press

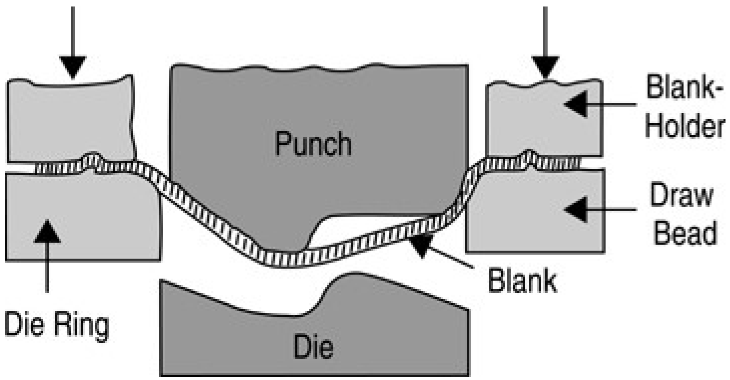
- two actions above the die, one action below the die.

# Tooling

Basic tools used with a metalworking press are the punch and the die.

- Punch - A convex tool for making holes by shearing , or making surface or displacing metal with a hammer.
  - Punch is moving element
- Die - A concave die

Punch and die in stamping

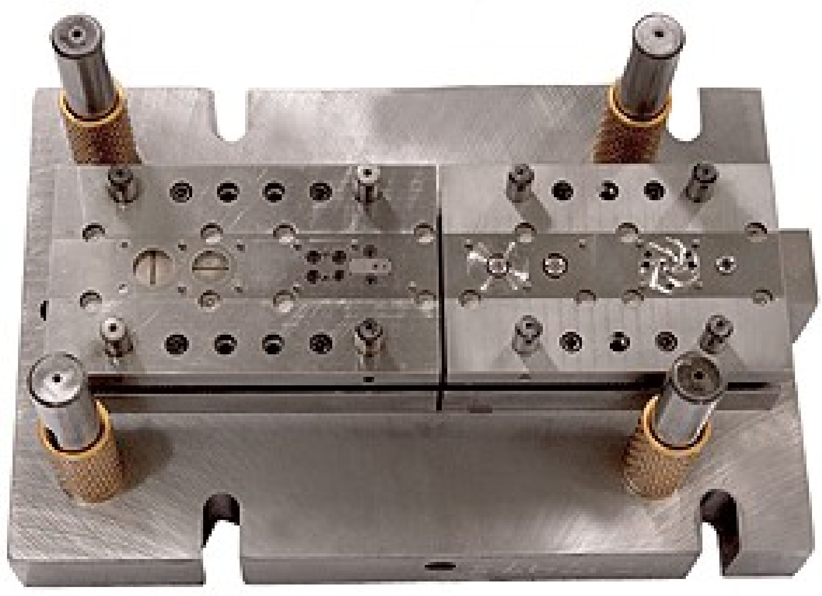



Punch and die in stamping

Die Materials:
High alloy steels heat treated for the punches and dies.

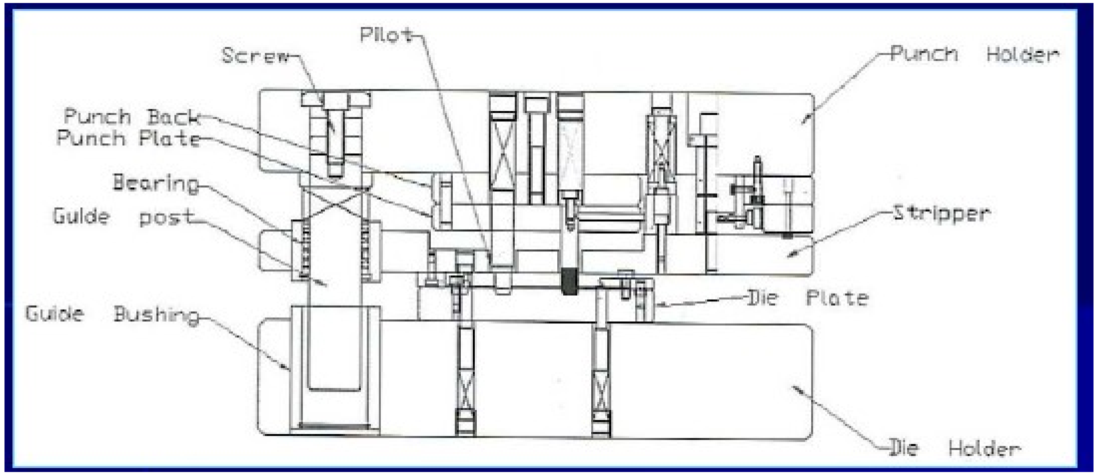
## Compound dies

- Several operations can be performed on the same piece in one stroke of the press.
- Combined processes and create a complex product in one shot.
- Used in metal stamping processes of thin sheets.



## Transfer dies

- Transfer dies are also called compounding type dies.
- The part is moved from station to station within the press for each operation.




A die set is composed of

1) Punch holder which holds punch plate connected with blanking and piecing punches for cutting the metal sheet.
2) Die block consists of die holder and die plate which was designed to give the desired shape of the product.
3) Pilot is used to align metal sheet at the correct position before blanking at each step.
4) Striper plate used for
    - a) alignment of punch and die blocks
    - b) navigate the punch into the die using

# Forming Method

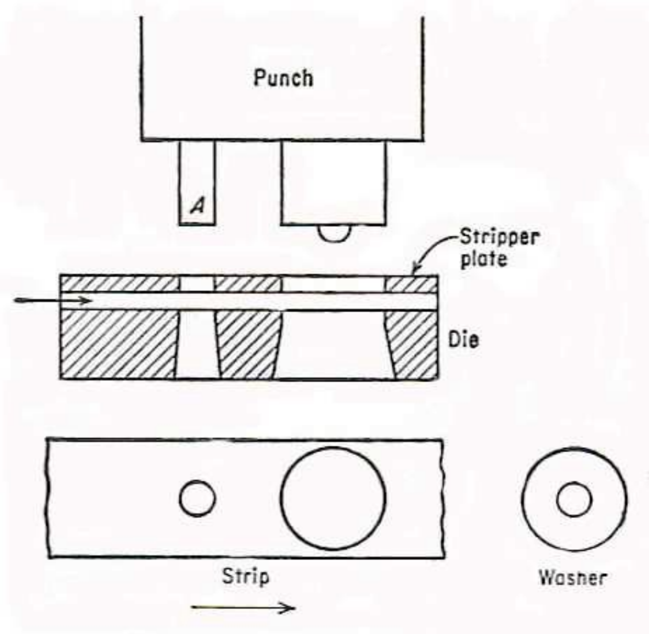
There are a great variety of sheet metal forming methods, mainly using shear and tensile forces in the operation.

- Progressive forming
- Rubber hydroforming
- Bending and contouring
- Spinning processes
- Explosive forming
- Shearing and blanking
- Stretch forming
- Deep drawing

## Progressive forming

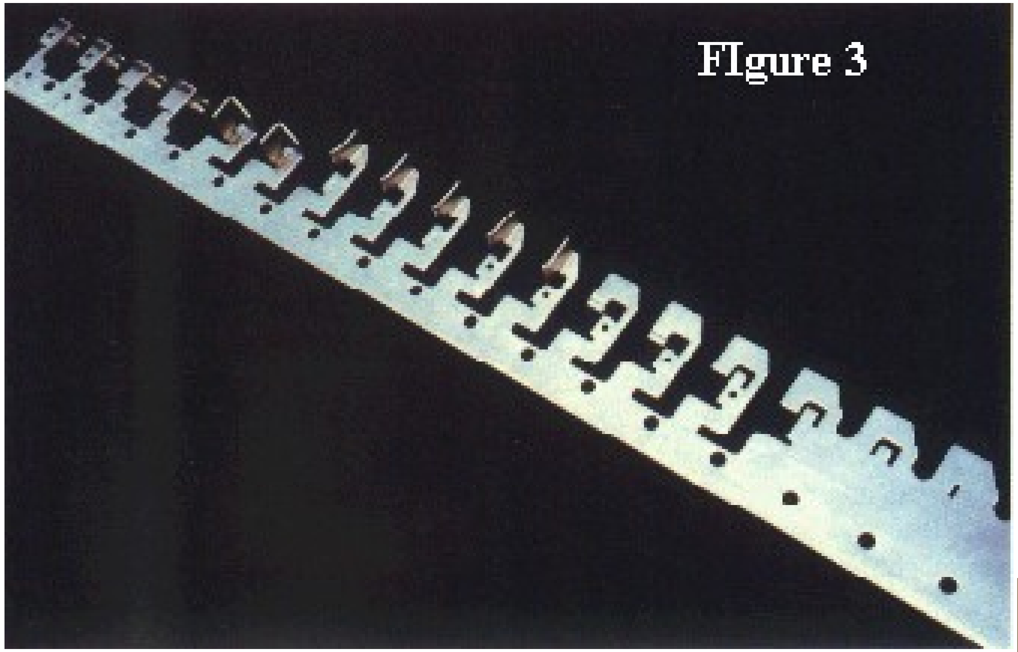
- Punches and dies are designed so that successive stages in the forming of the part are carried out in the same die on each stroke of the press.
- Progressive dies are also known as multi-stage dies.

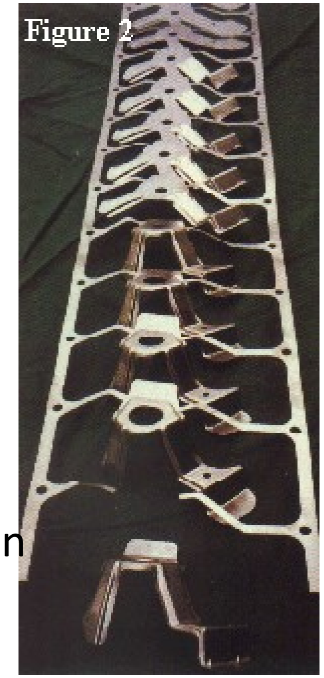
Example: progressive blanking and piercing of flat washer.



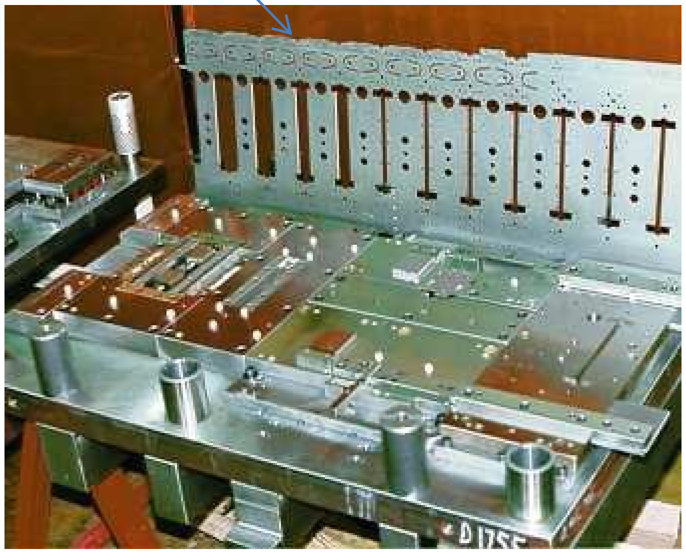

- The strip is fed from left to right.
- The first punch is to make the hole for the washer.
- The washer is then blanked from the strip. At the same time, the punch A is piercing the hole for the next washer.

# Progressive die




Metal sheet used in blanking process

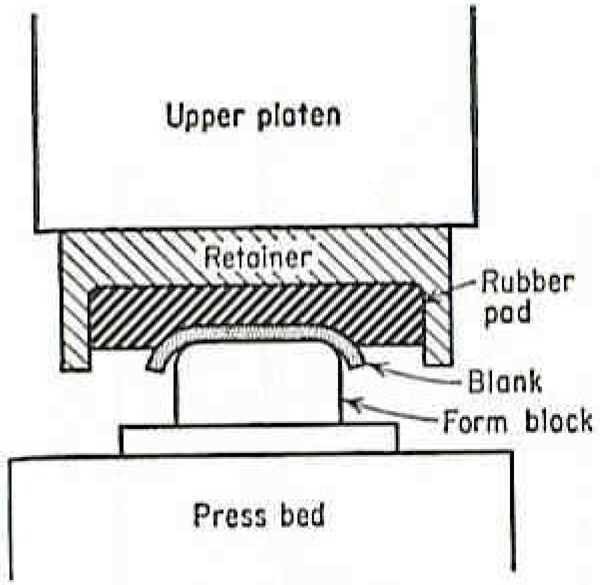


Progressive die

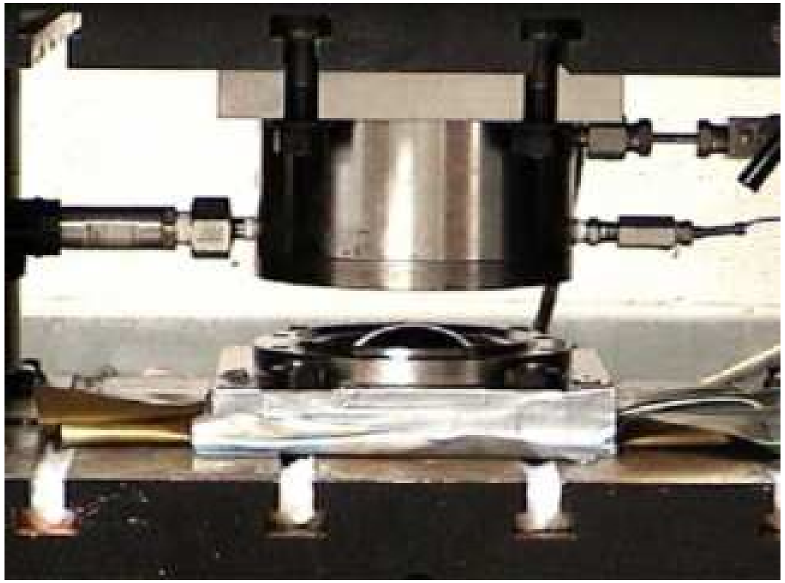
- Optimise the material usage.
- Determining factors are
  1) volume of production
  2) the complexity of the shape

# Rubber hydroforming

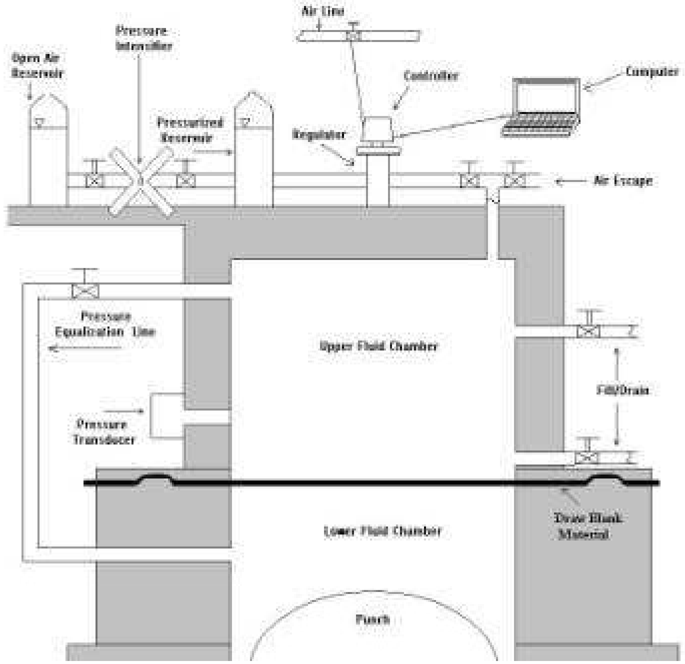
- Using a pad of rubber or polyurethane as a die.
- A metal blank is placed over the form block, which is fastened to the bed of a single - action hydraulic press.
- During forming the rubber (placed in the retainer box on the upper platen of the press) transmits a nearly uniform hydrostatic pressure against the sheet.
- Pressure ~ 10 MPa, and where higher local pressure can be obtained by using auxiliary tooling.



# Hydroforming

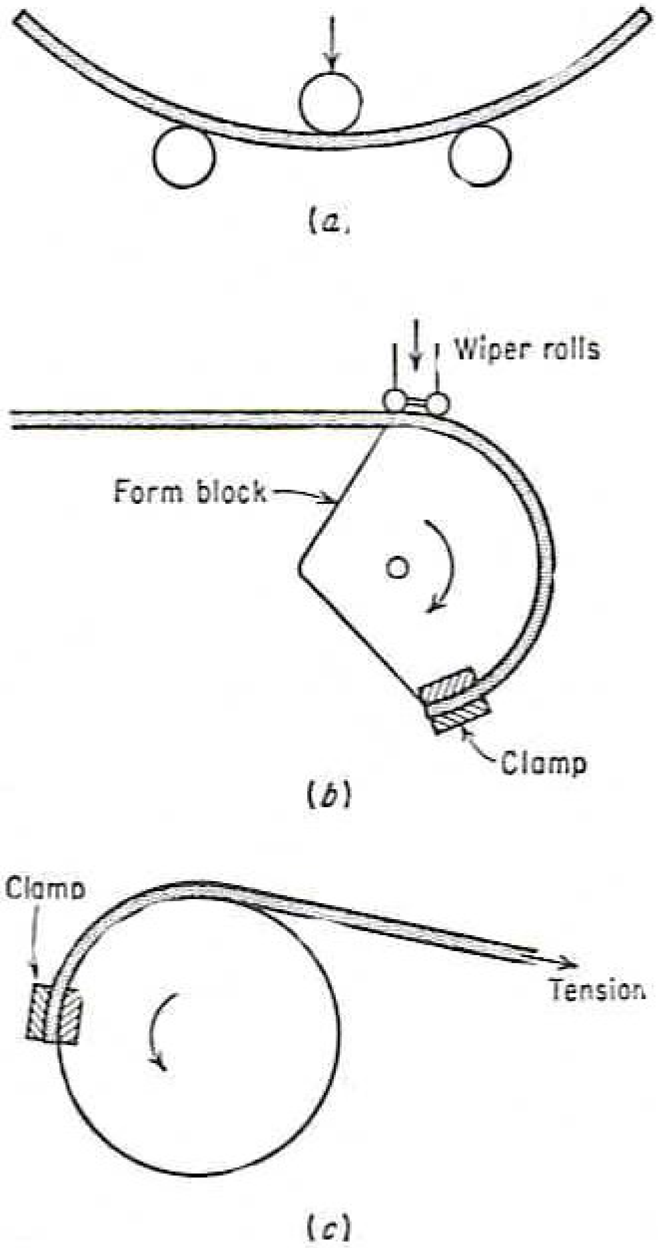


Stamp hydroforming machine setup with a fluid supplied from one side of the draw blank




A drawing of hydroforming setup with fluid supplied from to both sides of the materials.

- Used for sheet forming of aluminium alloys and reinforced thermoplastics.




# Bending and contouring

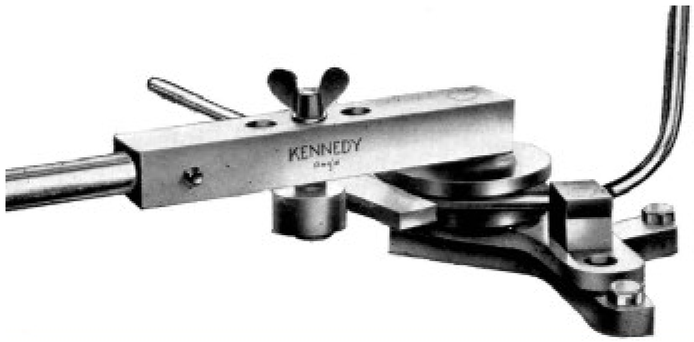
a) Three-roll bender: sometimes does not provide uniform deformation in thin-gauge sheet due to the midpoint of the span → localisation of the strain. Often need the forth roll.

(b) Wiper-type bender: The contour is formed by successive hammer blows on the sheet, which is clamped at one end against the form block. Wiper rolls must be pressed against the block with a uniform pressure supplied by a hydraulic cylinder.

(c) Wrap forming: The sheet is compressed against a form block, and at the same time a longitudinal stress is applied to prevent buckling and wrinkling.

Ex: coiling of a spring around a mandrel.

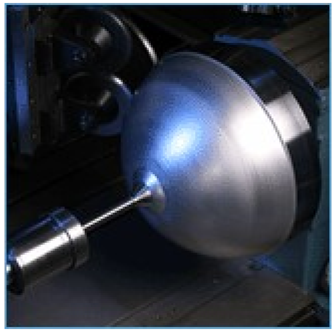
# Bending and contouring machines

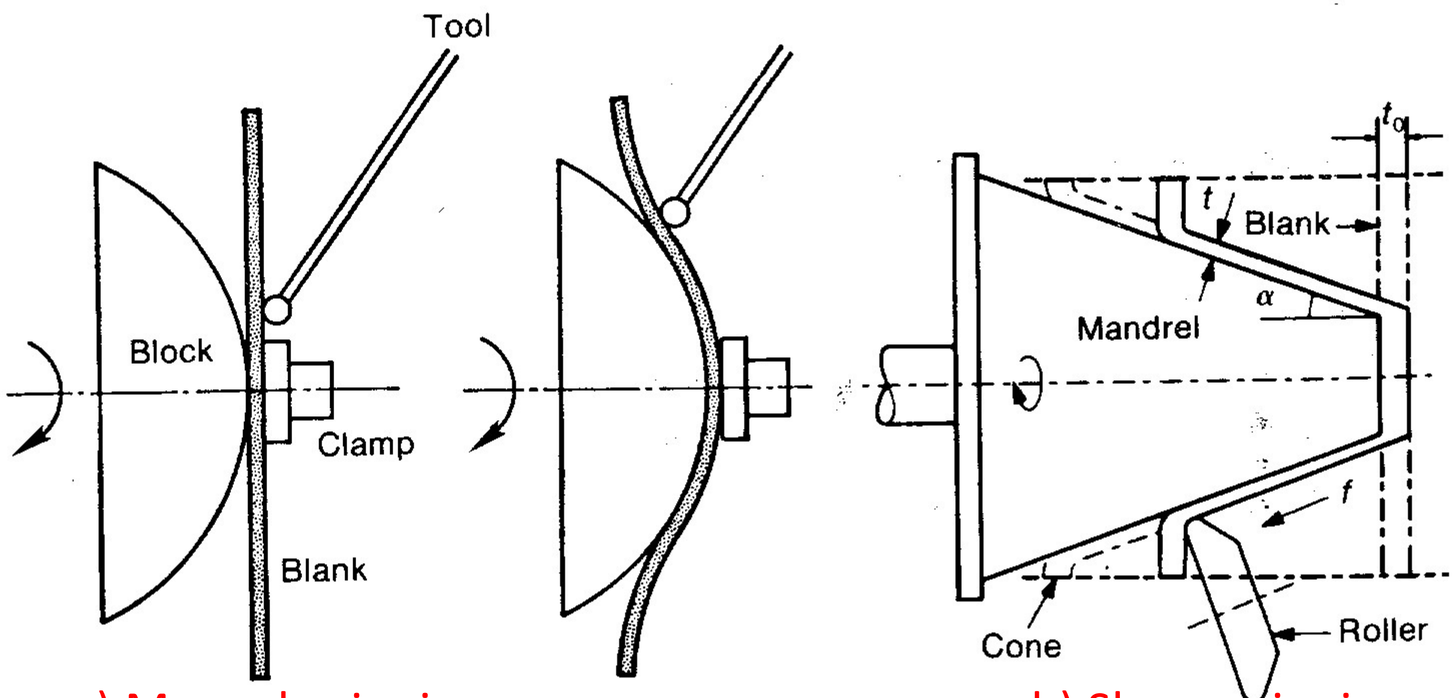



# Spinning Processes

Deep parts of circular symmetry stainless steel, such as tank heads, television cones.

Materials: aluminium and alloys, high strength - low alloy steels, copper, brass and alloys






a) Manual spinning b) Shear spinning

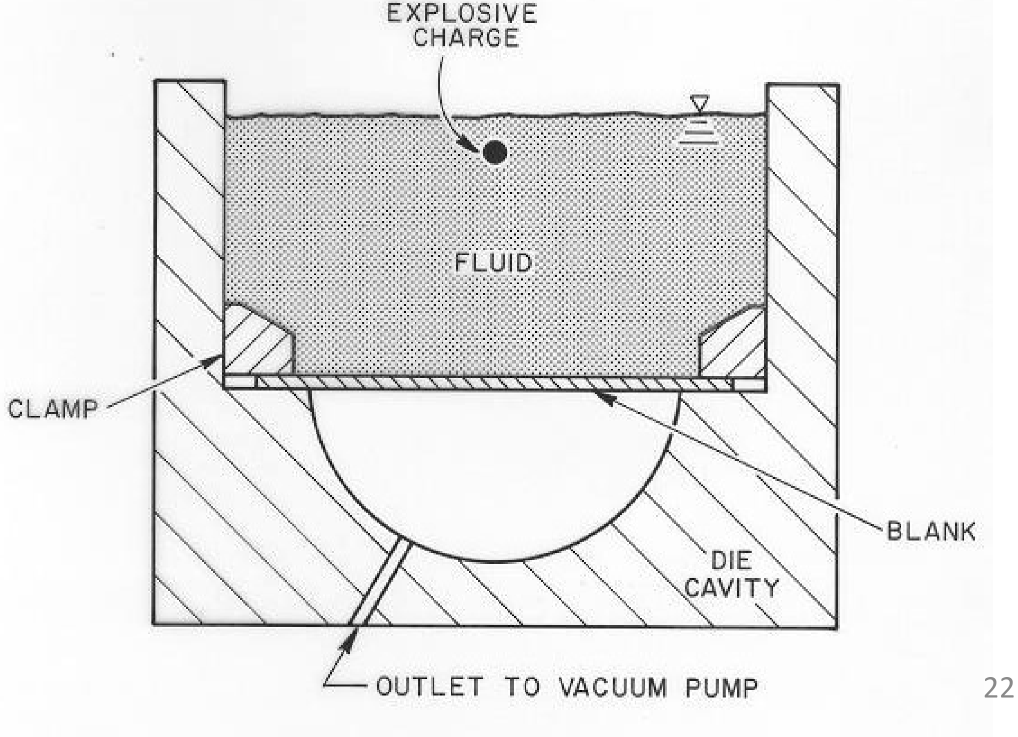
- The metal blank is clamped against a form block, which is rotated at high speed.
- The blank is progressively formed against the block, by a manual tool or by means of small-diameter work rolls.

Note: (a) no change in thickness but diameter,

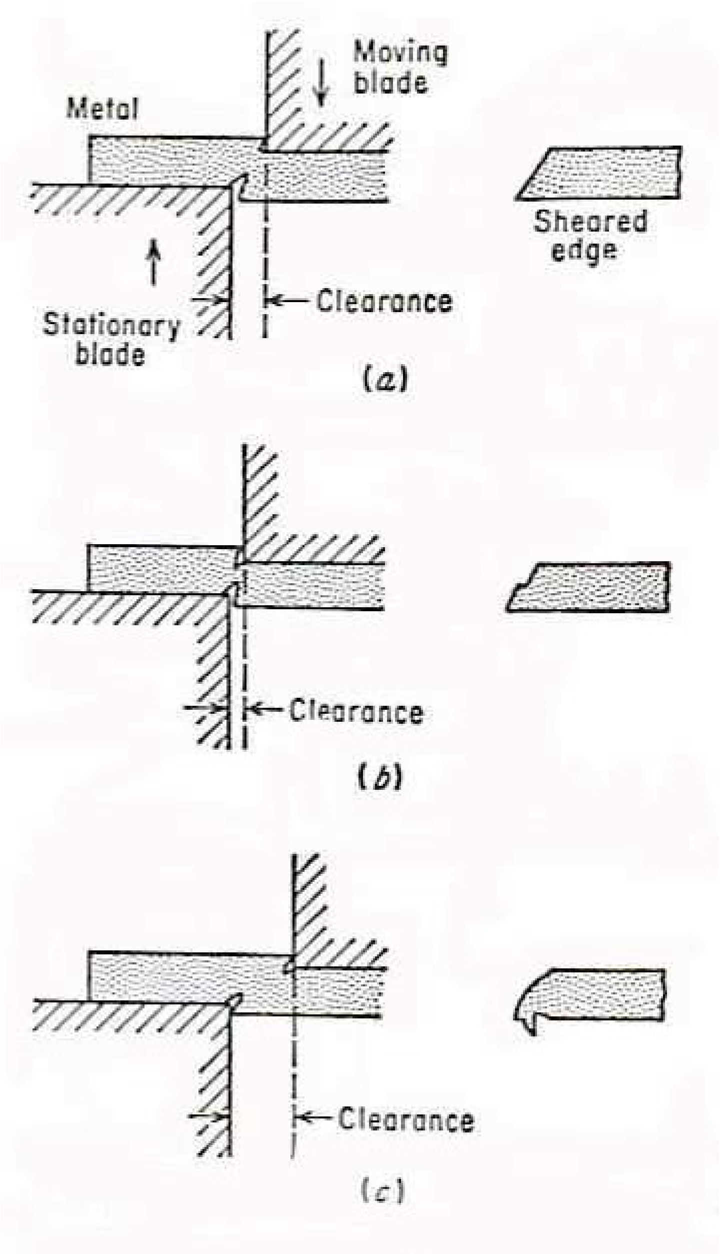
(b) diameter equals to blank diameter but thickness stays the same.

# Explosive forming

- Produce large parts with a relatively low production lot size.
- The sheet metal blank is placed over a die cavity and an explosive charge is detonated in medium (water) at an appropriate standoff distance from the blank at a very high velocity.
- The shockwave propagating from the explosion serves as a 'friction-less punch'



# Shearing and Blanking



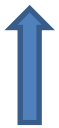
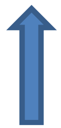

## Shearing:

The separation of metal by the movement of two blades operated based on shearing forces.

- A narrow strip of metal is severely plastically deformed to the point where it fractures at the surfaces in contact with the blades.
- The fracture then propagates inward to provide complete separation.

## Clearance

- Proper → clean fracture surface.
- Insufficient → ragged fracture surface.
- Excessive → greater distortion, greater energy required to separate metal.

Thickness  Clearance 

# Maximum punch force

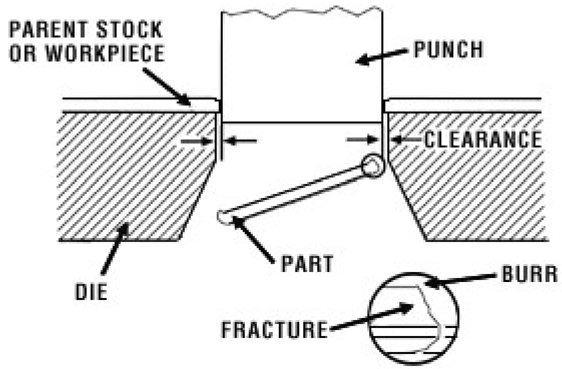
- No friction condition.
- The force required to shear a metal sheet ~ length cut, sheet thickness, shearing strength.
- The maximum punch force to produce shearing is given by

$$P_{\max} \approx 0.7 \sigma_u h l$$

where $\sigma_u$ = the ultimate tensile strength
h = sheet thickness
L = total length of the sheared edge

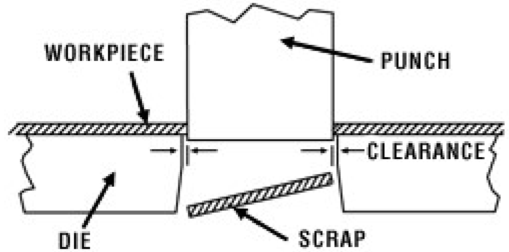
The shearing force ⇩ by making the edges of the cutting tool at an inclined angle

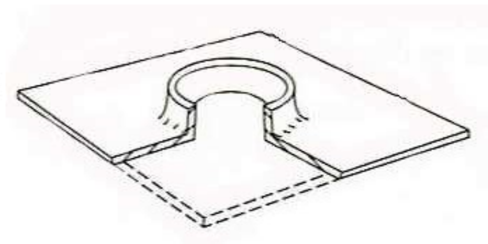
Blanking : The shearing of close contours, when the metal inside the contour is the desired part.



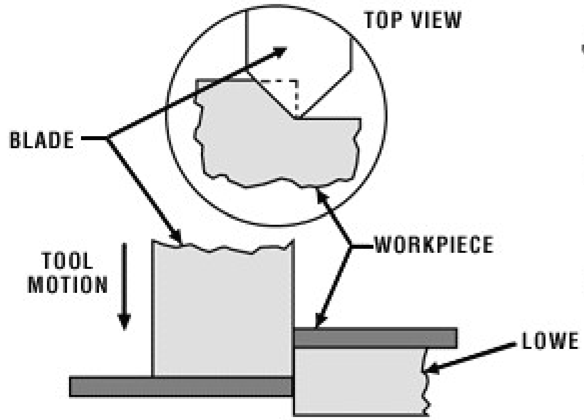

Punching or piercing :

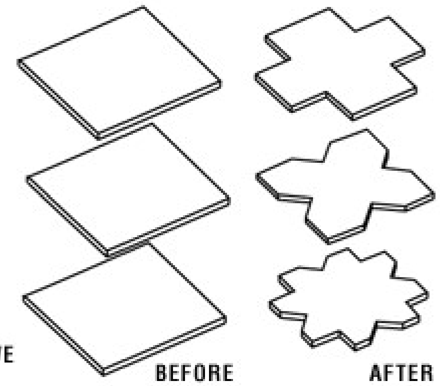
The shearing of the material when the metal inside the contour is discarded.



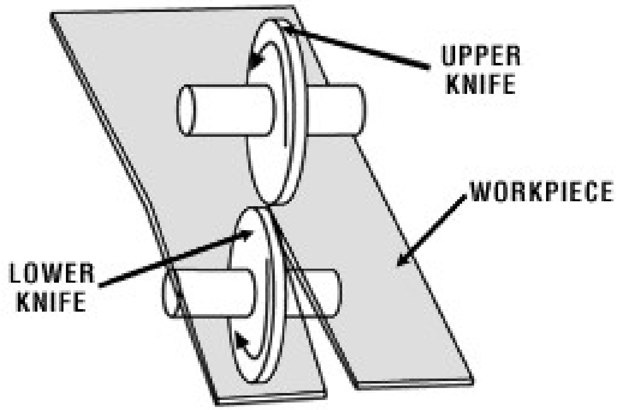
Notching : The punch removes material from the edge or corner of a strip or blank or part.



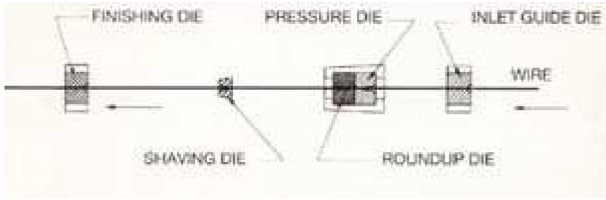
Parting : The simultaneous cutting along at least two lines which balance each other from the standpoint of side thrust on the parting tool.

Slitting : Cutting or shearing along single lines to cut strips from a sheet or to cut along lines of a given length or contour in a sheet or workpiece.

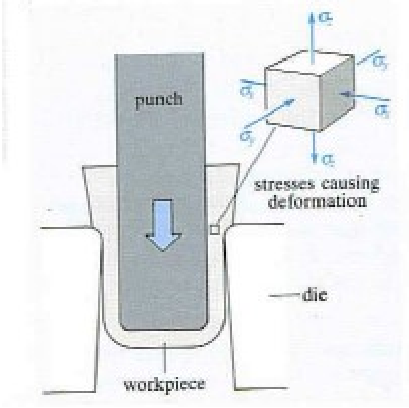



Trimming : Operation of cutting scrap off a partially or fully shaped part to an established trim line.

Shaving : A secondary shearing or cutting operation in which the surface of a previously cut edge is finished or smoothed by removing a minimal amount of stock.



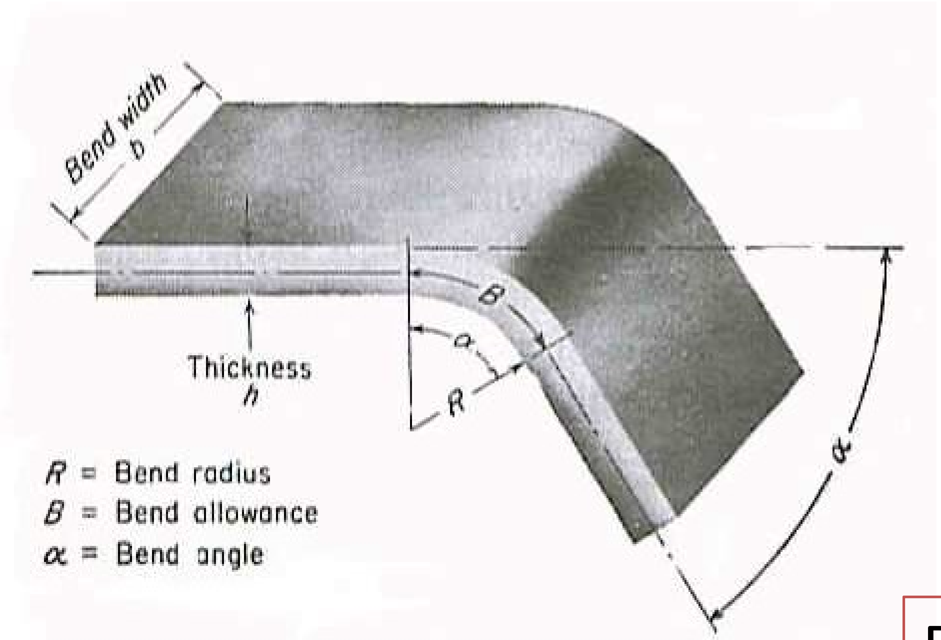

Ironing : A continuous thinning process and often accompanies deep drawing, i.e., thinning of the wall of a cylindrical cup by passing it though an ironing die.




Fine blanking : Very smooth and square edges are produced in small parts such as gears, cams, and levers

# Bending

The process by which a straight length is transformed into a curve length. Ex.: channel, drums, tanks tec.




Fibres on the outer surface are strained and fibres on the inner surface are contracted. Fibres at the mid thickness is stretched.

The bend radius R = the radius of curvature on the concave, or inside surface of the bend.

Decrease in thickness (radius direction) at the bend to preserve the constancy of volume.

R ↓ thickness on bending ↓

Condition:

- No change in thickness
- The neutral axis will remain at the centre fibre.
- Circumferential stretch on the top surface $e_a$ = shrink on the bottom surface, $e_b$

R ↓ strain ↑

R bend radius

h thickness

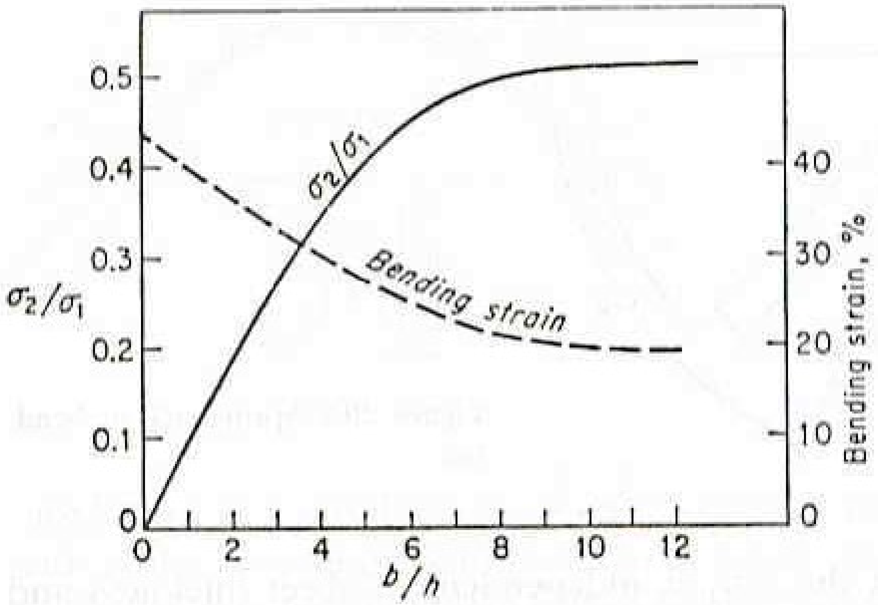
$$e_a = -e_b = \frac{1}{(2R/h)+1}$$

**The minimum bend radius**

- For a given bending operation, the smallest bend radius can be made without cracking on the outer tensile surface.
- Normally expressed in multiples of sheet thickness.

Example: a 3T bend radius means the metal can be bend without cracking though a radius equal to three times the sheet thickness T.

# Effect of b/h ratio on ductility




Effect of b/h on biaxiality and bend ductility

- Stress state is biaxial ($\sigma_2/\sigma_1$ ratio)
- Width / thickness = b/h ratio

b/h ↑ biaxiality ↑

⇓

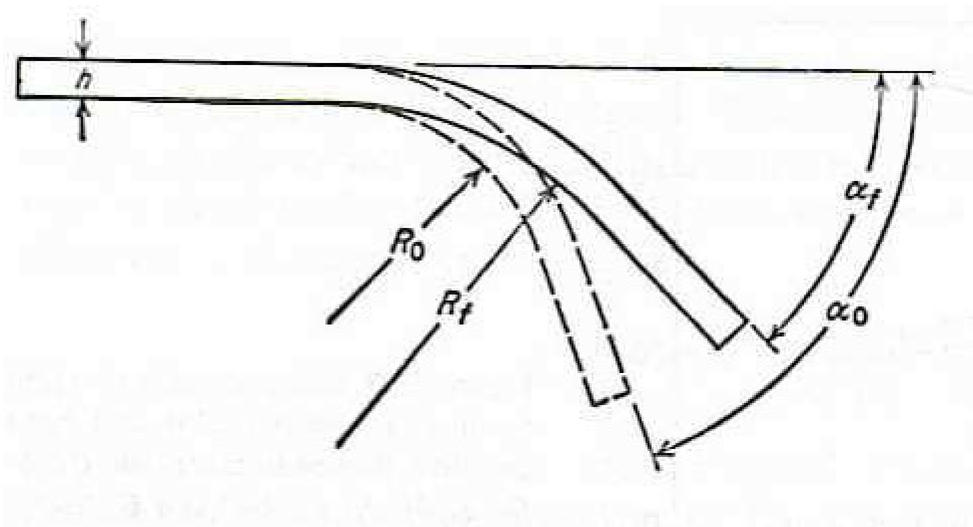
Strain, ductility ↓

⇓

Cracks occur near the centre of the street

# Springback

Dimensional change of the formed part after releasing the pressure of the forming tool due to the changes in strain produced by elastic recovery.




Yield stress ↑
Elastic modulus ↓

↓

Plastic strain ↑
Spring back ↑

Springback is encountered in all forming operations, but most easily occurs in bending.

For aluminium alloys and austenitic stainless steels, approximate springback in bending can be expressed by

$$\frac{R_o}{R_f} = 4\left(\frac{R_o \sigma}{Eh}\right)^3 - 3\frac{R_o \sigma}{Eh} + 1$$

Where $R_o$ = the radius of curvature before release of load

$R_f$ = the radius of curvature after release of lead

and $R_o < R_f$

**Solutions:** compensating the springback by bending to a smaller radius of curvature than is desired (over bending). By trial-and-error.

The force $P_b$ required to bend a length L about a radius R may be estimated from

$$P_b = \frac{\sigma_o L h^2}{2(R + h/2)} \tan\frac{\alpha}{2}$$

# Tube bending

- Bending of tube and structural material for industry, architecture, medical, refinery.

- Heat induction and hot slap bending require the heating of pipe, tube or structural shapes.

- Heat Induction bending is typically a higher cost bending process and is primarily used in large diameter material.

# Stretch forming

• Forming by using tensile forces to stretch the material over a tool or form block.

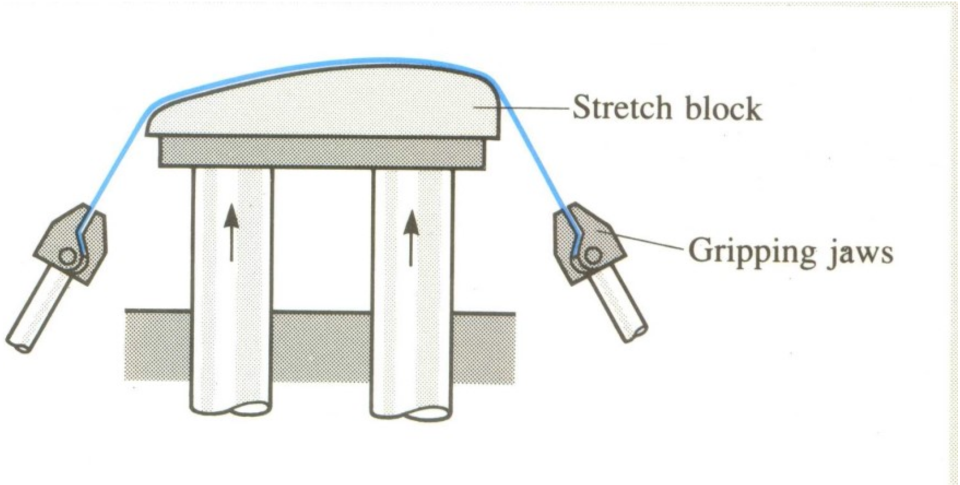
• used most extensively in the aircraft industry to produce parts of large radius of curvature. (normally for uniform cross section).

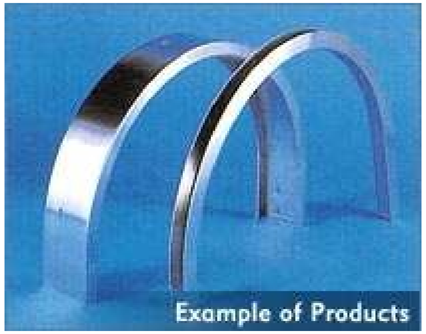
• required materials with appreciable ductility.

Specialized stretch form machines up to 1600 tons

• Springback is largely eliminated because the stress gradient is relatively uniform.

# Stretch forming equipment




- Using a hydraulic driven ram (normally vertical).
- Sheet is gripped by two jaws at its edges.
- Form block is slowly raised by the ram to deform sheet above its yield point.
- The sheet is strained plastically to the required final shape.

Examples: large thin panel, most complex automotive stamping involve a stretching component.

**Diffuse necking :** ( a limit of forming)

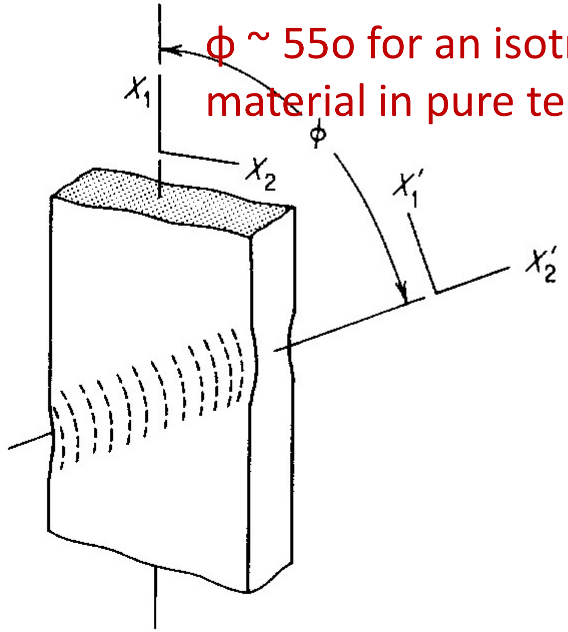
In biaxial tension, the necking which occurs in uniaxial tension is inhibited if $\sigma_2/\sigma_1 > 1/2$, and the materials then develops diffuse necking. (not visible)

The limit of uniform deformation in strip loading occurs at a strain equals to the strain-hardening exponent n. $\varepsilon_u = n$

**Localised necking**

- Plastic instability of a thin sheet will occur in the form of a narrow localised neck. → followed by fracture of the sheet.
- Normal strain along $X'_2$ must be zero.

ϕ ~ 55o for an isotropic material in pure tension

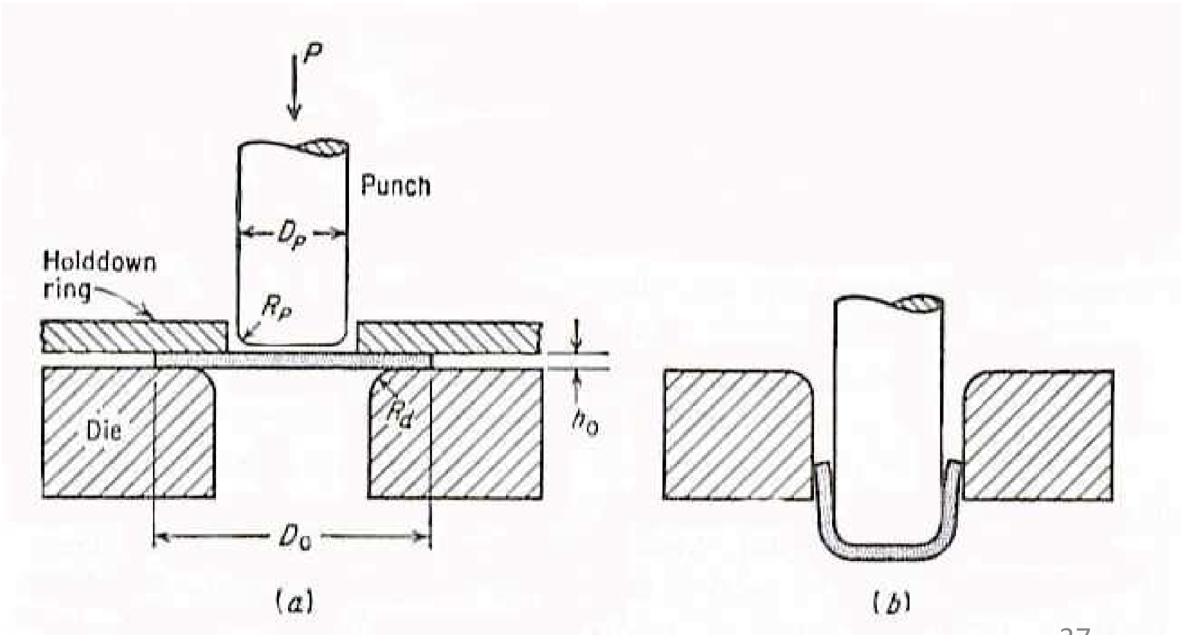


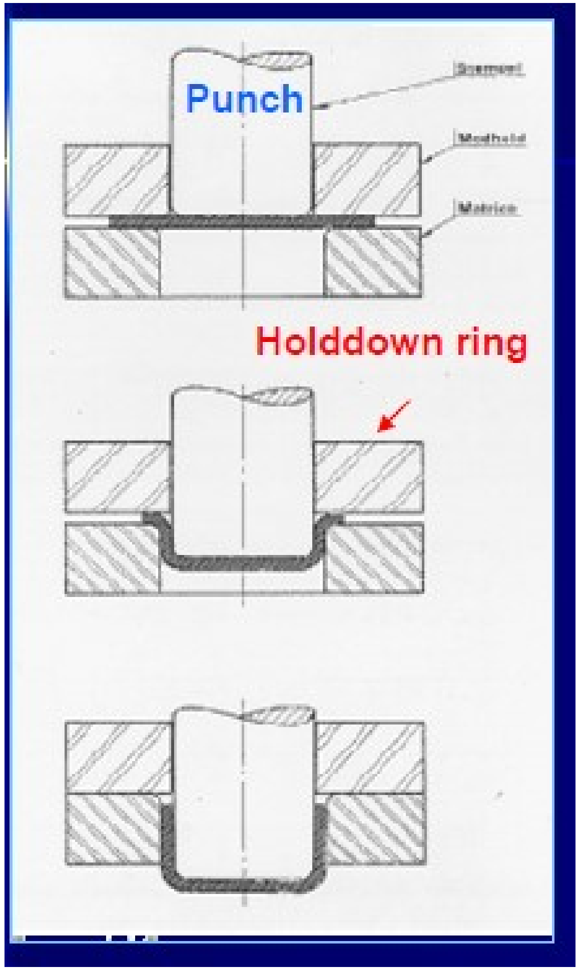

Loca … n

# Deep drawing

- The metalworking process used for shaping  flat sheets into cup-shaped articles.
- Examples: bathtubs, shell cases, automobile panels.

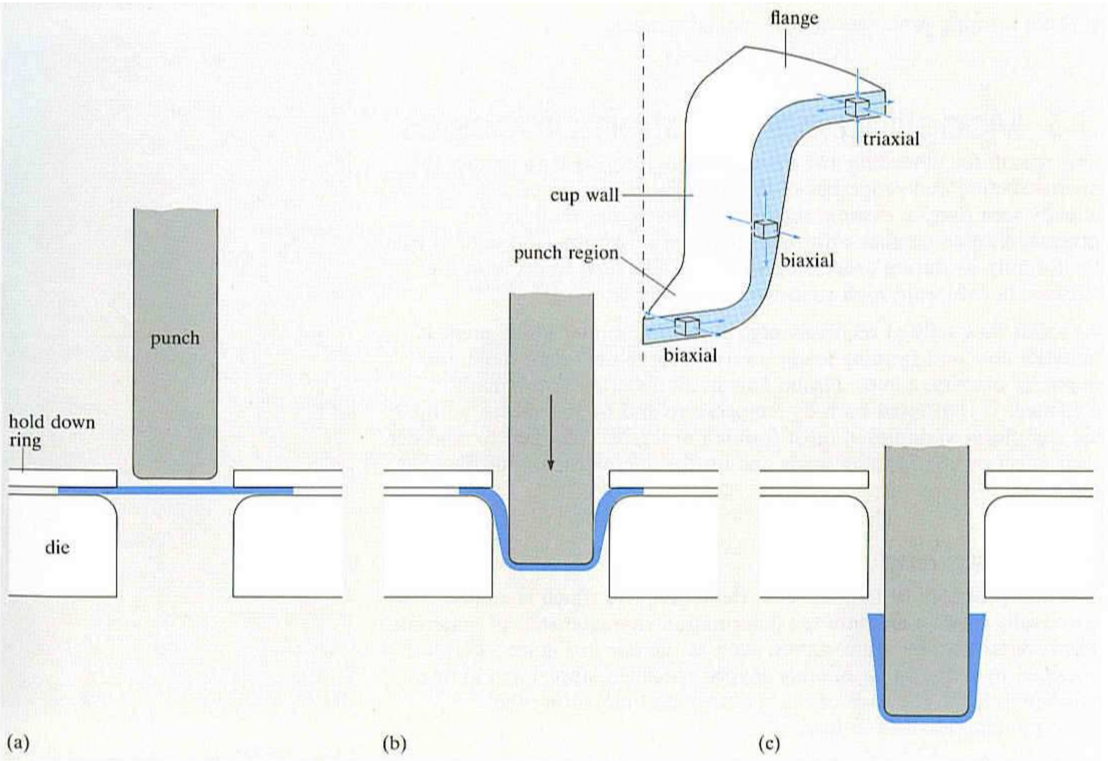
Pressing the metal blank of appropriate size into a shaped die with a punch.





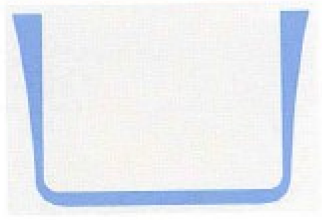

It is best done with double-action press.

- Using a blank holder or a holddown ring
- Complex interaction between metal and die depending on geometry.
- No precise mathematical description can be used to represent the processes in simple terms.




As the metal being drawn,

- Change in radius
- Increase in cup wall



*Thickness profile of drawn cup*

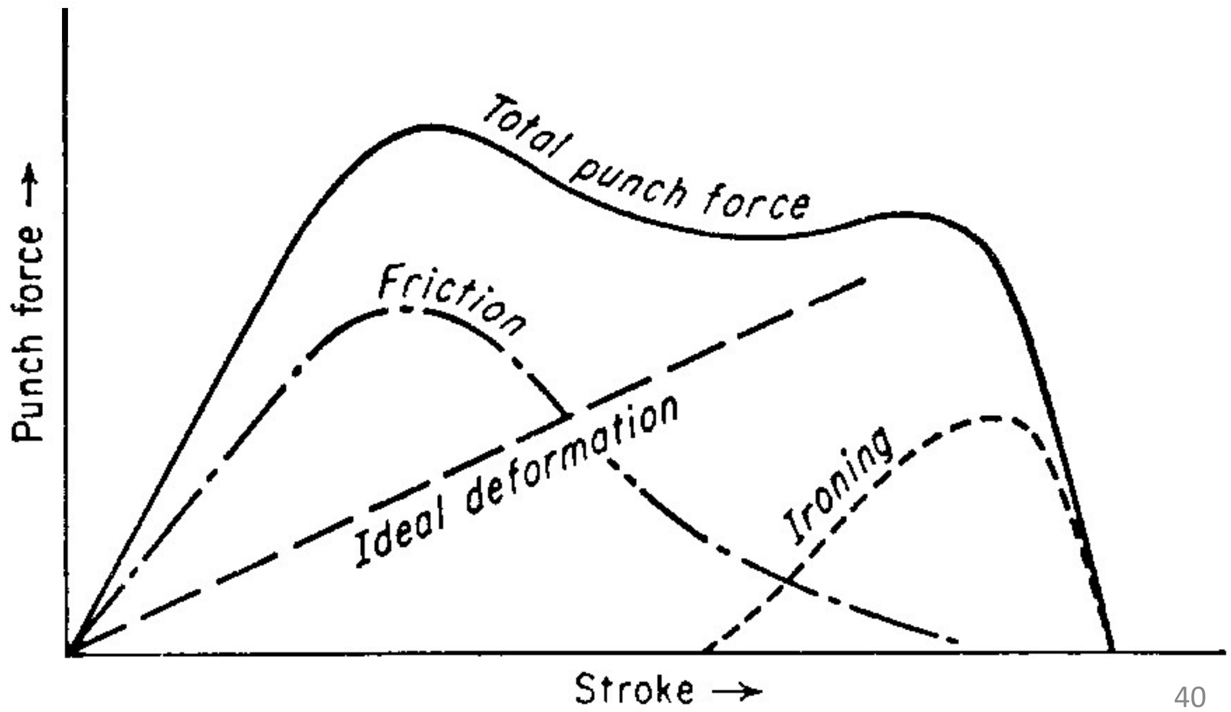
Clearance between the punch and the die > 10-20% thickness.

- Metal in the punch region is thinned down → biaxial tensile stress
- Metal in the cup wall is subjected to a circumference strain, or hoop and a radial tensile strain.
- Metal at the flange is bent and straightened as well as subjected to a tensile stress at the same time.

# Punch force vs. punch stroke

Punch force $= F_{deformation} + F_{frictional} + (F_{ironing})$

- $F_{deformation}$ - varies with length of travel
- $F_{frictional}$ - mainly from hold down pressure
- $F_{ironing}$ - after the cup has reached the maximum thickness.
- Additional factor is the force required to bend and unbend the metal around the radius of the die



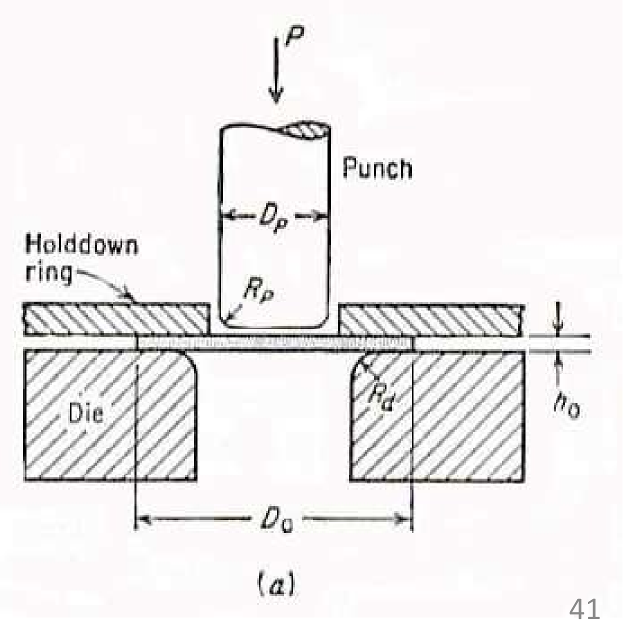
# Drawability (deep drawing)

Drawability is a ratio of the initial blank diameter ($D_o$) to the diameter of the cup drawn from the blank ~ punch diameter ($D_P$)

Limiting draw ratio (LDR), $$LDR \approx \left(\frac{D_o}{D_p}\right)_{max} \approx e^{\eta}$$

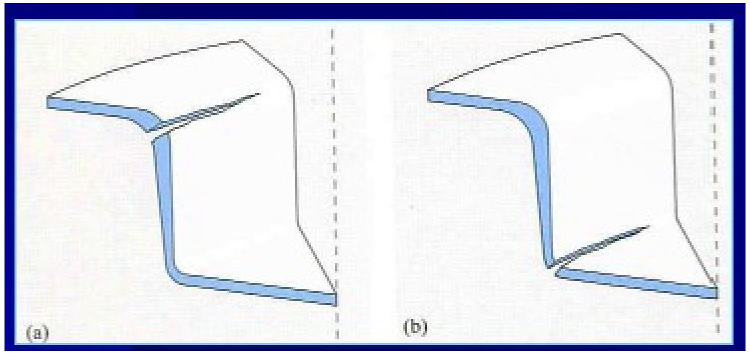
Where η is an efficiency term accounting for frictional losses.

Normally the average maximum reduction in deep drawing is ~50%



# Practical considerations affecting drawability

- Die radius – should be about 10 x sheet thickness.
- Punch radius – a sharp radius leads to local thinning and tearing.
- Clearance between punch and die should be about 20- 40% > sheet thickness.
- Hold-down pressure – about 2% of average $\sigma_o$ and $\sigma_u$.
- Lubrication of die side - to reduce friction in drawing.
- Material properties - low yield stress, high work hardening rates, high values of strain ratio of width to thickness R.

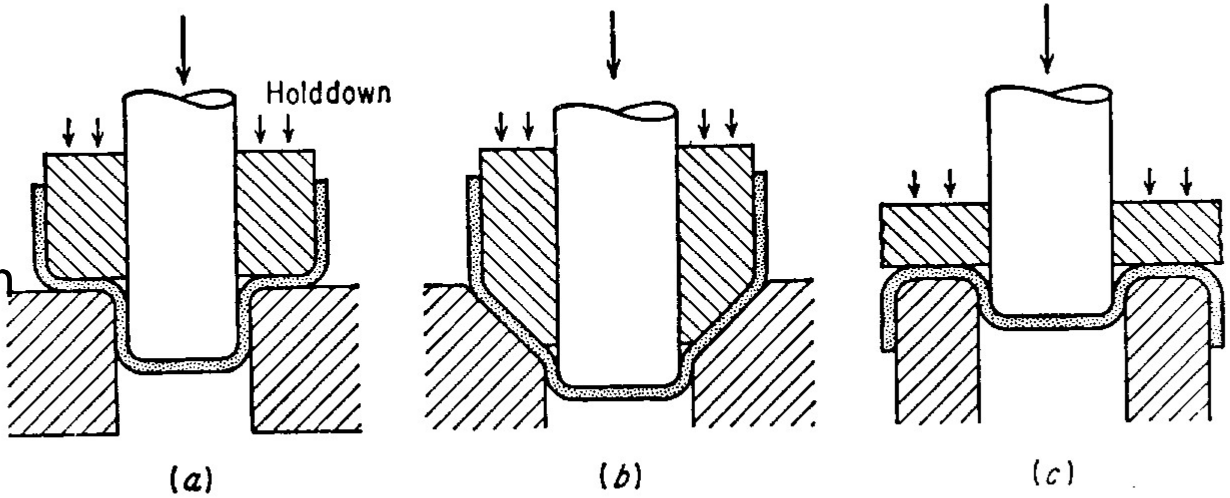



- Since the forming load is carried by the side wall of the cup, failure therefore occurs at the thinnest part.
- In practice the materials always fails either at (a) the shoulder of the die and (b) the shoulder of the punch.

# Redrawing

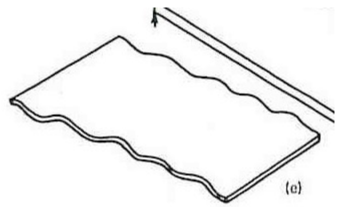
• Use successive drawing operations by reducing a cup or drawn part to a smaller diameter and increased height – known as redrawing.

Examples: slender cups such as cartridge case and closed end tubes.

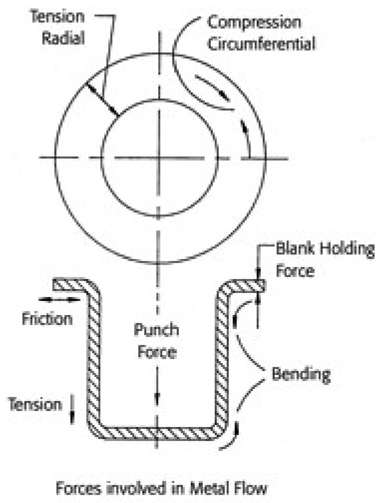



1) Direct or regular redrawing :
smaller diameter is produced by means of a hold-down ring. The metal must be bent at the punch and unbent at the die radii see Fig (a). Tapered die allows lower punch load, Fig (b).

2) Reverse or indirect redrawing :
the cup is turned inside surface into outside surface. Fig (c). Better control of wrinkling is necessary and no geometrical limitations to the use of a holddown ring.



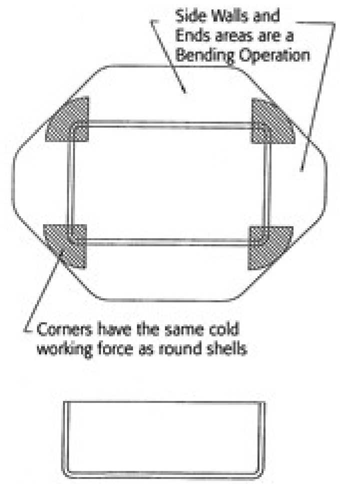
# Practical considerations for round and rectangular shells




Round shell

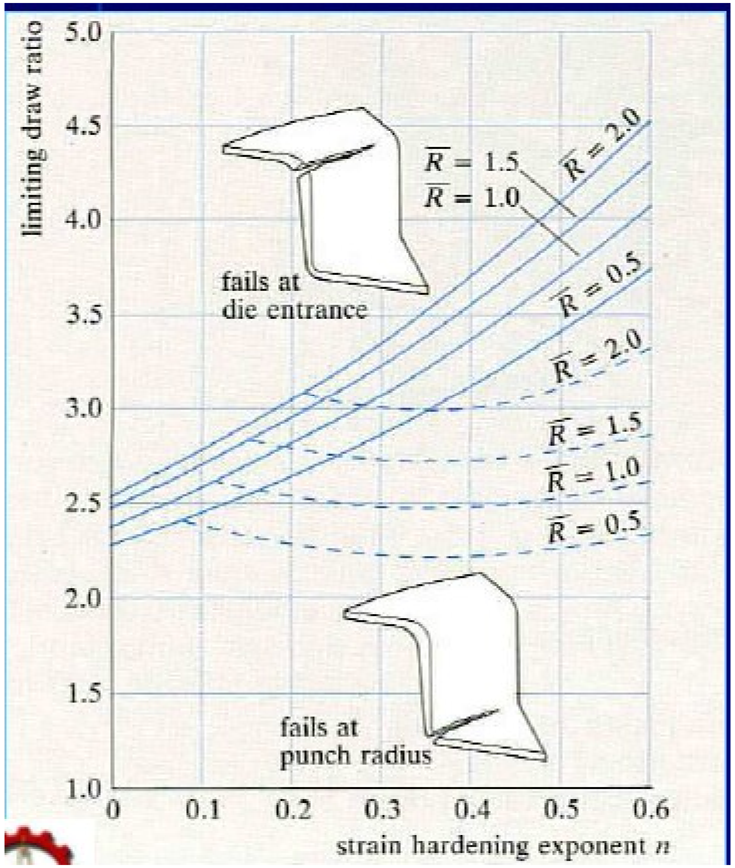
- Different pressures (tension, compression, friction, bending) force the material into shape, perhaps with multiple successive operations.

- Different flow patterns at sides and corners.
- Corners require similar flow as round shells while sides need simple bending.
- The corner radii control the maximum draw depth.
- Centre to center distance of corners ≥ 6 x corner radius
- Bottom radius ≥ corner radius




Rectangular shell

# To improve drawability




The dependence of limiting draw ratio on R and work hardening rate, n

- To avoid failures in the thin parts (at the punch or flange), metal in that part need to be strengthened, or weaken the metal in other parts (to correct the weakest link).

- If sufficient friction is generated between punch and workpiece, more of the forming load is carried by the thicker parts.

- Concerning about crystallographic texture (slip system), degree of anisotropy or strain ratio R.

The plastic strain ratio R measures the normal anisotropy, which denotes high resistance to thinning in the thickness direction.

$$R = \frac{\ln(w_o / w)}{\ln(h_o / h)}$$

Where $w_o$ and w are the initial and final width

$h_o$ and h are the initial and final thickness.

But it is difficult to measure thickness on thin sheets, therefore we have

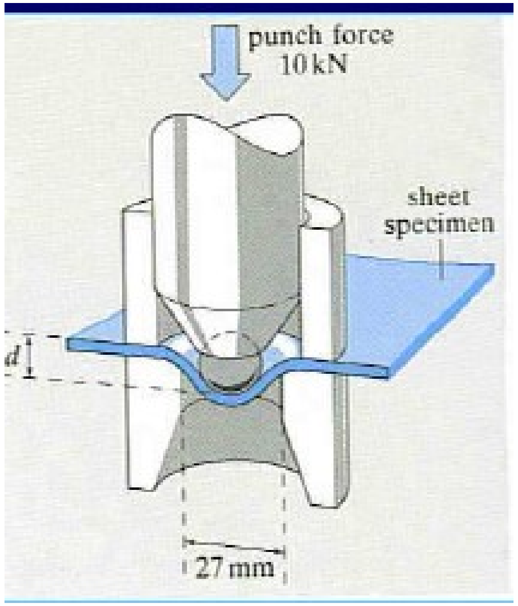
$$R = \frac{\ln(w_o / w)}{\ln(wL / w_o L_o)}$$

# Forming limit criteria

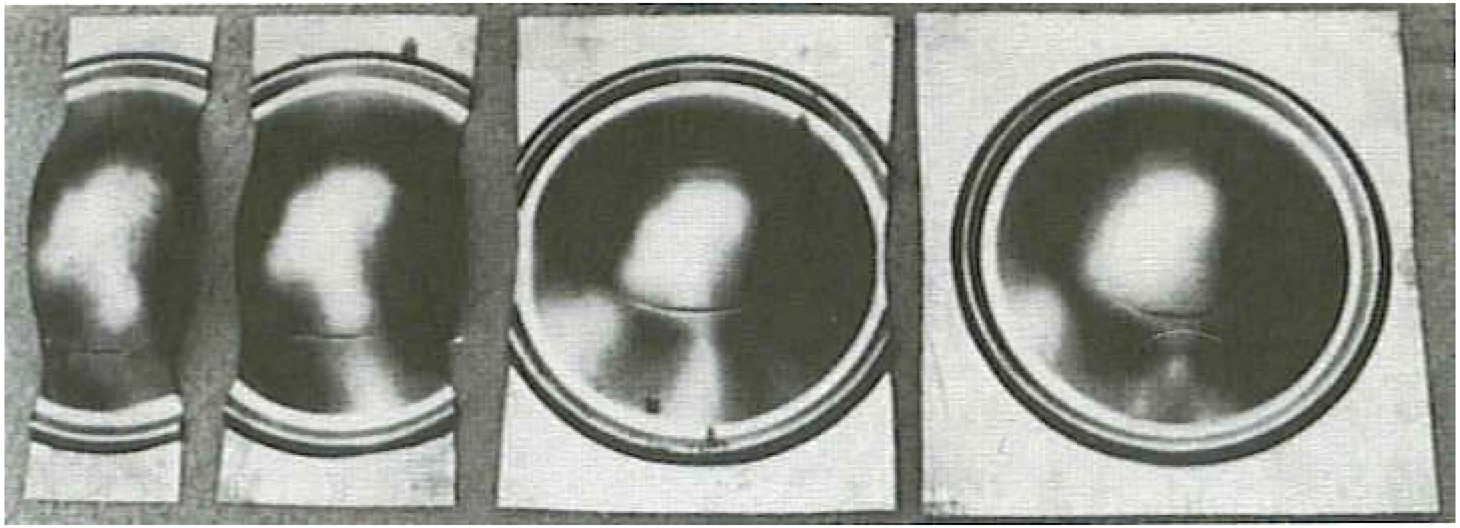
- Tensile test only provides ductility, work hardening, but it is in a uniaxial tension with frictionless, which cannot truly represent material behaviours obtained from unequal biaxial stretching occurring in sheet metal forming.

- Sheet metal formability tests are designed to measure the ductility of a materials under condition similar to those found in sheet metal forming.

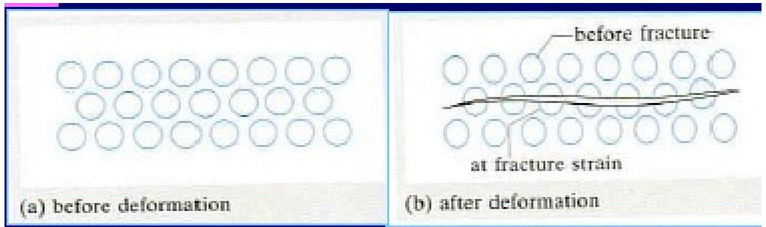
# Erichsen cupping test



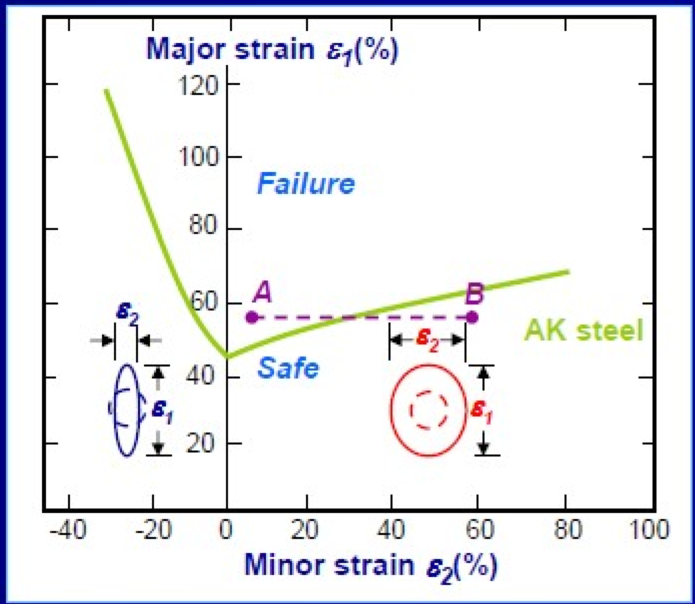

- Simple and easy.
- symmetrical and equal biaxial stretching.
- Allow effects of tool-workpiece interaction and lubrication on formability to be studied.
- The sheet metal specimen is hydraulically punched with a 20 mm diameter steel ball at a constant load of 1000 kg.
- The distance d is measured in millimetres and known as Erichsen number.



# Forming limit diagram




*Grid analysis (a) before (b) after deformation of sheet.*




*Forming limit diagram*

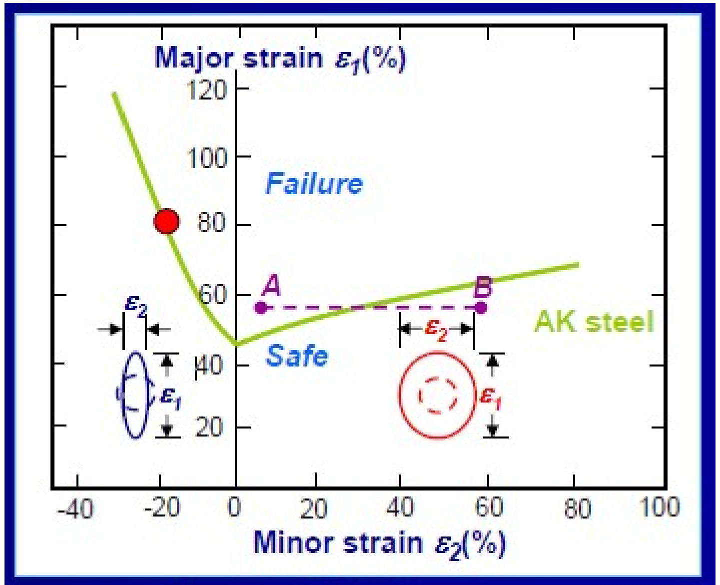
- The sheet is marked with a close packed array of circles using chemical etching or photo printing techniques.
- The blank is then stretched over a punch, resulting in stretching of circles into ellipses.
- The major and minor axes of an ellipse represent the two principal strain directions in the stamping.
- The percentage changes in these strains are compared in the diagram.
- Comparison is done in a given thickness of the sheet.

Example: A grid of 2.5 mm circles is electroetched on a blank of sheet steel. After forming into a complex shape the circle in the region of critical strain is distorted into and ellipse with major diameter 4.5 mm and minor diameter 2.0 mm. How close is the part to failing in this critical region?

Major Strain e1= (4.5-2.5)/2.5 x 100 = 80%

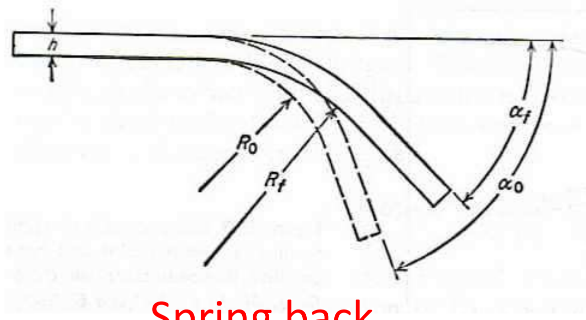
Minor strain e2=(2.0-2.5)/2.5 x 100 = -20%

The coordinates indicate that the part is in imminent danger of failure.



Forming limit diagram

# Defects in formed parts

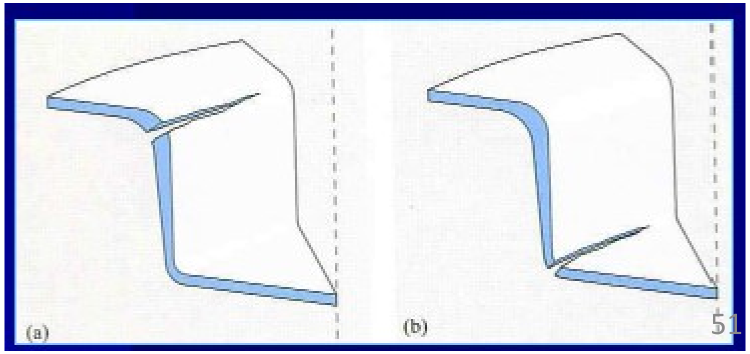



Spring back


Edge condition of blanking

- Edge conditions for blanking.
- Local necking or thinning or buckling and wrinkling in regions of compressive stress.
- Springback tolerance problems.
- Cracks near the punch region in deep drawing → minimised by increasing punch radius, lowering punch load.

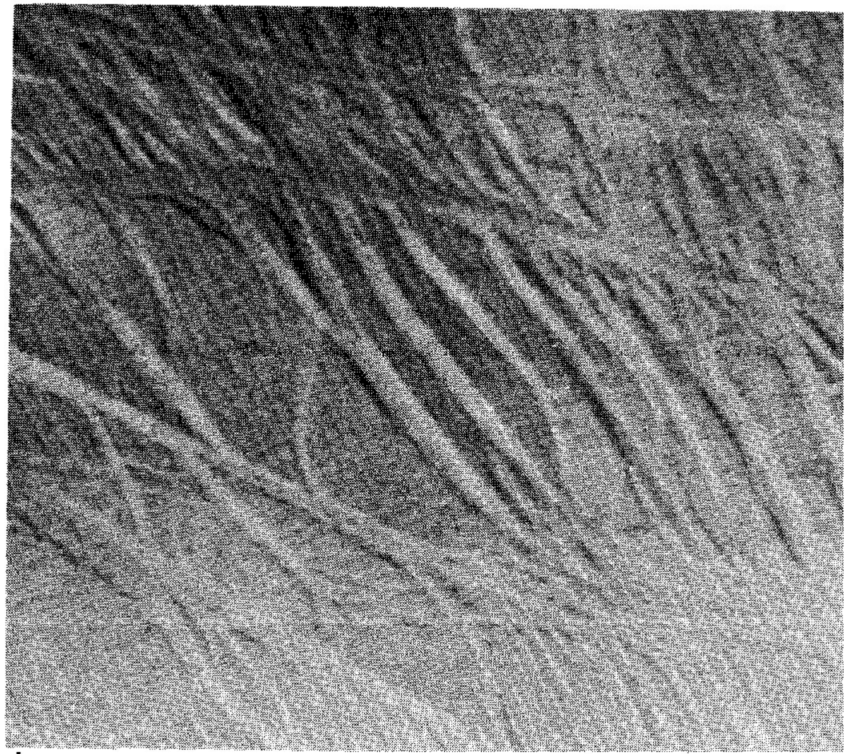
Cracks new punch region

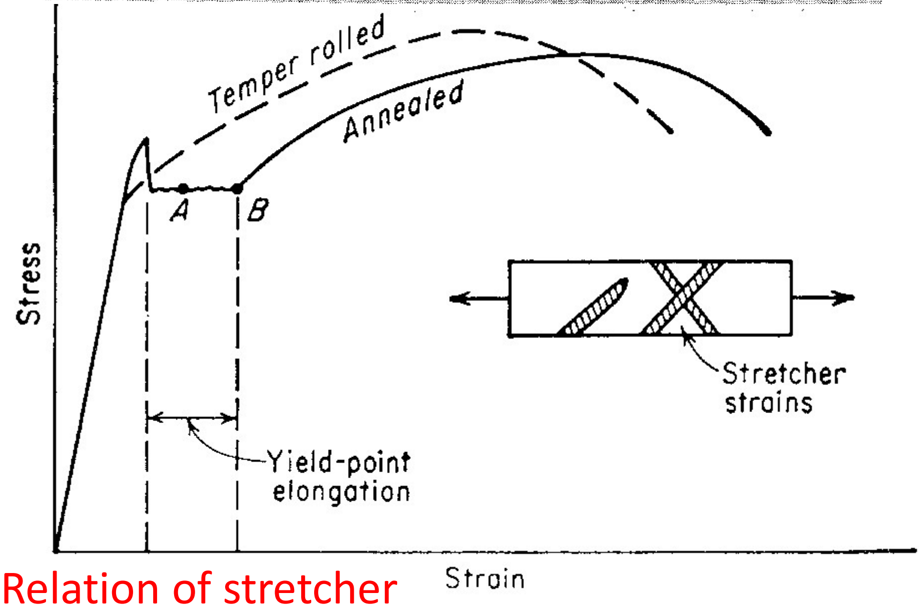


- Radial cracks in the flanges and edge of the cup due to not sufficient ductility to withstand large circumferential shrinking.
- Wrinkling of the flanges or the edges of the cup resulting from buckling of the sheet (due to circumferential compressive stresses) solved by using sufficient hold-down pressure to suppress the buckling.
- Surface blemishes due to large surface area. EX: orange peeling (pronounced surface roughness in regions of the part which have undergone appreciable deformation) especially in large grain sized metals because each grain tends to deform independently use finer grained metals.
- Mechanical fibering has little effect on formability.
- Crystallographic fibering or preferred orientation may have a large effect. Ex: when bend line is parallel to the rolling direction is difficult than perpendicular direction.

  Ex: Earing in deep drawn cup due to anisotropic properties. Earing → wavy edge on the tope of drawn cup which require extensive trimming.

Earing in drawn can






Relation of stretcher

- <u>Stretcher strains </u>or 'worms' (flamel ike patterns of depressions). Associated with yield point elongation.
- Observed in low carbon steel
- The metal in the stretcher strains has been strained an amount = B, while the remaining received essentially zero strain.
- The elongation of the part is given by some intermediate strain A.
- The number of stretcher strains increase during deformation. The strain will increase until the when the entire part is covered it has a strain equal to B.

Solution: give the steel sheet a small cold reduction (usually 0.5-2% reduction in thickness).
Ex: temper-rolling, skin-rolling to Eliminate strain to stress yield point.