Sheet-metal forming

Subjects of interest

- *Introduction/objectives*

- *Deformation geometry*

- *Forming equipments*

- *Shearing and blanking*

- *Bending*

- *Stretch forming*

- *Deep drawing*

- *Forming limit criteria*

- *Defects in formed parts*

Objectives

• Methods of sheet metal processes such as stretching, shearing, blanking, bending, deep drawing, redrawing are introduced.

• Variables in sheet forming process will be discussed together with formability and test methods.

• Defects occurring during the forming process will be emphasised. The solutions to such defect problems will also be given.

Introduction
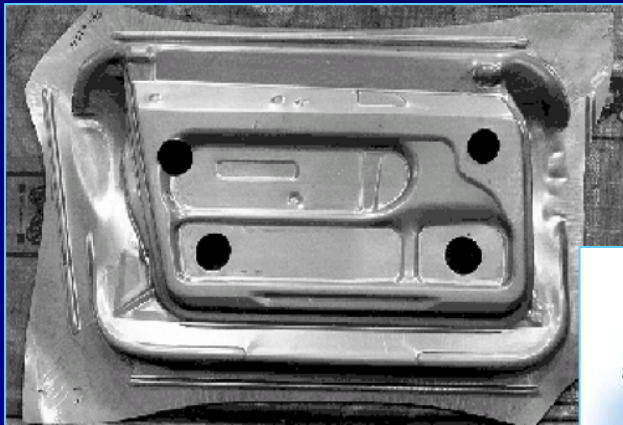
- **<u>Sheet metal forming</u>** is a process that materials undergo **permanent deformation** by cold forming to produce a variety of complex three dimensional shapes.

- The process is carried out in the plane of sheet by **tensile forces** with **high ratio of surface area to thickness.**

- **Friction conditions** at the tool-metal interface are very important and controlled by press conditions, lubrication, tool material and surface condition, and strip surface condition.

- **High rate of production** and **formability** is determined by its mechanical properties.
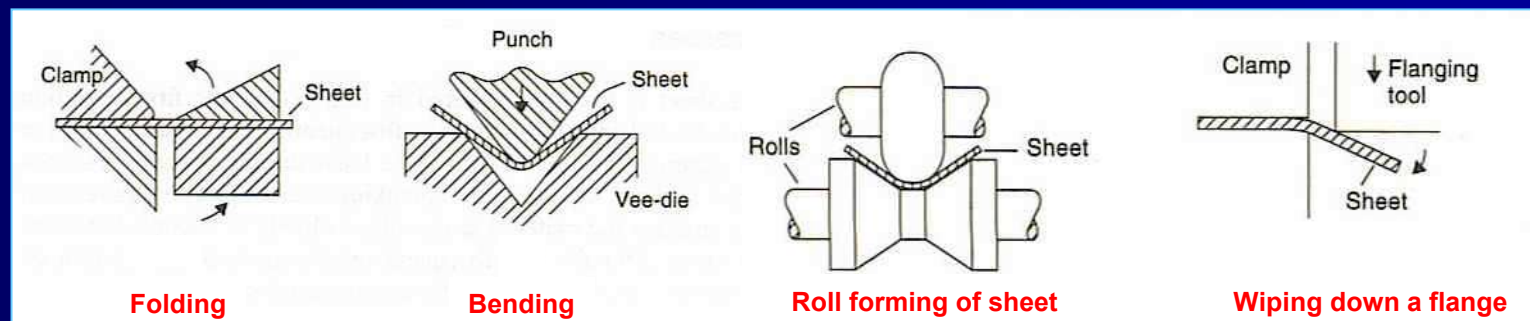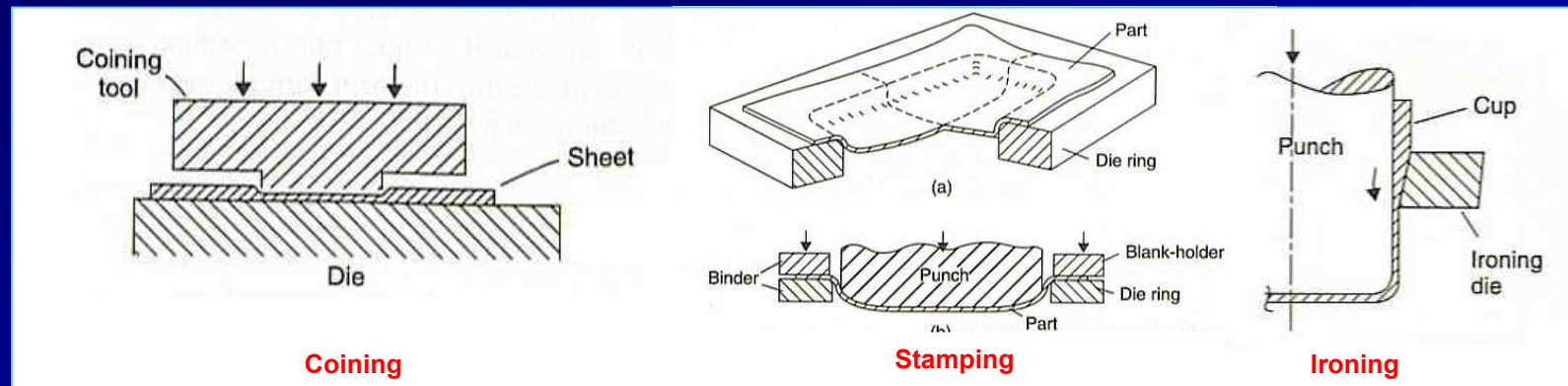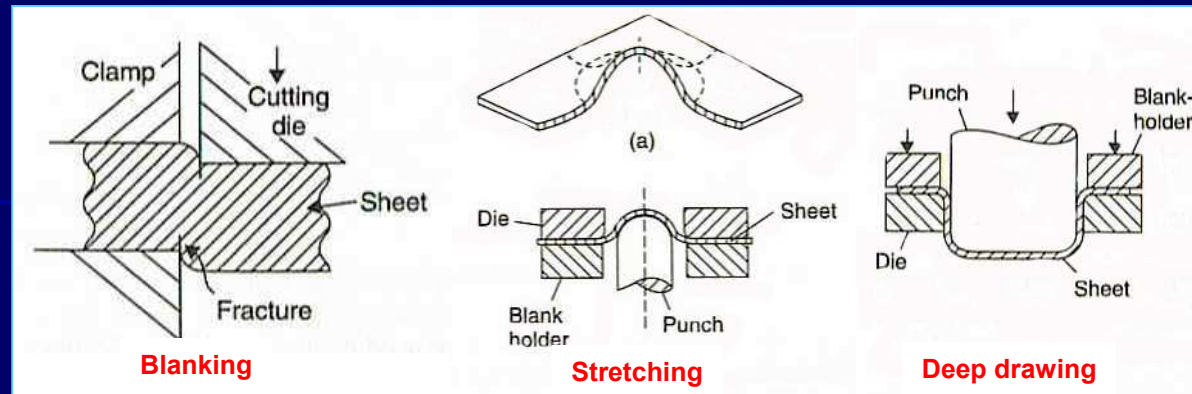
Classification of sheet metal parts (based on contour)

(a) Singly curve

(b) Stretch flange

(c) Shrink flange

(d) Curved section

(e) Deep drawn cup
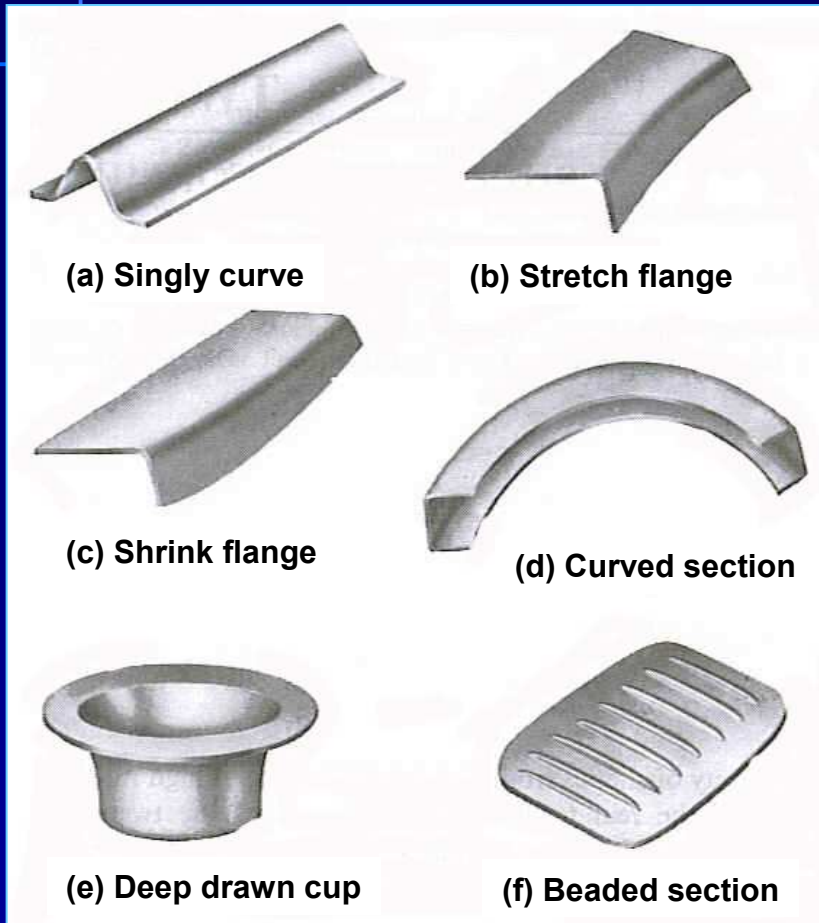
(f) Beaded section

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.

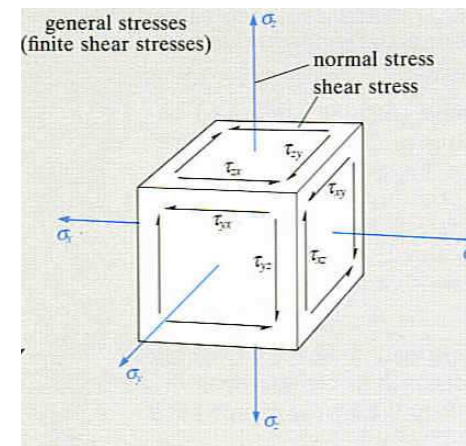# *Classification of sheet metal forming* (based on operations)

Blanking   Stretching   Deep drawing

Coining   Stamping   Ironing

Folding   Bending   Roll forming of sheet   Wiping down a flange

Stress state in deformation processes

- The *geometry* of the workpiece can be essentially *three dimensional* (i.e., rod or bar stock) or *two dimensional* (i.e., thin sheets).

- The *state of stress* is described by *three principal stresses*, which act along axes perpendicular to *principal planes*.

- The principal stresses are by convention called σ_1, σ_2 and σ_3 where $\sigma_1 > \sigma_2 > \sigma_3$

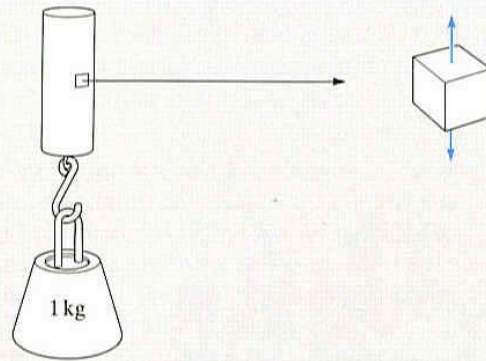σ_3

σ_2

σ_1
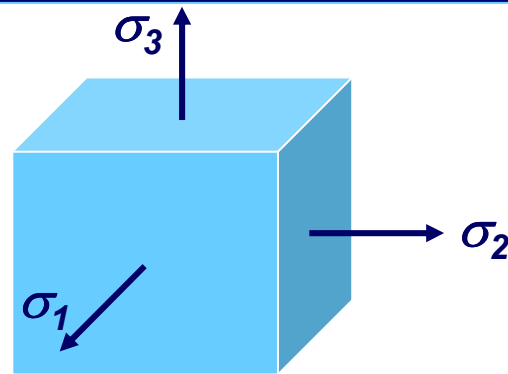
Principal stresses on an element in a three-dimensional stress state

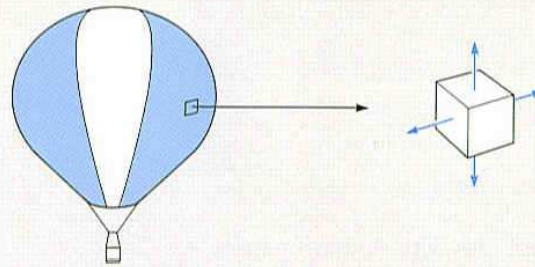general stresses (finite shear stresses)

normal stress
shear stress

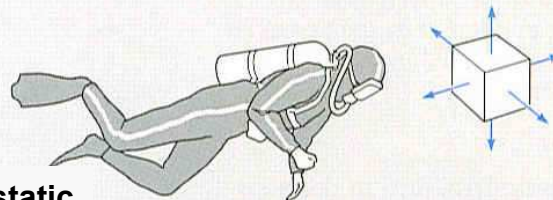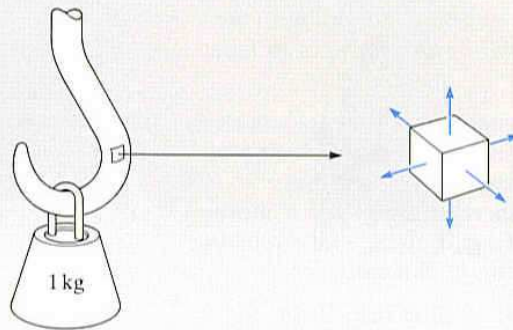- Hydrostatic stress state is when $\sigma_1 = \sigma_2 = \sigma_3$
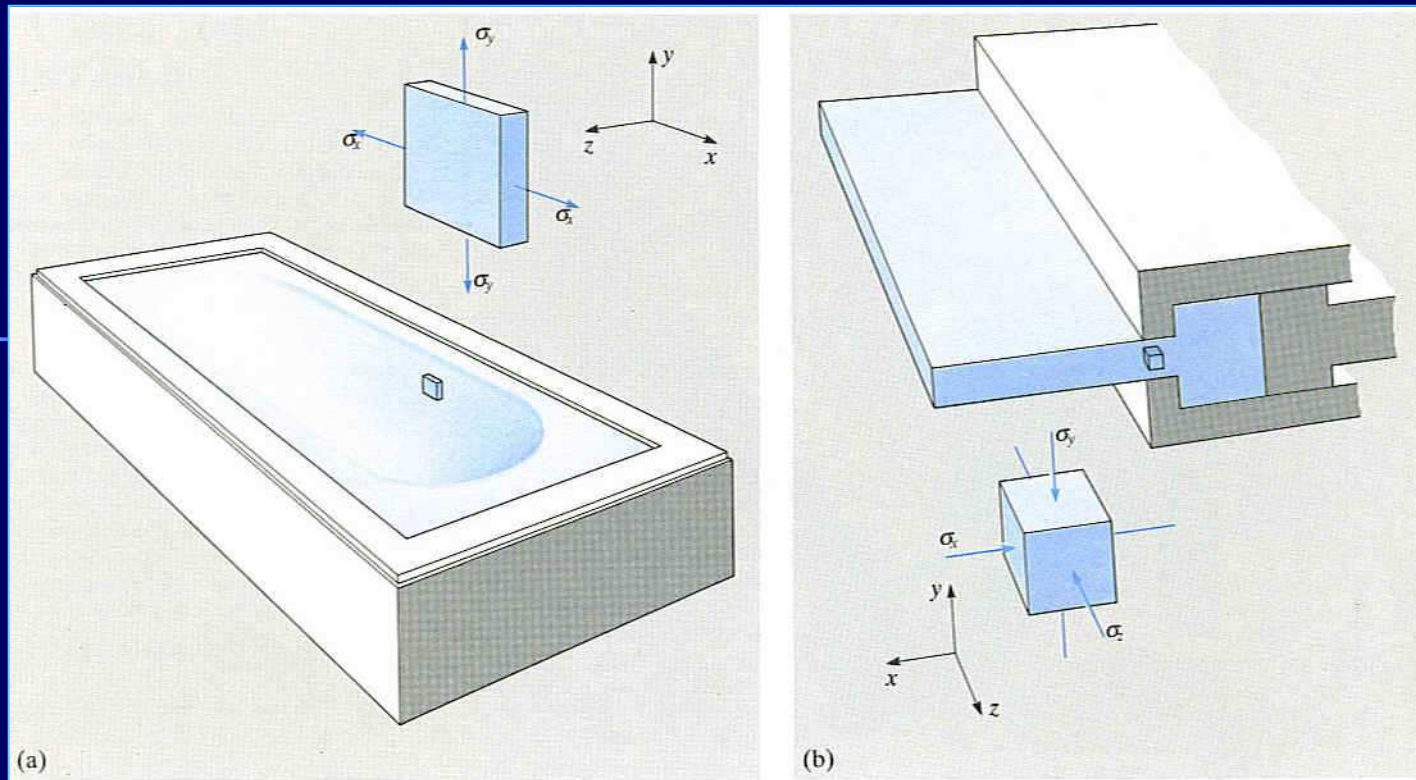
a) Uniaxial

b) Biaxial

c) Hydrostatic

d) Triaxial

- *Shear stresses* provide driving force for plastic deformation.

- *Hydrostatic stresses* cannot contribute to shape change but involve in failure processes

- *Tensile*
    → crack growth or void formation
- *Compressive*
    → hinder crack, close void.

Stress system in (a) sheet processes and (b) bulk processes.

• In **sheet deformation processes** (i.e., sheet metal forming, vacuum forming, blow moulding), the workpiece is subjected to two dimensional **biaxial stresses**. (also depending on geometry)
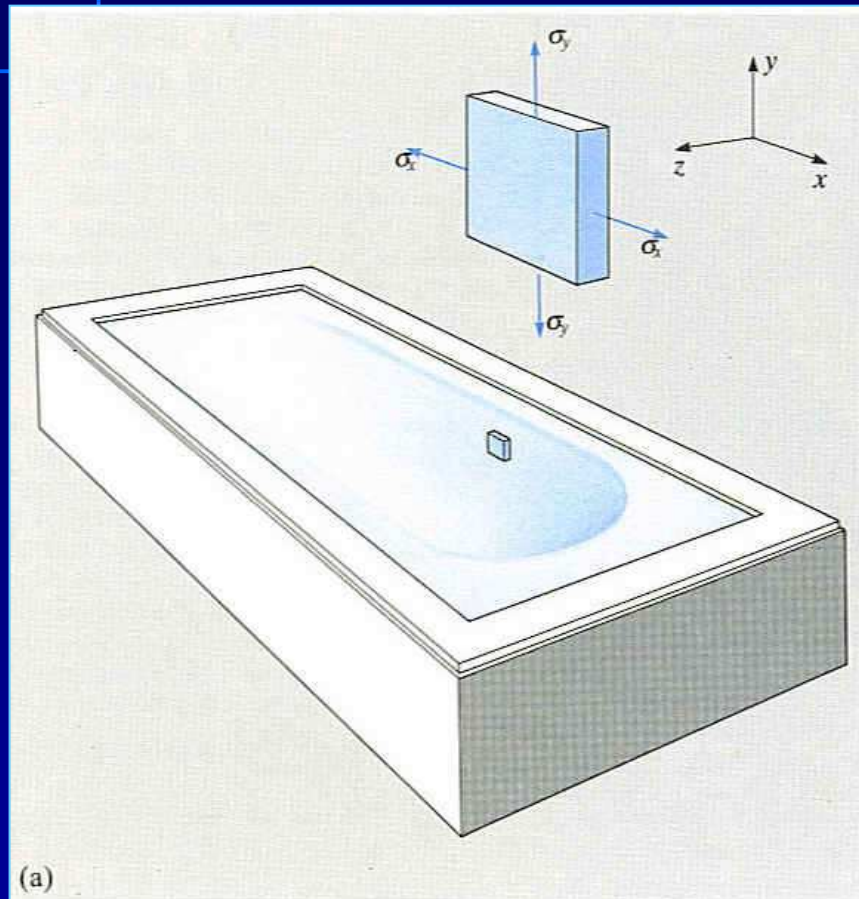
• In **bulk deformation processes** (i.e. forging, rolling and extrusion), the workpiece is subjected to **triaxial stresses**, which are normally **compressive**.

Deformation geometry

Plane stress

Plane stress condition

- *Principal stresses* σ_1 and σ_2 are set up together with their associated strain in the *x-y* plane.

- The sheet is free to contact (*not constrained*) in the σ_3 (*z*) direction. There is strain in this direction but no stress, thus σ_3 *= 0.*, resulting in *biaxial stress system.*

- Since the stress are effectively confined to one plane, this stress system is known as *plane stress*.

Plane strain

(b)

Plane strain condition
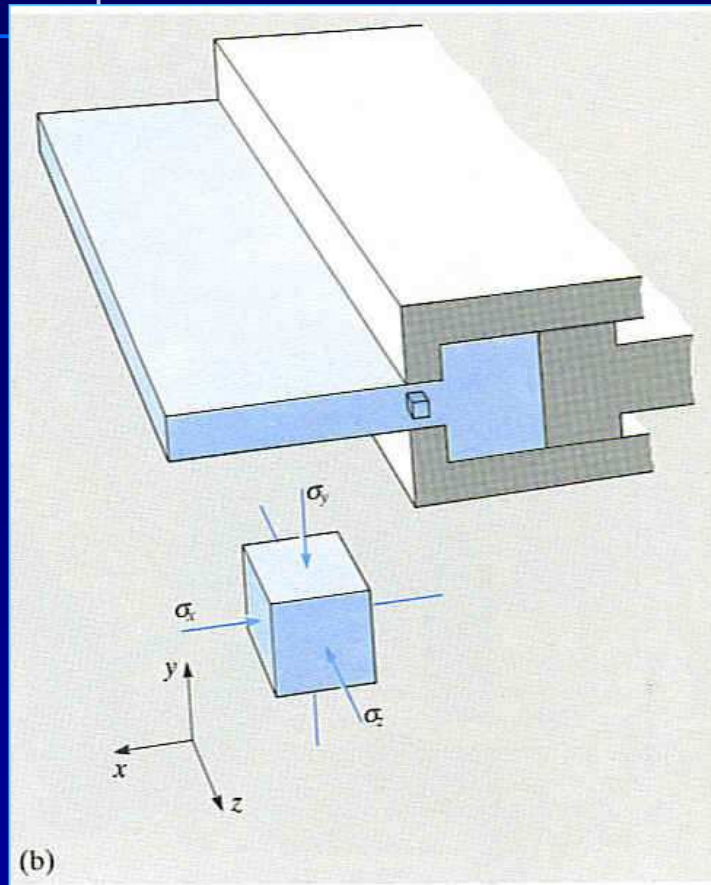
• Deformation (***strain***) often occurs in only two dimensions (parallel to σ_1 and σ_2).

• σ_3 is finite, preventing deformation (strain) in the **z** direction (constrained), which is known as ***plane strain***.

Example: the extrusion of a thin sheet where material in the centre is constrained in the **z** direction.

Forming equipments

Forming equipments include
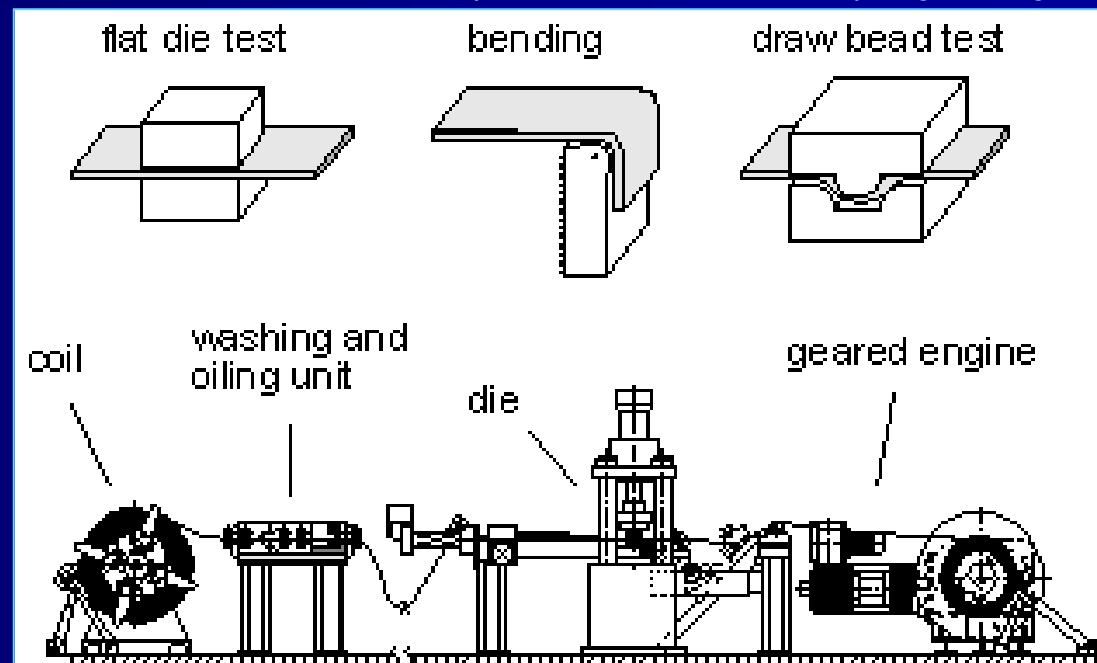
1) Forming presses

2) Dies

3) Tools

www.ptu.tu-darmstadt.de/.../ictmp/img00011.gif

Equipments in sheet metal forming process

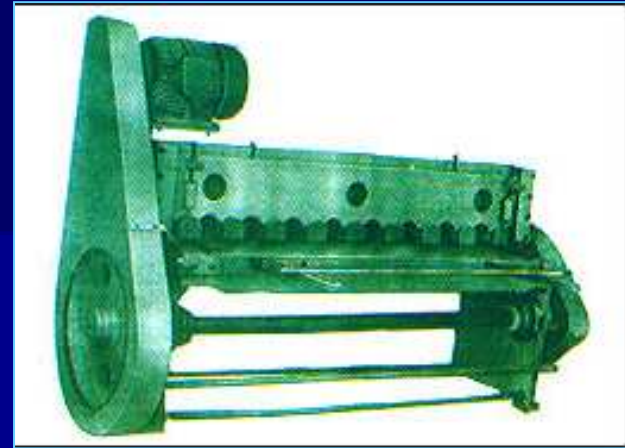# *Forming machines*

Shearing machine (mechanical)

• Using mechanical or hydraulic presses.

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.

Hydraulic deep drawing press

Actions 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.
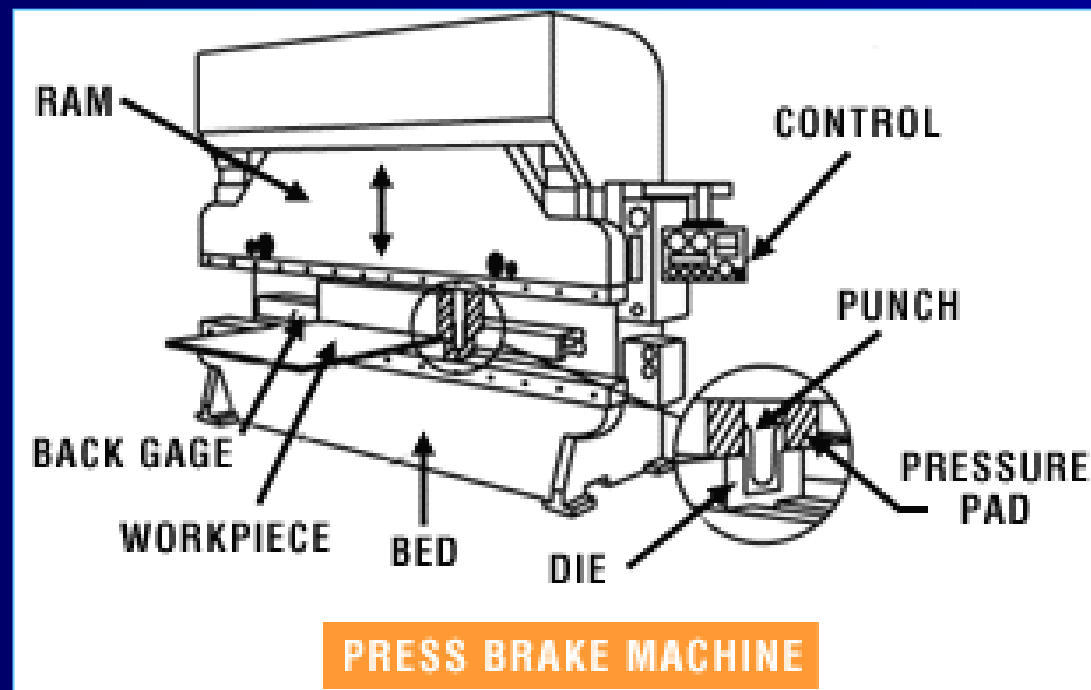
3) **Triple - action press**
   - two actions above the die, one action below the die.

Example:

Press brake – single action

• *A single action press* with a very long narrow bed.

• Used to form *long, straight bends* in pieces such as channels and corrugated sheets.

PRESS BRAKE MACHINE

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.

• ***Die*** → A ***concave die***, which is the female part as opposed to punch which is the male part.

Punches and dies
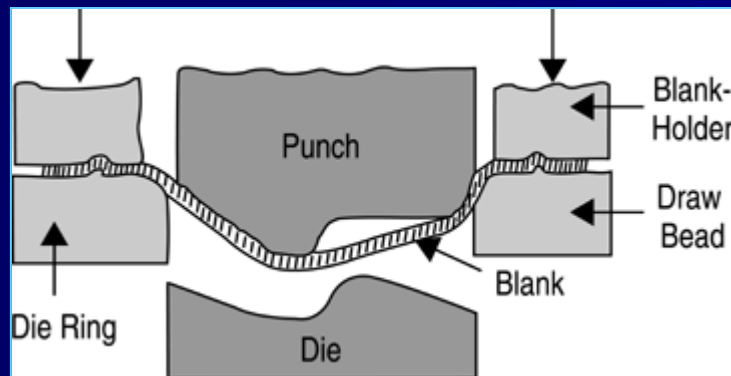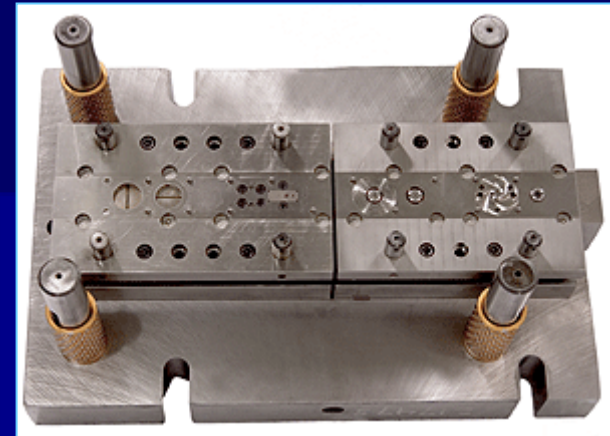

Punch and die in stamping

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.

Compound die

Transfer dies

- Transfer dies are also called *compounding type dies*.

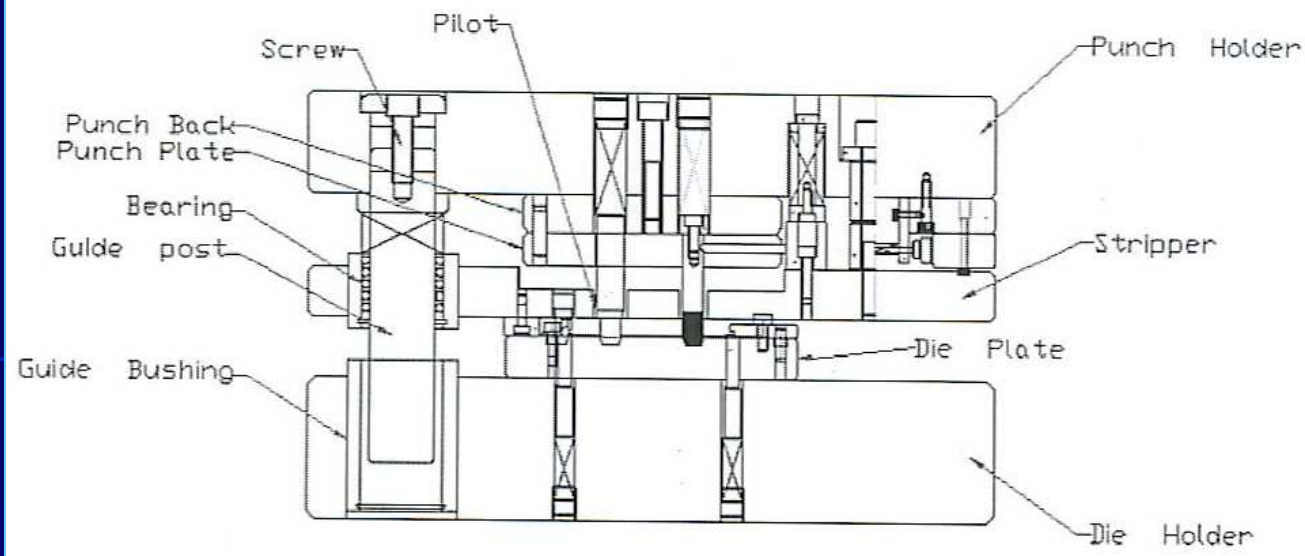- The part is *moved from station to station* within the press for each operation.

Transfer die
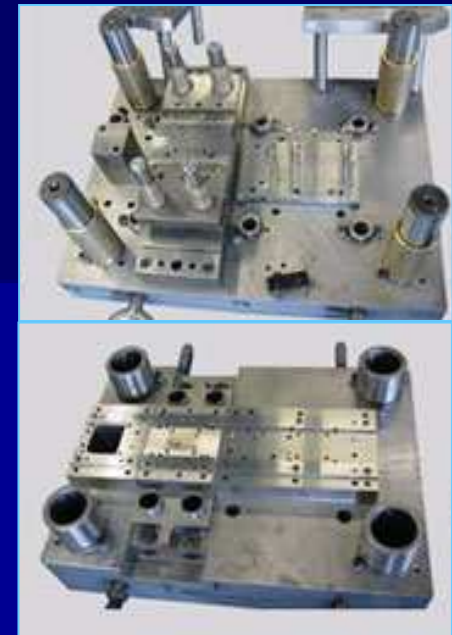
Schematic diagram of a die set

A die set is composed of
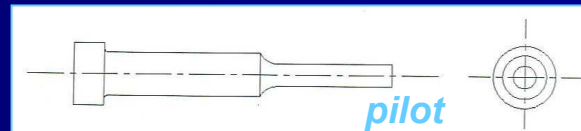
pilot

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 harden striper inserts and c) remove the cut piece from the punch.

Forming method

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

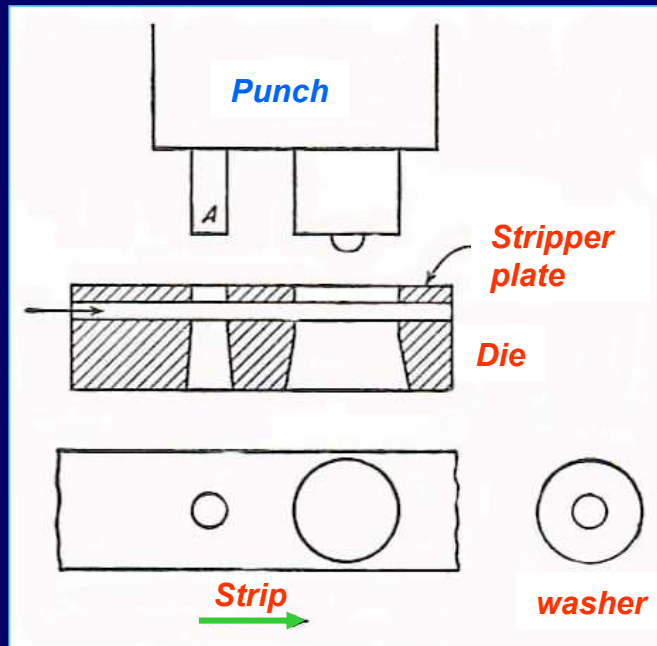- *Progressive forming*

- *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.

washers

Punch

Stripper plate

Die

Strip

washer

- The strip is fed from left to right.

- The *first punch* is to make the *hole* of the washer.

- The washer is then *blanked* from the strip.

- The punch *A* is piercing the hole for the next washer.

Progressive die

Metal sheet used in blanking process

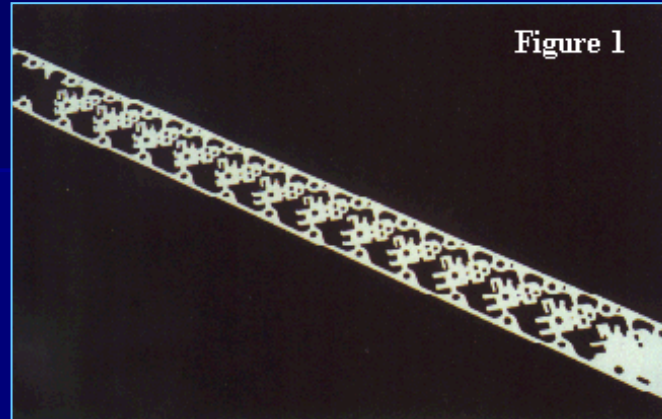www.hillengr.com

Figure 1

Figure 2

FIgure 3

Progressive die
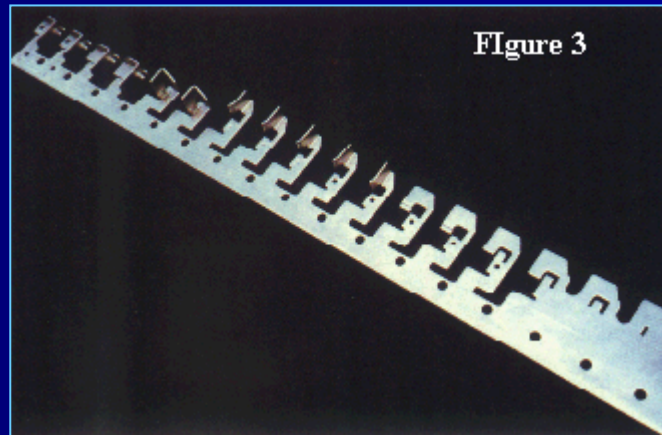
• *Optimise the material usage.*

• *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* ~ <u>10</u> MPa, and where higher local pressure can be obtained by using auxiliary tooling.
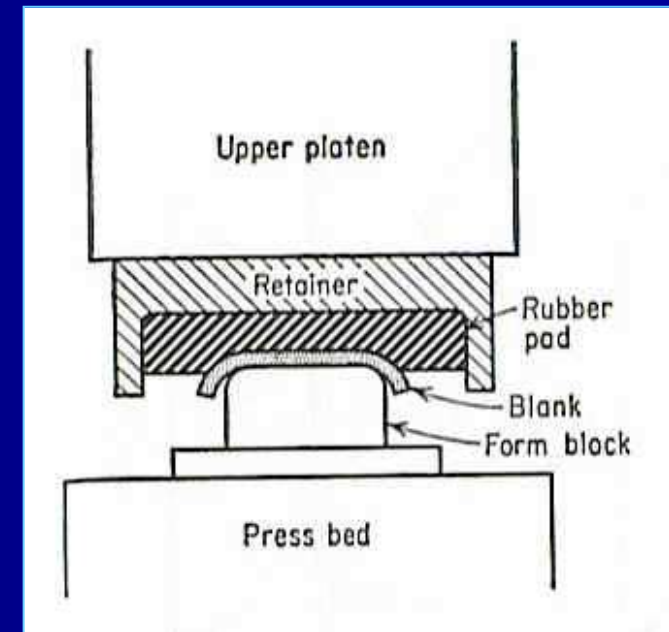
Guerin process

Hydroforming

www.egr.msu.edu

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

Upper fluid chamber

Lower fluid chamber

Draw blank material
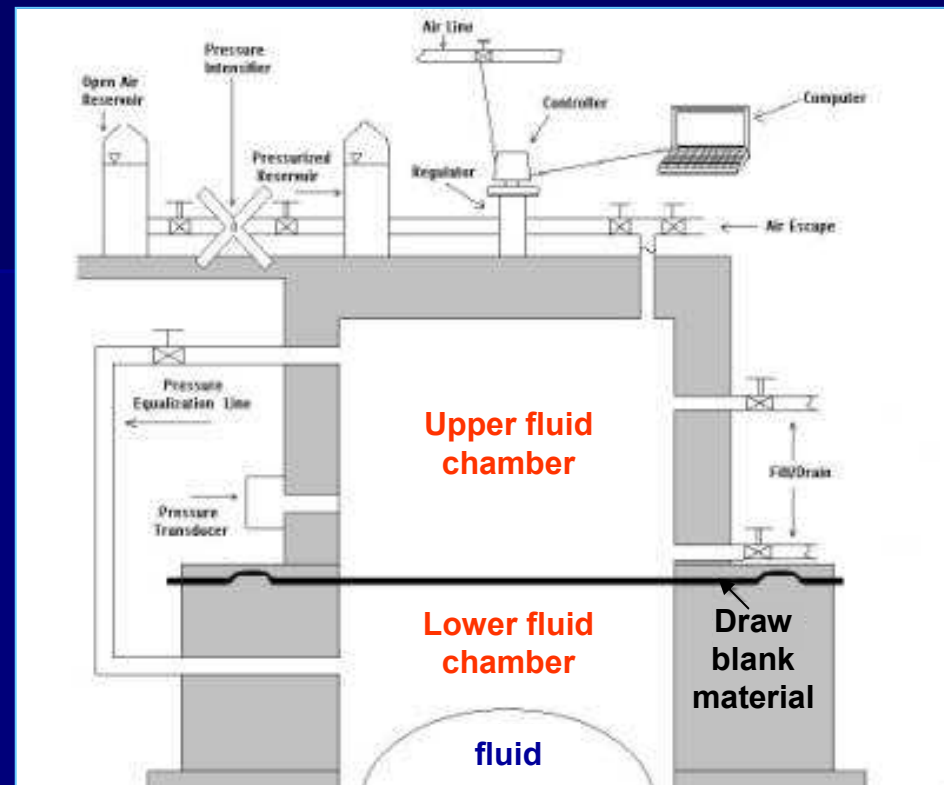
fluid

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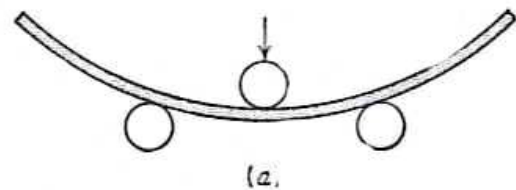supplied from to both sides of the materials.*

• Used for sheet forming of aluminium alloys and reinforced thermoplastics.
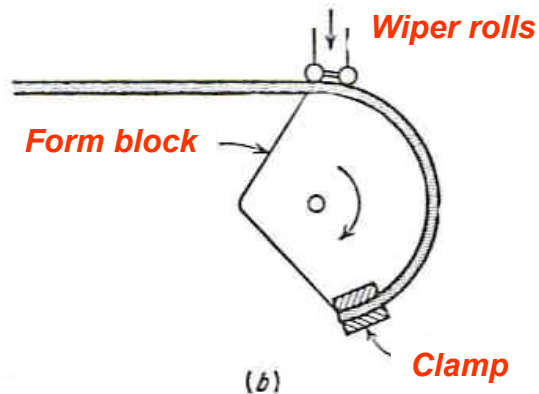
Bending and contouring

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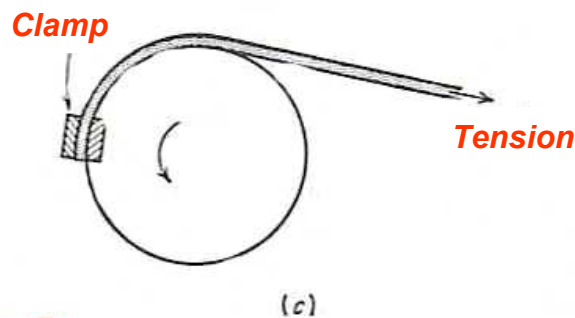
(a) Three-roll bender: sometimes does not provide uniform deformation in thin-gauge sheet due to the midpoint of the span → *localisation of the strain*. Often need the forth roll.

(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

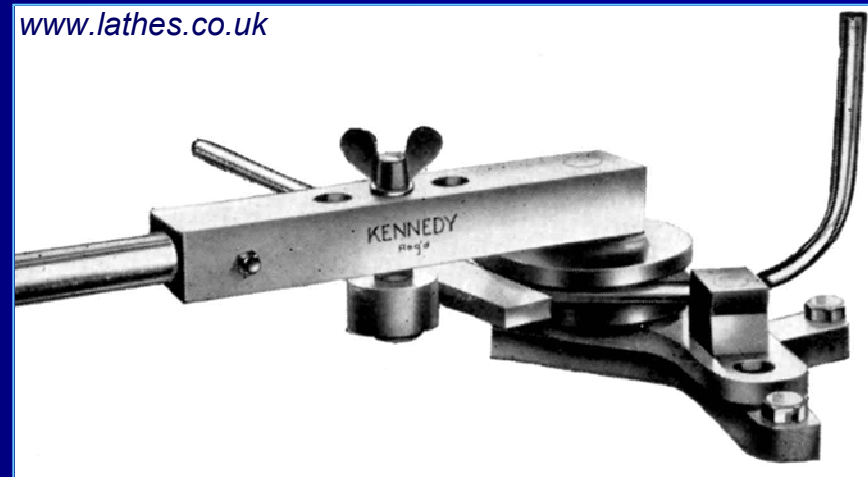www.rollfab.com.au

www.macri.it

Pipe bending machine

www.diydata.com

www.lathes.co.uk

Spinning processes

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

• Deep parts of circular symmetry such as tank heads, television cones.
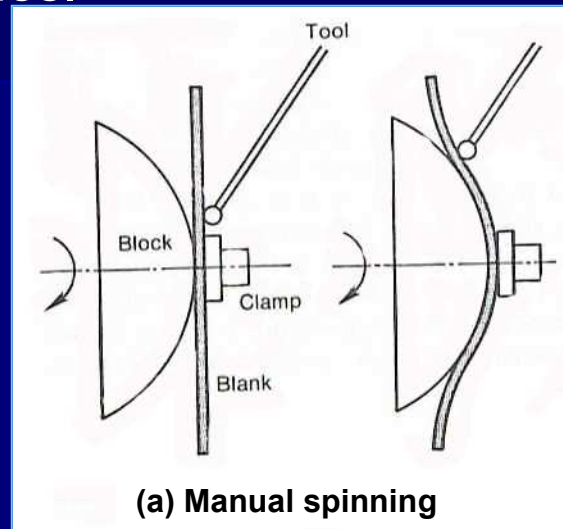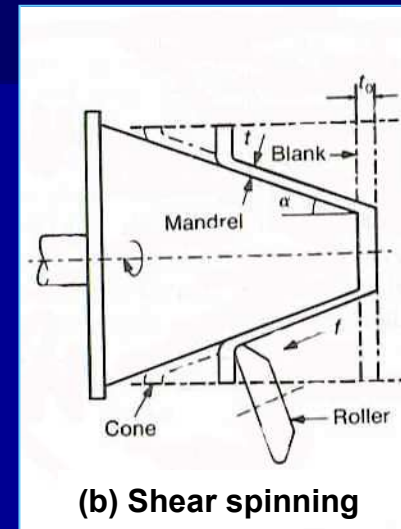
(a) Manual spinning   **(b) Shear spinning**

• 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*'
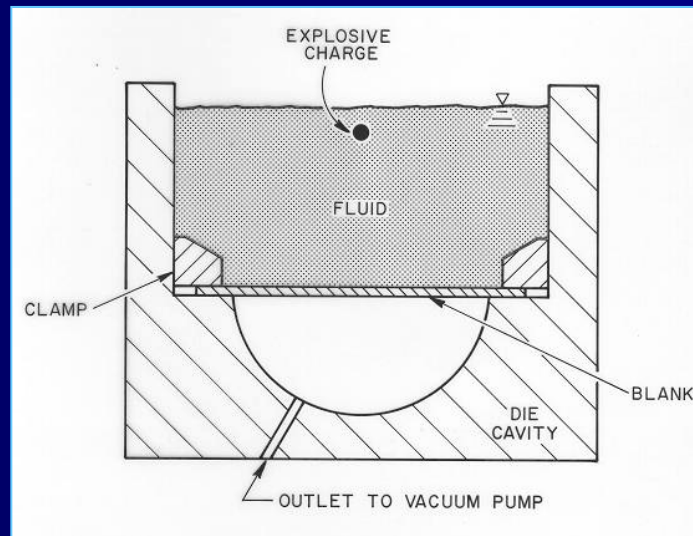
Shearing and blanking

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

(a) Proper clearance

Ragged surface

(b) Insufficient clearance

blurr

(c) Excessive clearance

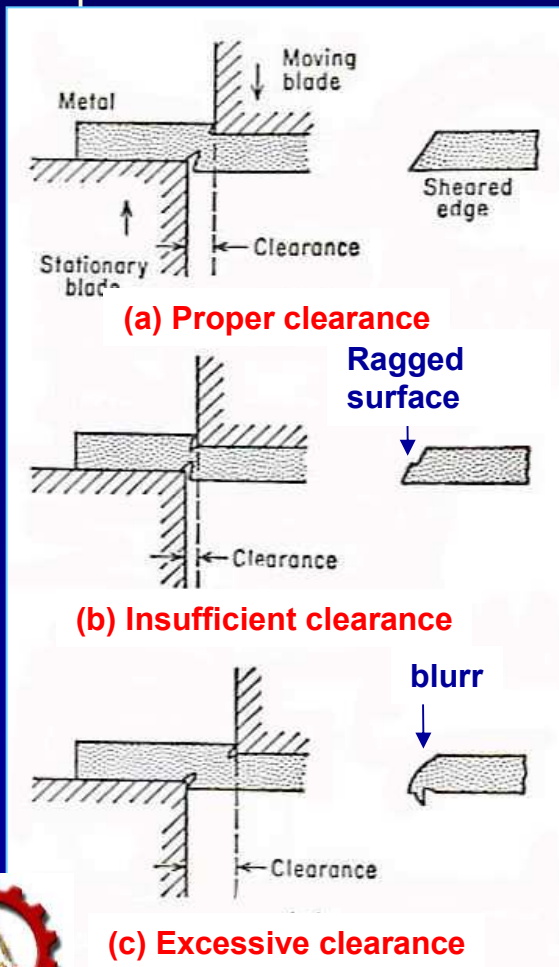• A narrow strip of metal is severely plastically deformed to the point where it *fractures* at the surfaces in contact with the blades.

• The fracture then propagates inward to provide complete separation.

Clearance   (normally 2-10% thickness)

• *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

$$P_{\max} \approx 0.7\sigma_u hL$$

where σ_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.
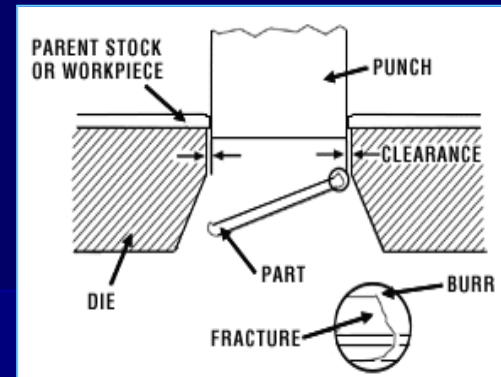
Punching or piercing _:_ The shearing of the material when the metal inside the contour is **_discarded_**.
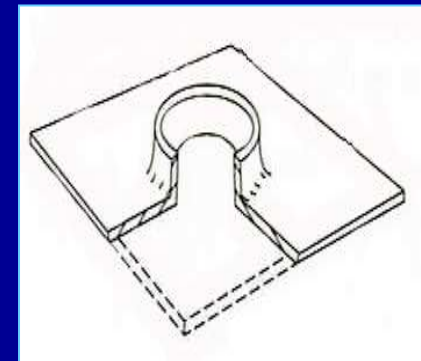
Notching _:_ The punch removes material from the edge or corner of a strip or blank or part.
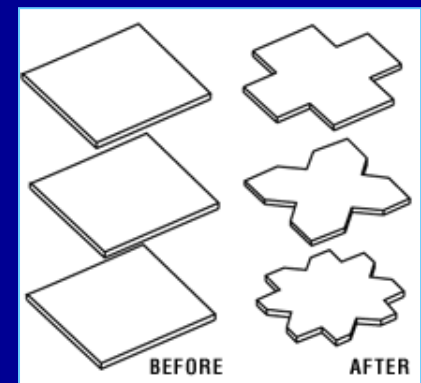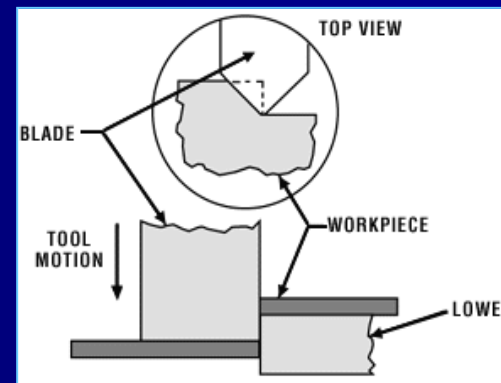
Parting _:_ The simultaneous cutting along at least two lines which balance each other from the standpoint of side thrust on the parting tool.
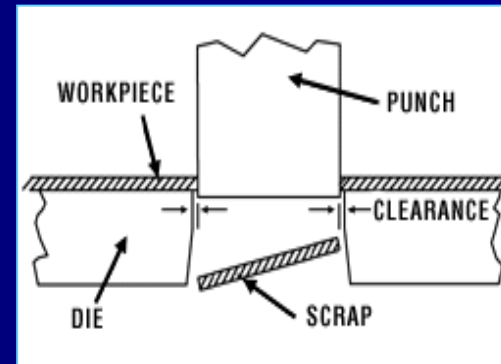
Slitting _:_ Cutting or shearing along single lines to cut strips from a sheet or to cut along lines of a given length or contour in a sheet or workpiece.

UPPER KNIFE
WORKPIECE
LOWER KNIFE
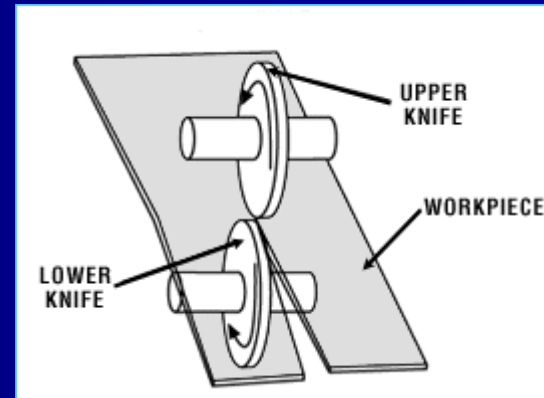
Trimming _:_ Operation of cutting scrap off a partially or fully shaped part to an established trim line.

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.
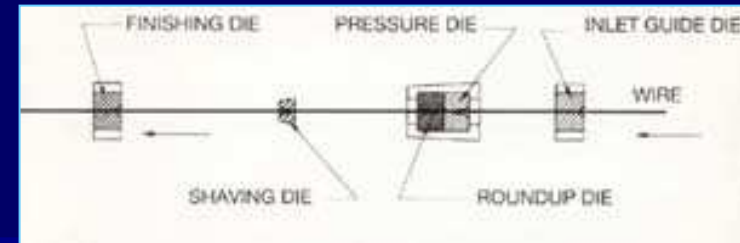
Ironing : A continuous thinning process and often accompanies deep drawing, i.e., thinning of the wall of a cylindrical cup by passing it though an ironing die.
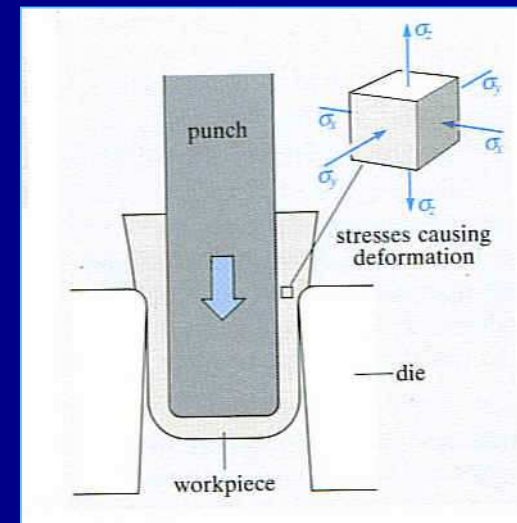
Fine blanking : Very smooth and square edges are produced in small parts such as gears, cams, and levers.

Bending

• A process by which a straight length is transformed into a curved length.

• produce channels, drums, tanks.
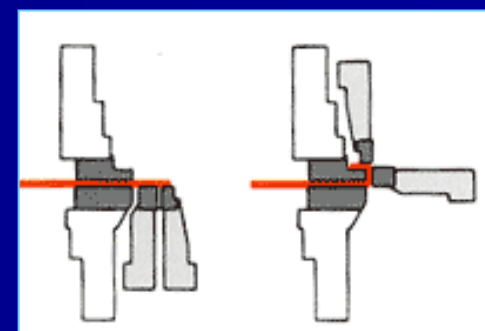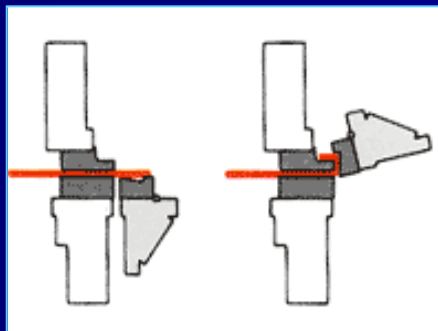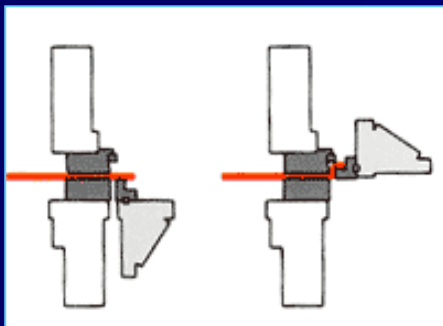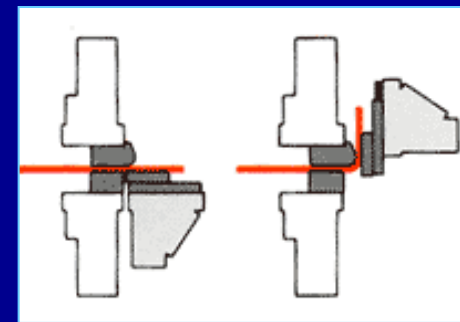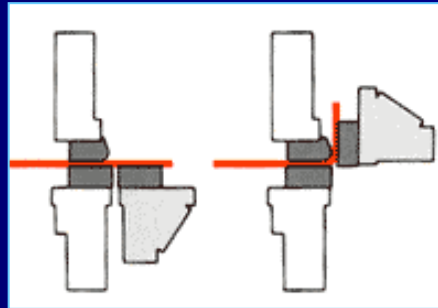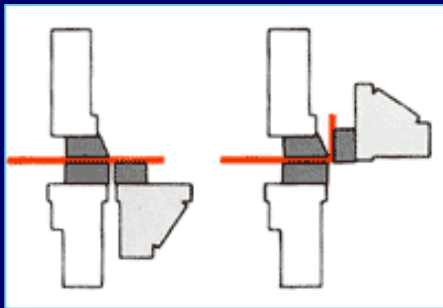
Bending

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

R = Bend radius
B = Bend allowance
α = Bend angle
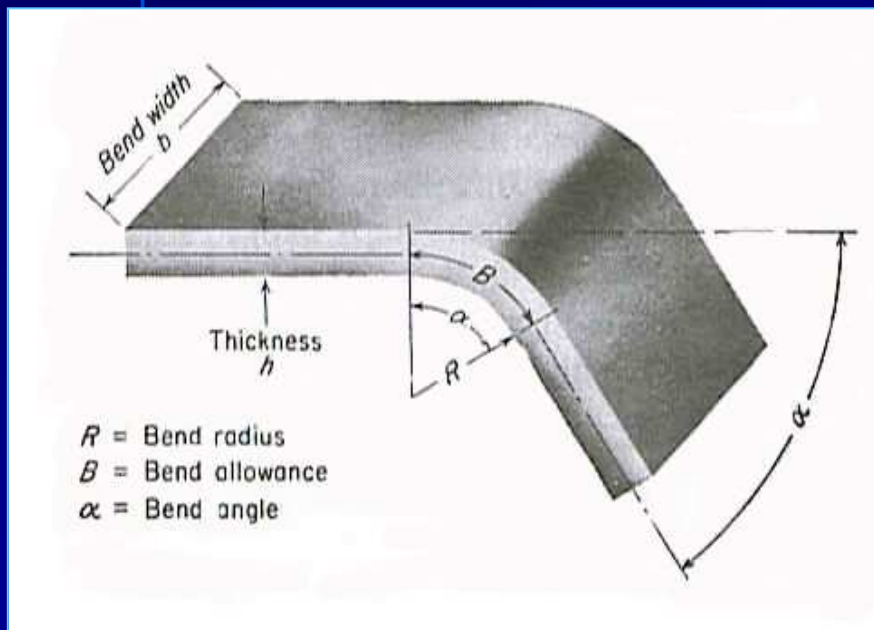
Fibres on the outer surface are *strained* more than fibres on the inner surface are *contracted*. Fibres at the mid thickness is *stretched*.

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

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

…Eq.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

- Stress state is **biaxial (σ_2/σ_1 ratio)**

- Width / thickness **b/h** ratio
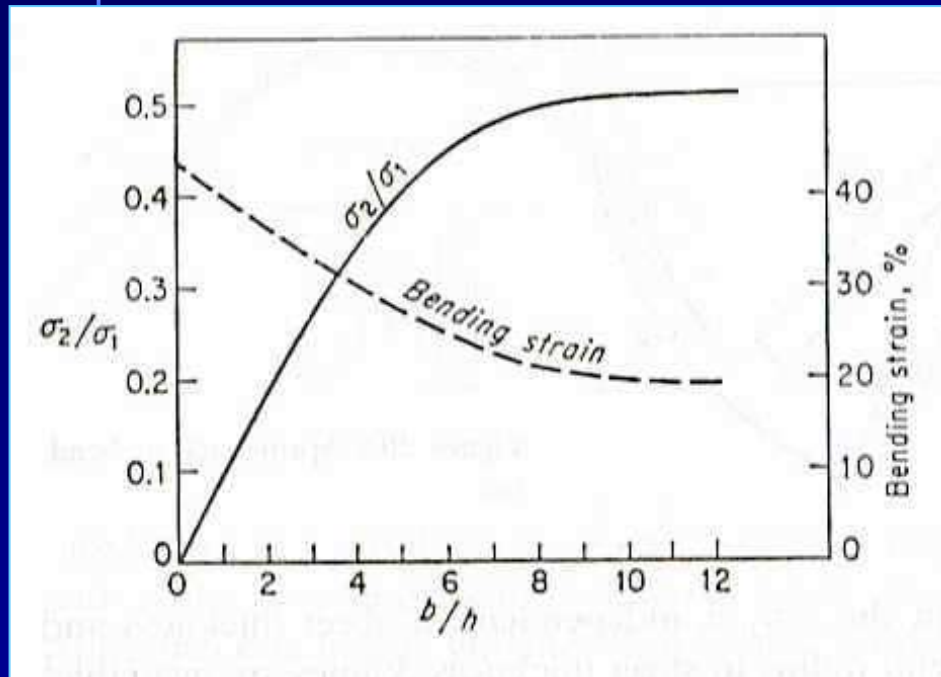
b/h ⬆ **biaxiality** ⬆

⬇

Strain, ductility ⬇

⬇

Cracks occur near the centre of the sheet

Effect of b/h on biaxiality and bend ductility

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*.
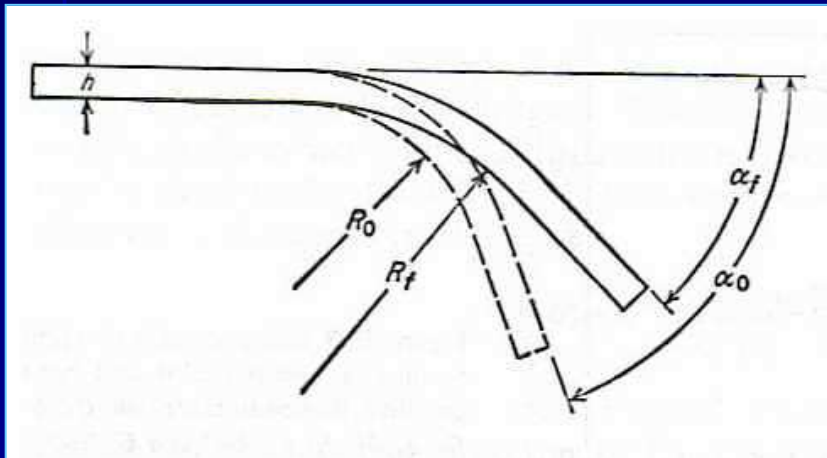
| Yield stress ⬆ |
| Elastic modulus ⬇ |

| Plastic strain ⬆ |
| Spring back ⬆ |

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

For aluminium alloys and austenitic stainless steels in a number of cold-rolled tempers, approximate *springback* in bending can be expressed by

$$\frac{R_o}{R_f} = 4\left(\frac{R_o\sigma}{Eh}\right)^3 - 3\frac{R_o\sigma}{Eh} + 1 \qquad \textit{…Eq.2}$$

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 (overbending). By trial-and-error.*

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

$$P_b = \frac{\sigma_o L h^2}{2(R + h/2)} \tan\frac{\alpha}{2} \qquad \textit{…Eq.3}$$

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.

www.precision-tube-bending.com

Stretch forming

www.dynabil.com

Stretch forming feasible for aluminium, stainless steel, titanium.

• 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.**

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

Specialized stretch form machines up to 1600 tons

Stretch forming equipment
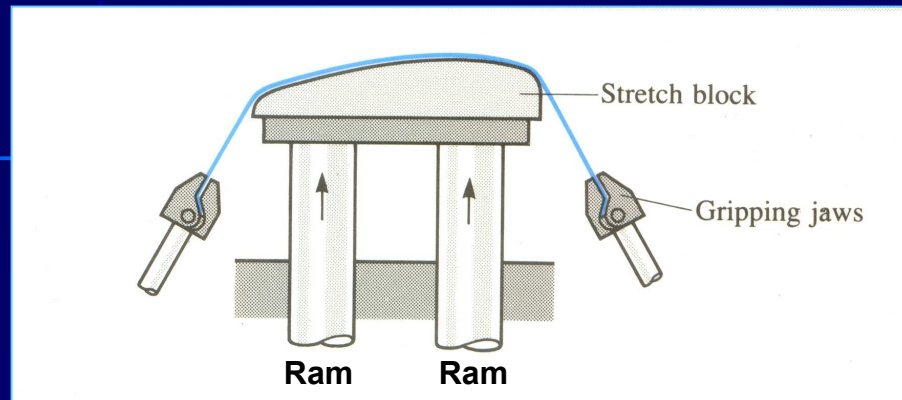
- Using a hydraulic driven ram (normally vertical).

- 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 to 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

$\phi \sim 55^o$ for an isotropic material in pure tension

• 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.

$$\varepsilon_u = 2n$$
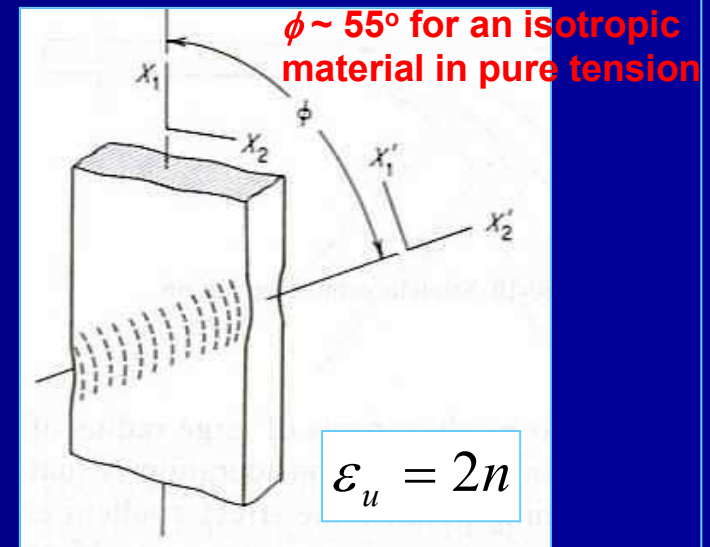
Localised necking in a strip in tension

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*.

Deep drawing of a cylindrical cup

Before drawing   **After drawing**

Punch
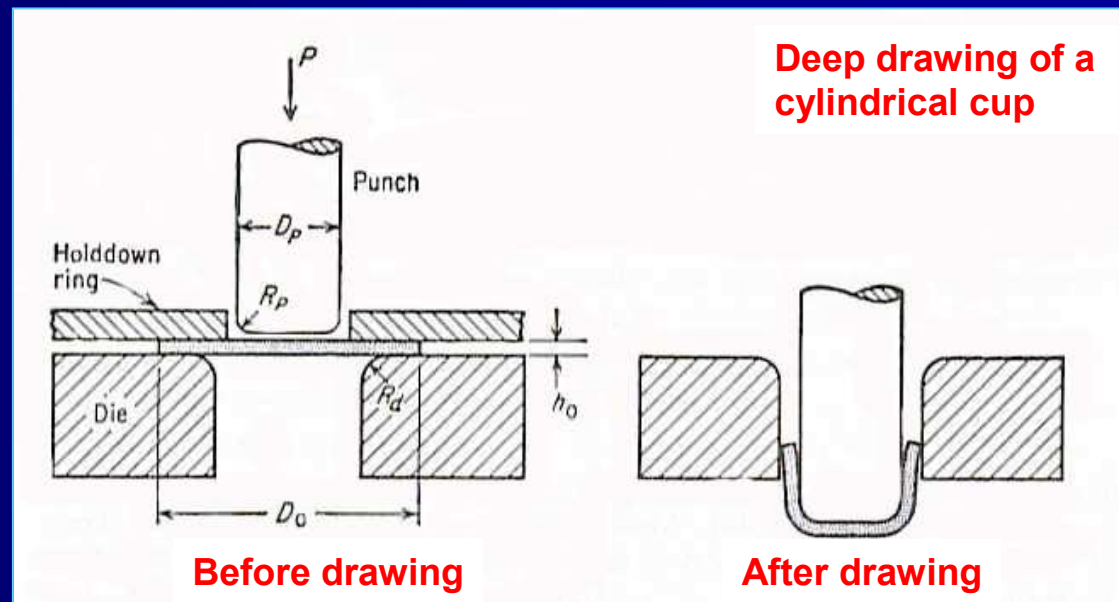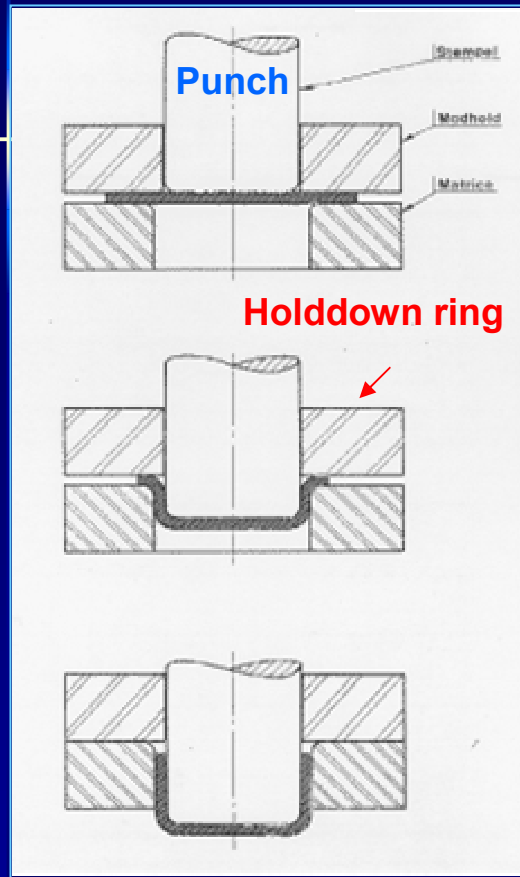
Holddown ring

- 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.

A cup is subjected to three different types of deformation.

Flange

Triaxial

Cup wall

Punch region

Biaxial

Biaxial

punch

hold down ring

die
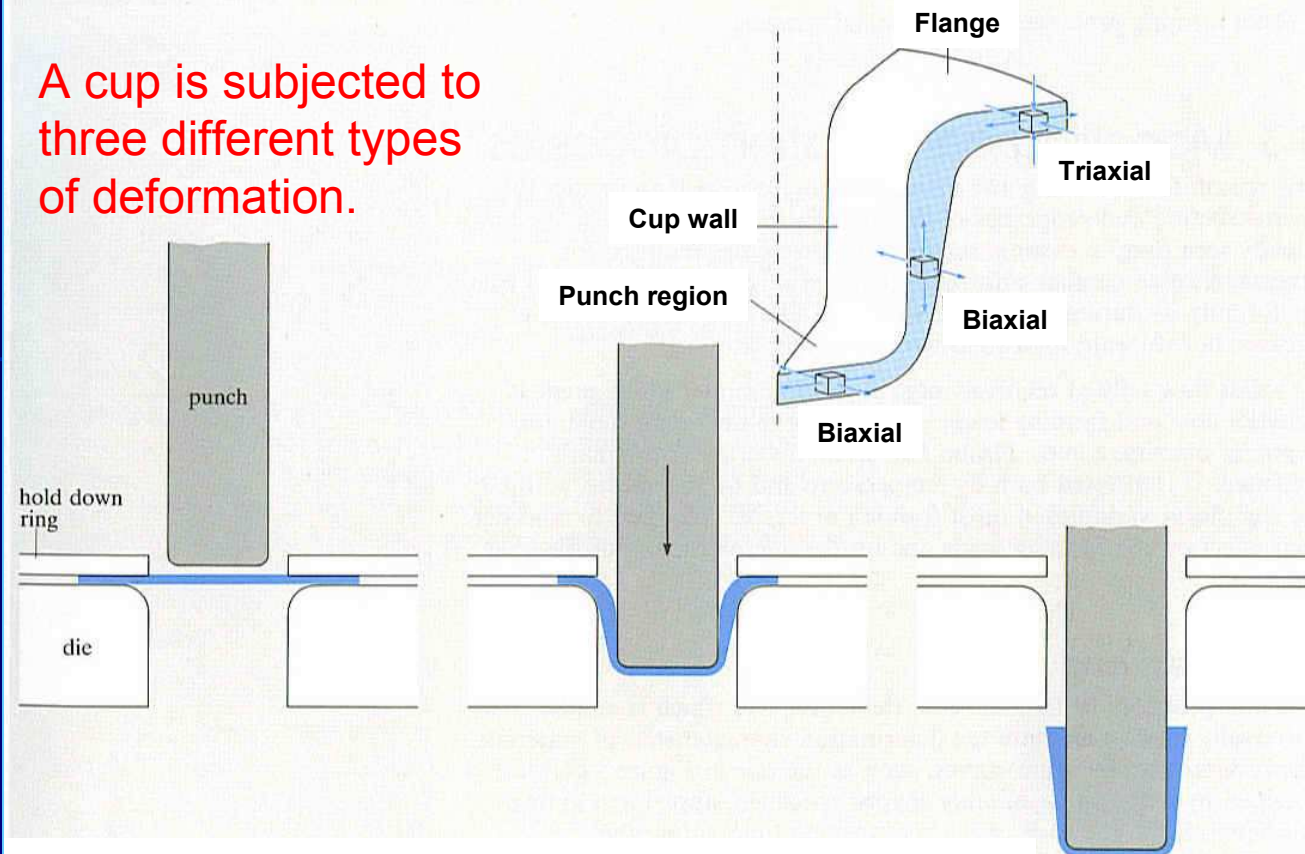
Stresses and deformation in a section from a drawn cup

<u>*As the metal being drawn,*</u>

• Change in radius

• Increase in cup wall
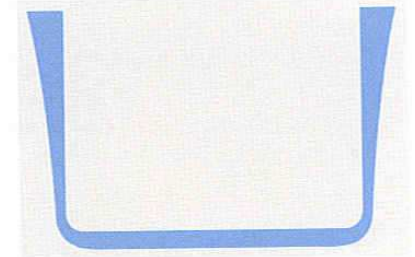
Thickness profile of drawn cup

Clearance between the punch and the die > <u>10-20%</u> 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.

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)*.
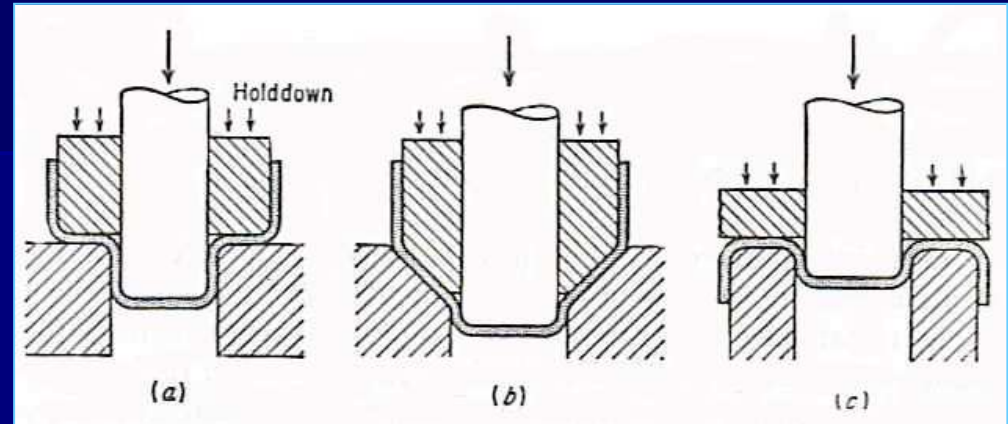
2) Reverse or indirect redrawing : the cup is turned inside out → the outside surface becomes the inside surface, *Fig (c)*. Better control of *wrinkling* and no *geometrical limitations* to the use of a hold-down ring.

Punch force vs. punch stroke

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

$F_{deformation}$ - varies with length of travel

$F_{frictional}$ - mainly from hold down pressure

$F_{ironing}$ - after the cup has reached the maximum thickness.

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)

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

...Eq.4

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 σ_o and σ_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*.

(a)   (b)
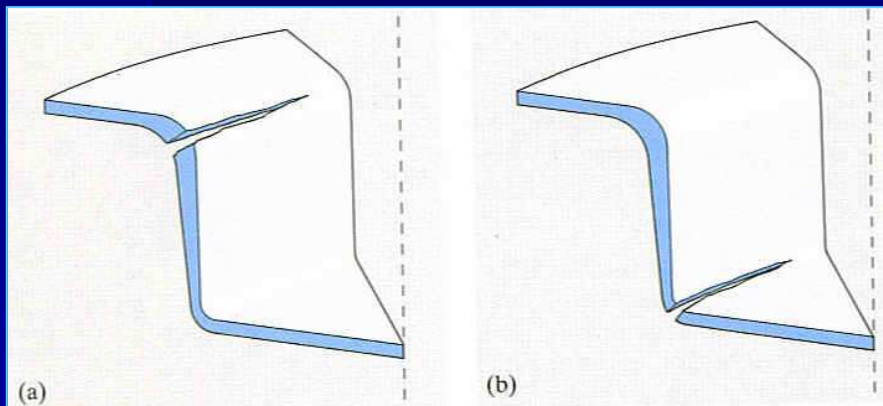
- Since the forming load is carried by the side wall of the cup, failure therefore occurs at the thinnest part.

- In practice the materials always fails either at *(a) the shoulder of the die* and *(b) the shoulder of the punch.*

Practical considerations for round and rectangular shells

Forces involved in Metal Flow
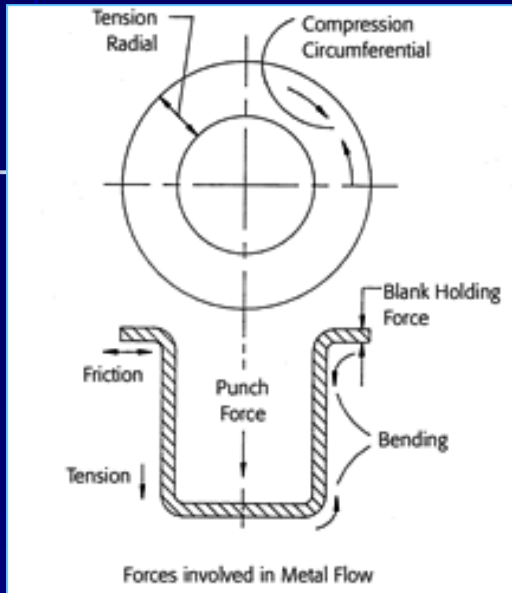
Round shell

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

www.drawform.com
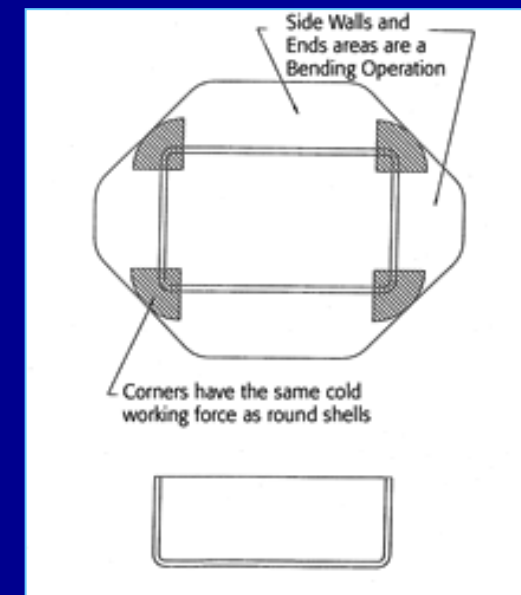

• *Different flow patterns* at sides and corners.

• *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 $\geq$ 6 x corner radius*

• *Bottom radius $\geq$ corner radius*

Rectangular shell

To improve drawability

The dependence of *limiting draw ratio* on R and work hardening rate, n
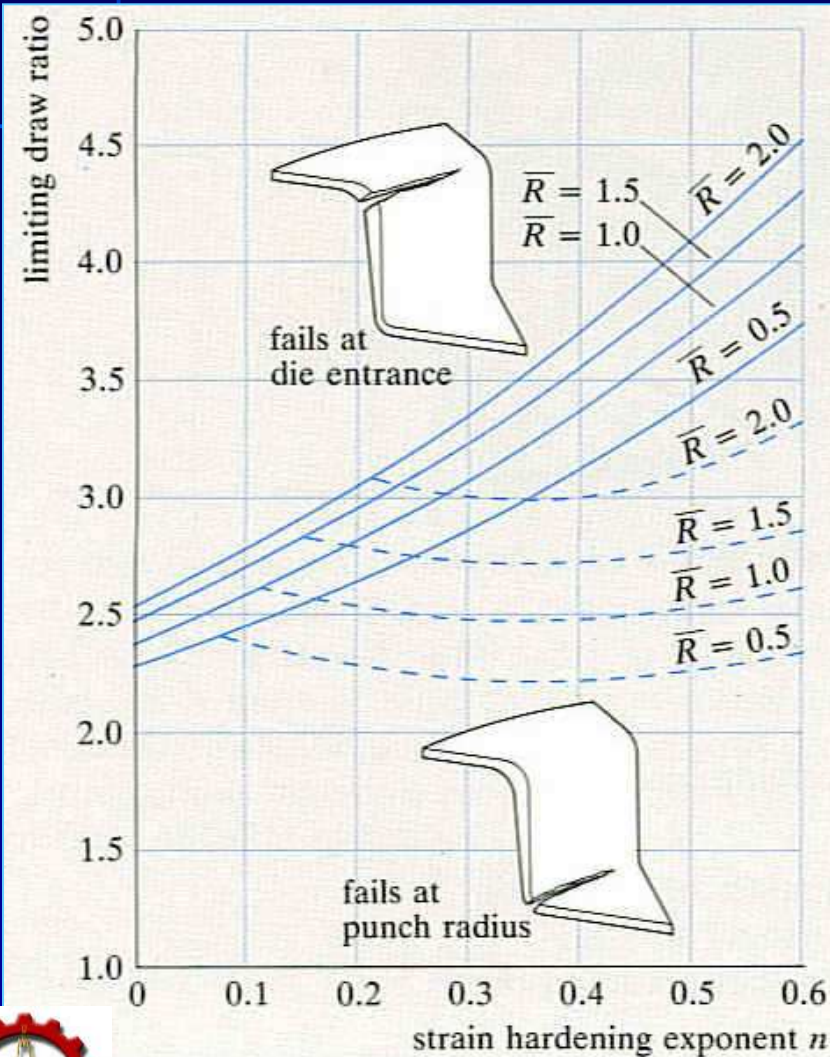
- To avoid failures in the thin parts (at the punch or flange), metal in that part need to be strengthened, or weaken the metal in other parts (to correct the weakest link).

- 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.

$$R = \frac{\ln(w_o / w)}{\ln(h_o / h)} \qquad \dots Eq.5$$

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

$$R = \frac{\ln(w_o / w)}{\ln(wL / w_o L_o)} \qquad \dots Eq.6$$

Example: _A tension test on a special deep-drawing steel showed a 30% elongation in length and a 16% decrease in width. What limiting draw ratio would be expected for the steel?_

$$\frac{L - L_o}{L_o} = 0.30$$

$$\frac{w - w_o}{w_o} = -0.16$$

$$\frac{L}{L_o} = 1.30$$

$$\frac{w}{w_o} = 1 - 0.16 = 0.84$$

$$R = \frac{\ln(w_o / w)}{\ln((w / w_o)(L / L_o))} = \frac{\ln(1 / 0.84)}{\ln(0.84 \times 1.30)} = \frac{\ln 1.190}{\ln 1.092} = 1.98$$

From **_Fig. 20-16_** Dieter page 673, the limiting draw ratio ~ 2.7

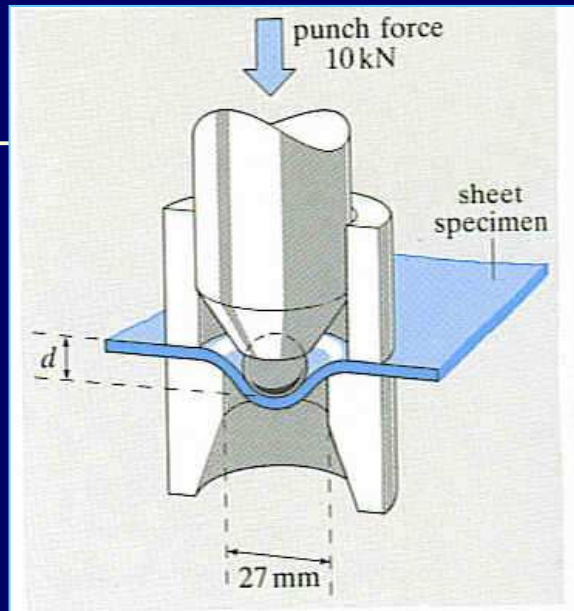# Forming limit criteria
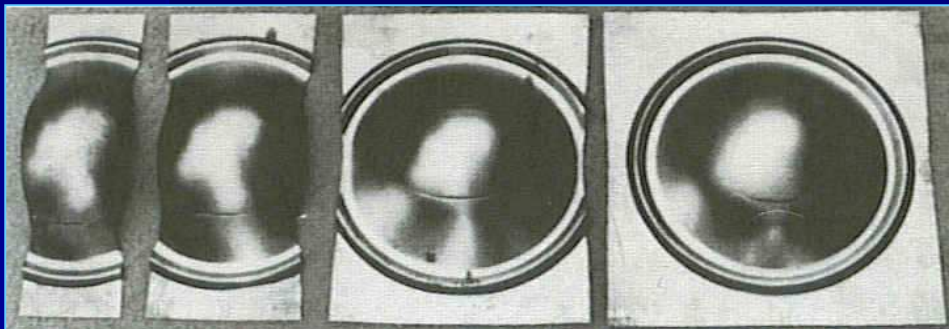
• *Tensile test* only provides ductility, work hardening, but it is in a uniaxial tension with frictionless, which cannot truly represent material behaviours obtained from unequal biaxial stretching occurring in sheet metal forming.

• *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

Results of cupping test on steel sheets.

- 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*.
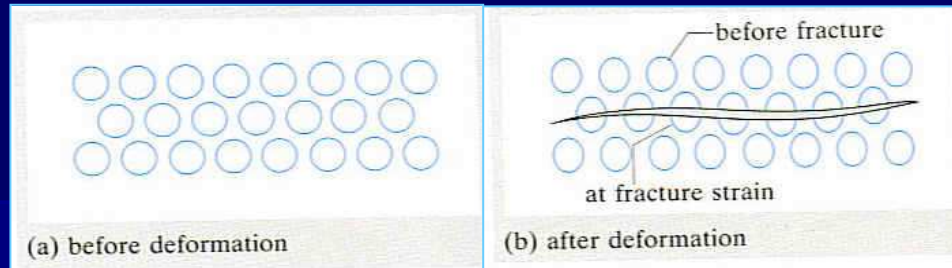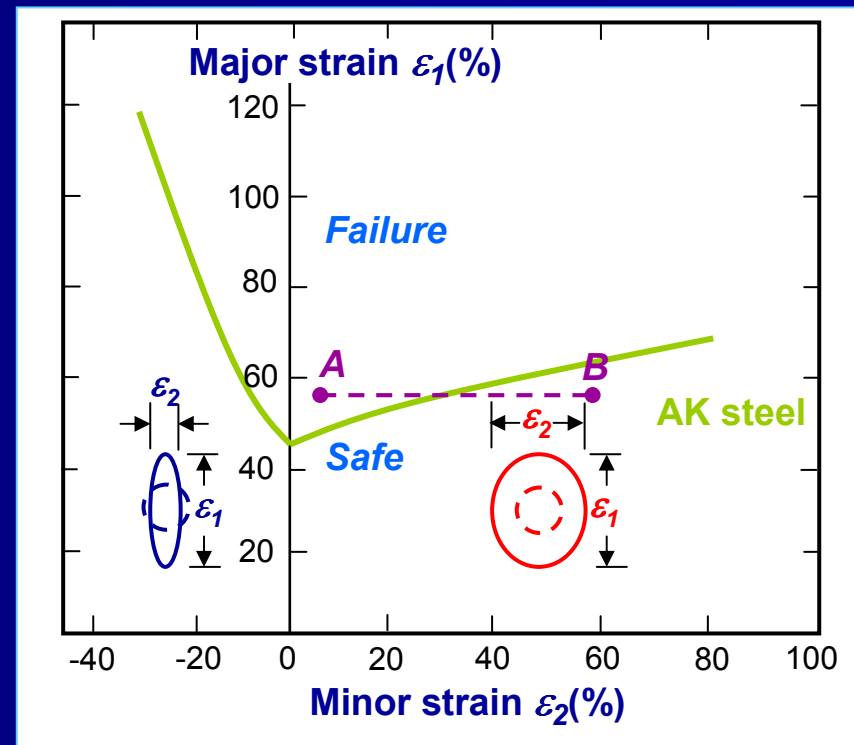
The forming limit diagram

• The sheet is marked with a **close packed array of circles** using chemical etching or photo printing techniques.

(a) before deformation   (b) after deformation

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

• 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.
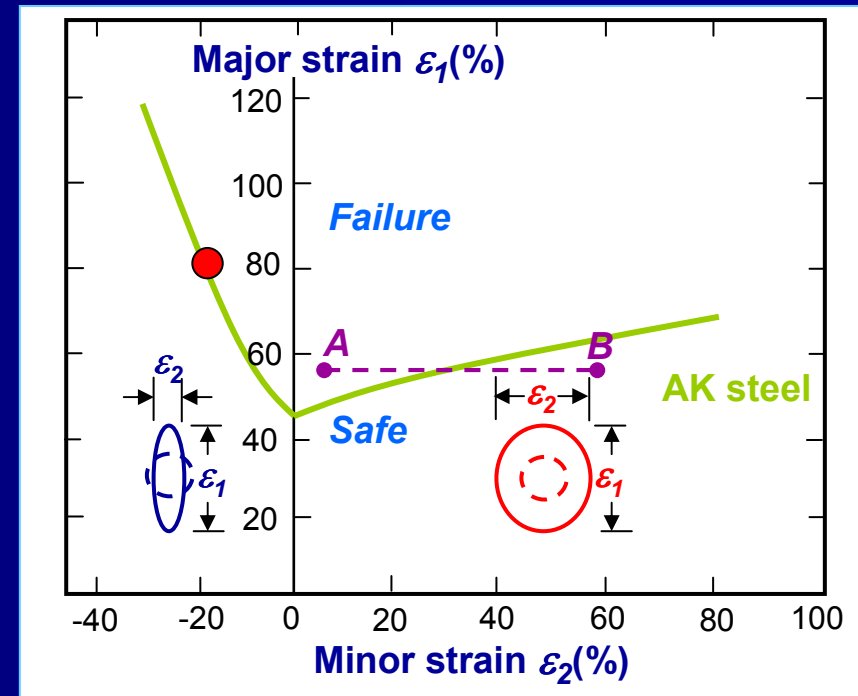

Forming limit diagram

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

$$e_1 = \frac{4.5 - 2.5}{2.5} \times 100 = 80\%$$

Minor strain

$$e_2 = \frac{2.0 - 2.5}{2.5} \times 100 = -20\%$$

Major strain ε_1**(%)**

Failure

A   B

Safe   AK steel

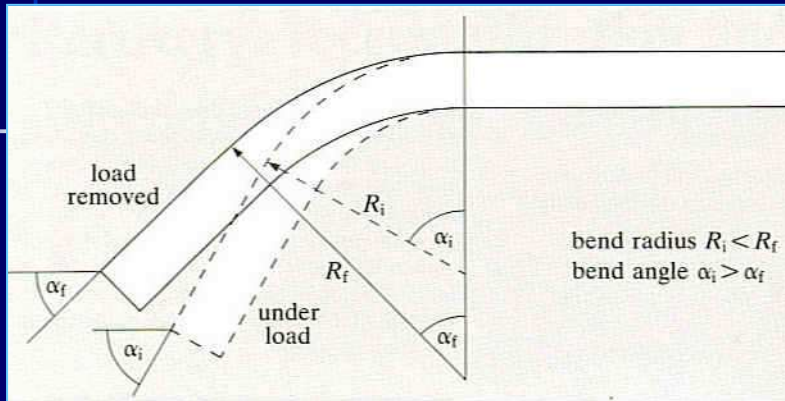**Minor strain** ε_2**(%)**

Forming limit diagram

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

Defects in formed parts

www.bgprecision.com

Springback problem

Standard   Good   Better   Clean-Edge®
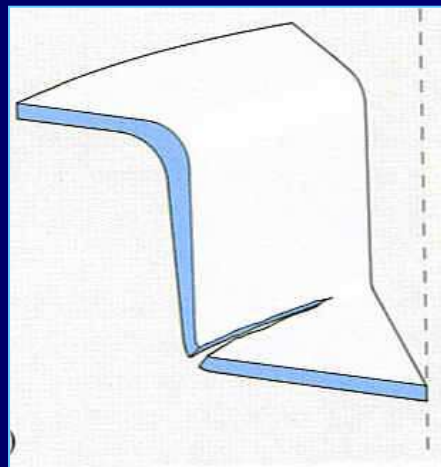
Crack near punch region

- 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.

- *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* 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, or earing in deep drawn cup due to anisotropic properties.
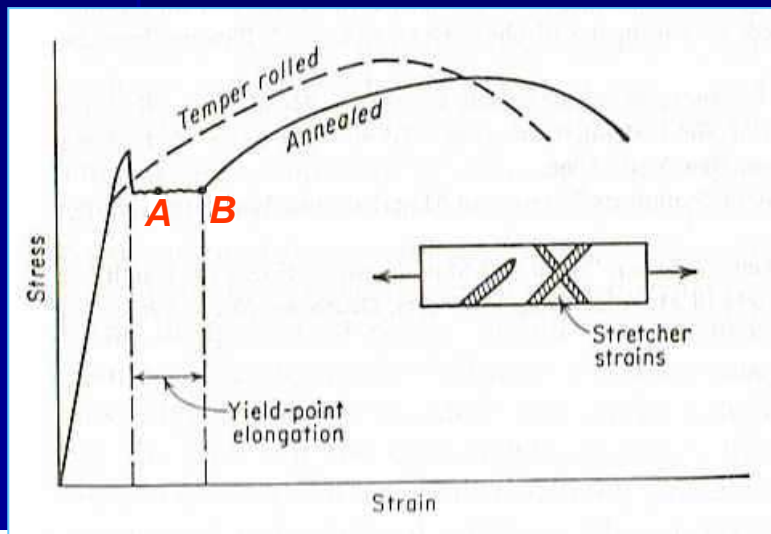
Earing in drawn can

aluminium.matter.org.uk

Stretcher strain in low-carbon steel.

Relation of stretcher strain to stress strain curve.

- *Stretcher strains* or *'worms'* (flamelike patterns of depressions). Associated with yield point elongation.

- 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 yield point.

References

- Dieter, G.E., ***Mechanical metallurgy***, 1988, SI metric edition, McGraw-Hill, ISBN 0-07-100406-8.
- Edwards, L. and Endean, M., ***Manufacturing with materials***, 1990, Butterworth Heinemann, ISBN 0-7506-2754-9.