ME 333 – Manufacturing Processes II

Chapter 7

Sheet Metal Working Processes

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- Sheet metalworking includes cutting and forming operations performed on thin sheets of metals (with thickness of 0.4 – 6 mm).

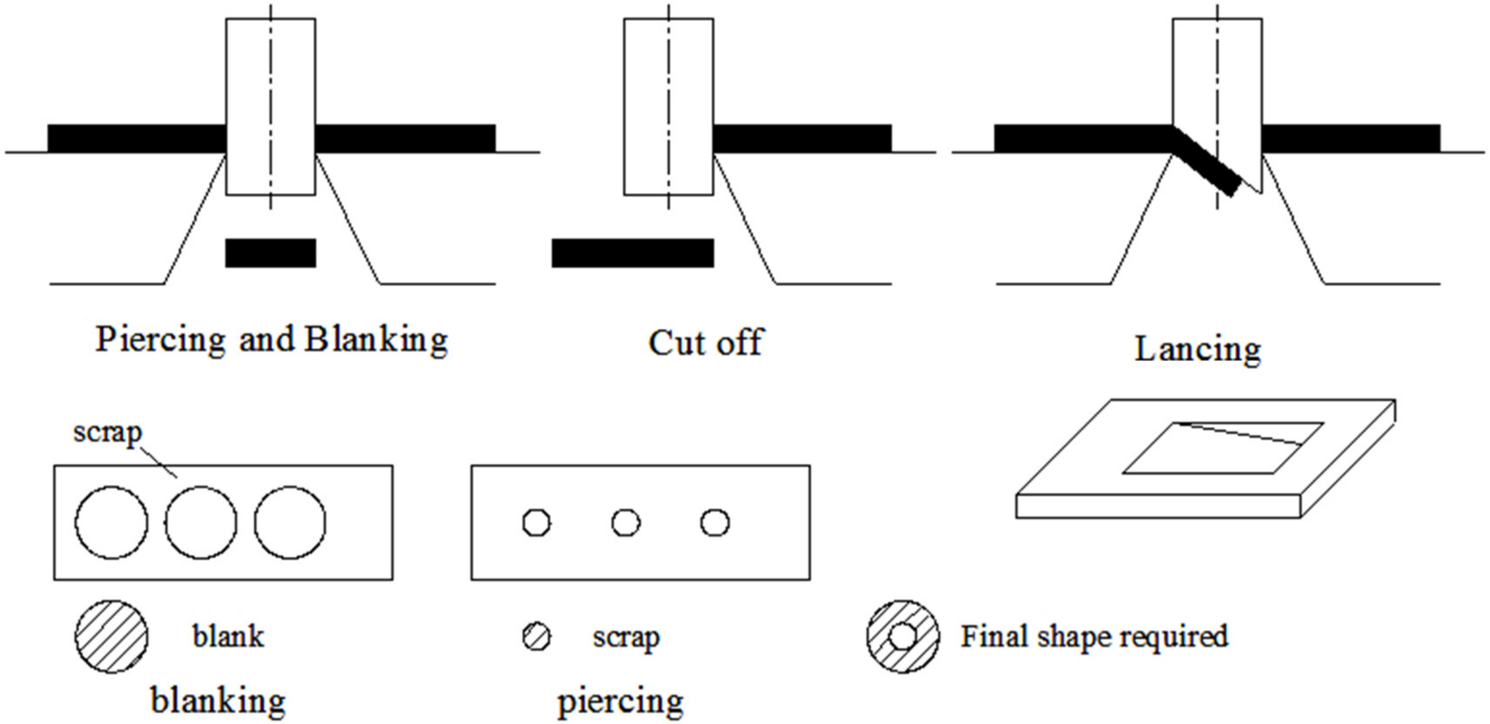
- The tooling used to perform sheet metalwork is called **punch and die**. Most sheet metal operations are performed **a stamping press**, which differs from the one used for forging and extrusion. The sheet metal products are called **stampings**.

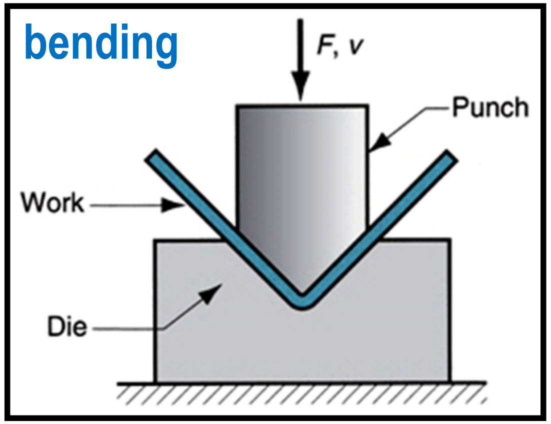
- The commercial importance of sheet metalworking is significant. **Consumer and industrial products** that include sheet metal parts are: *automobile and truck bodies, airplanes, railway cars and locomotives, farm and construction equipment, small and large appliances, office furniture, computers and office equipment, and more*.

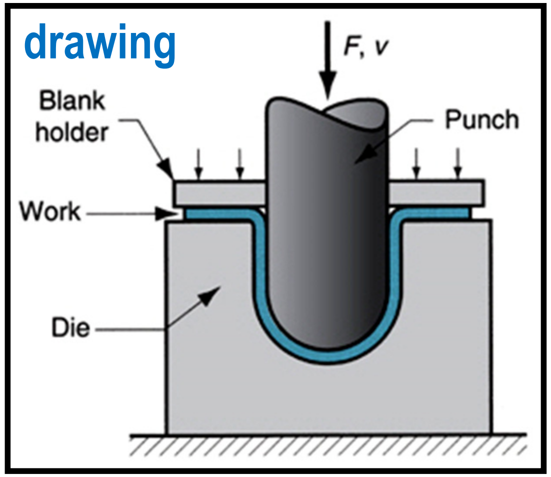
- Sheet metal parts are characterized by high strength, good dimensional tolerances, good surface finish, and relatively low cost.

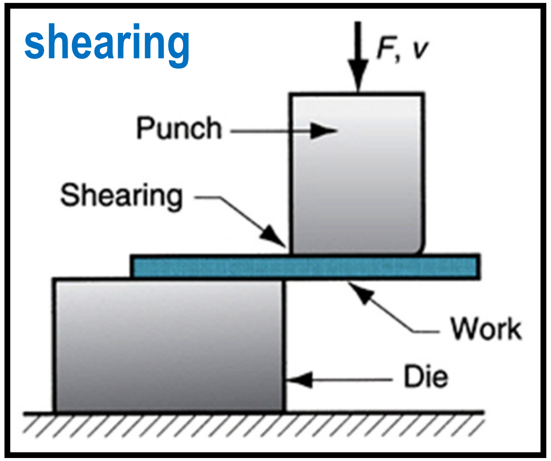
Sheet Metalworking Processes

- The major categories are: **cutting** (shearing, blanking, piercing), **bending**, and **drawing**.
- **Cutting** is used to separate large sheets into smaller pieces, to cut out a part perimeter, or to make holes (cavities) in a part.
- **Bending** and **drawing** are used to form sheet metal parts into their required shapes.

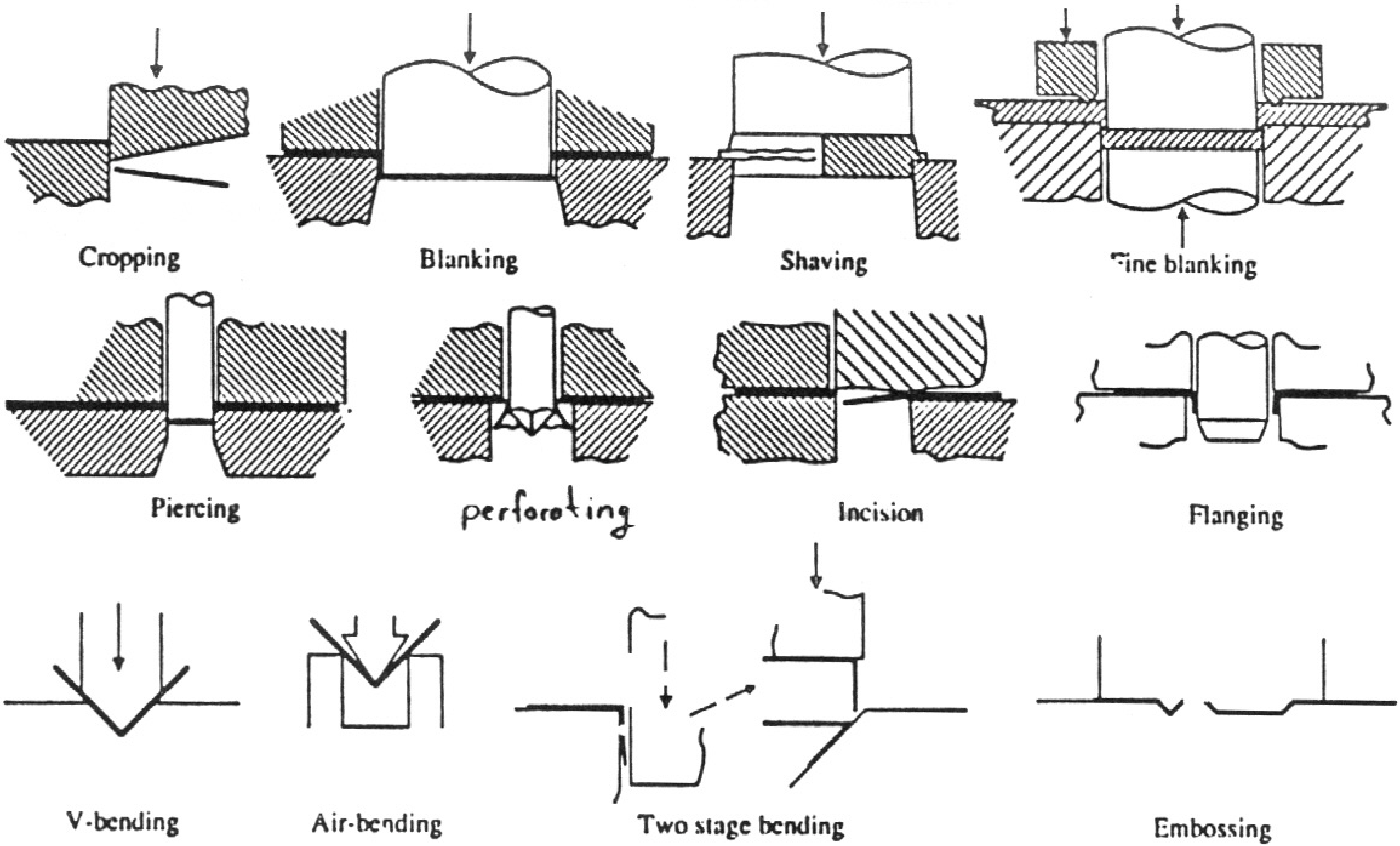




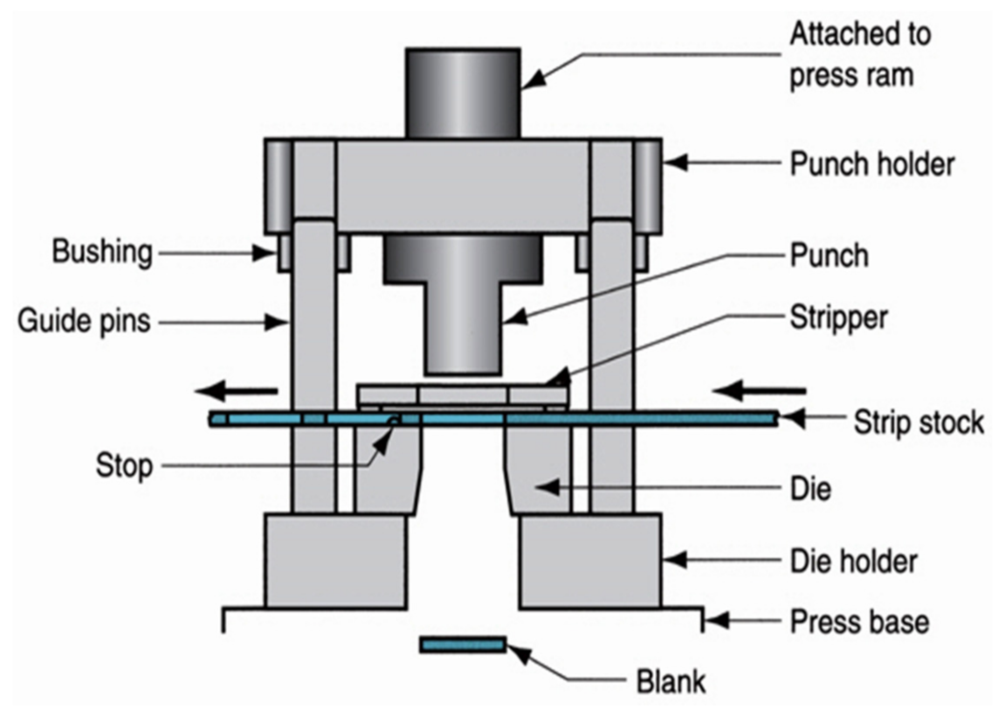




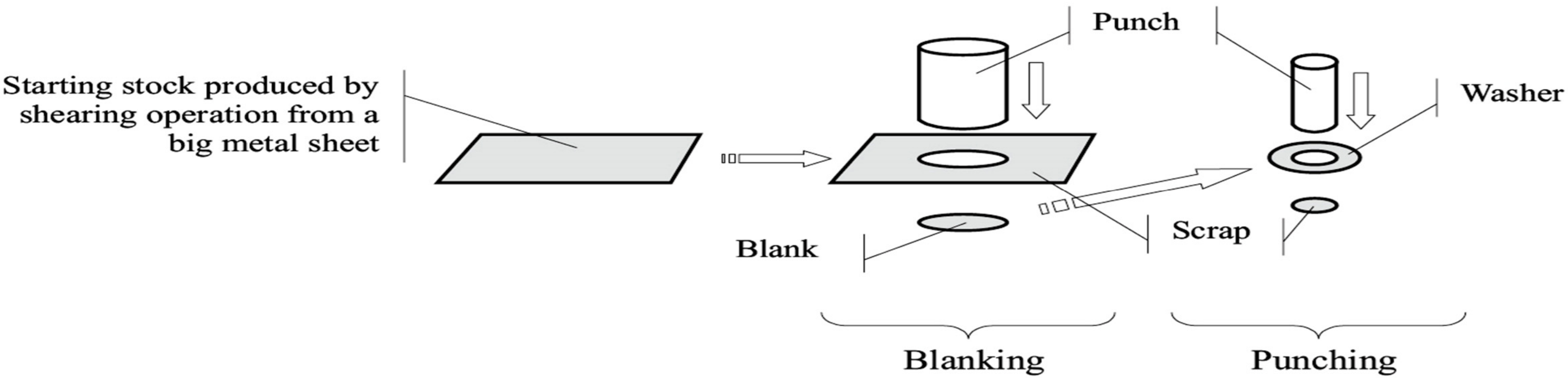
- The variations of sheet metalworking processes are illustrated below:



- **Blanking** and **punching** are similar sheet metal operations involving cutting the metal along a closed outline.
- If **the part to be cut out is the desired (final) product**, the operation is called **blanking** and the product is called **blank**.
- If **the remaining stock is the desired (final) part**, the operation is called **punching**.
- Both operations are illustrated below within the example of producing **a washer**:

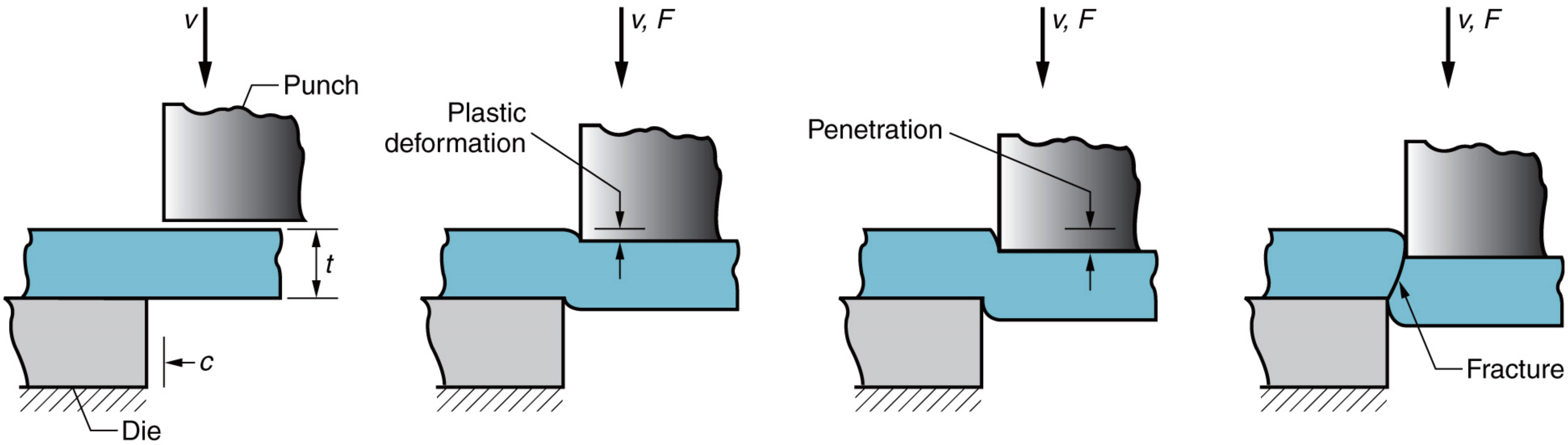


A commonly used piercing-blanking die set



Engineering Analysis

- Cutting of sheet metal is accomplished by a shearing action between two sharp edges.
- In an ideal cutting operation, punch penetrates the material to **a depth of about 1/3 of its thickness** before fracture occurs, and forces an equal portion of material into die opening.



(1) Just before punch contacts work

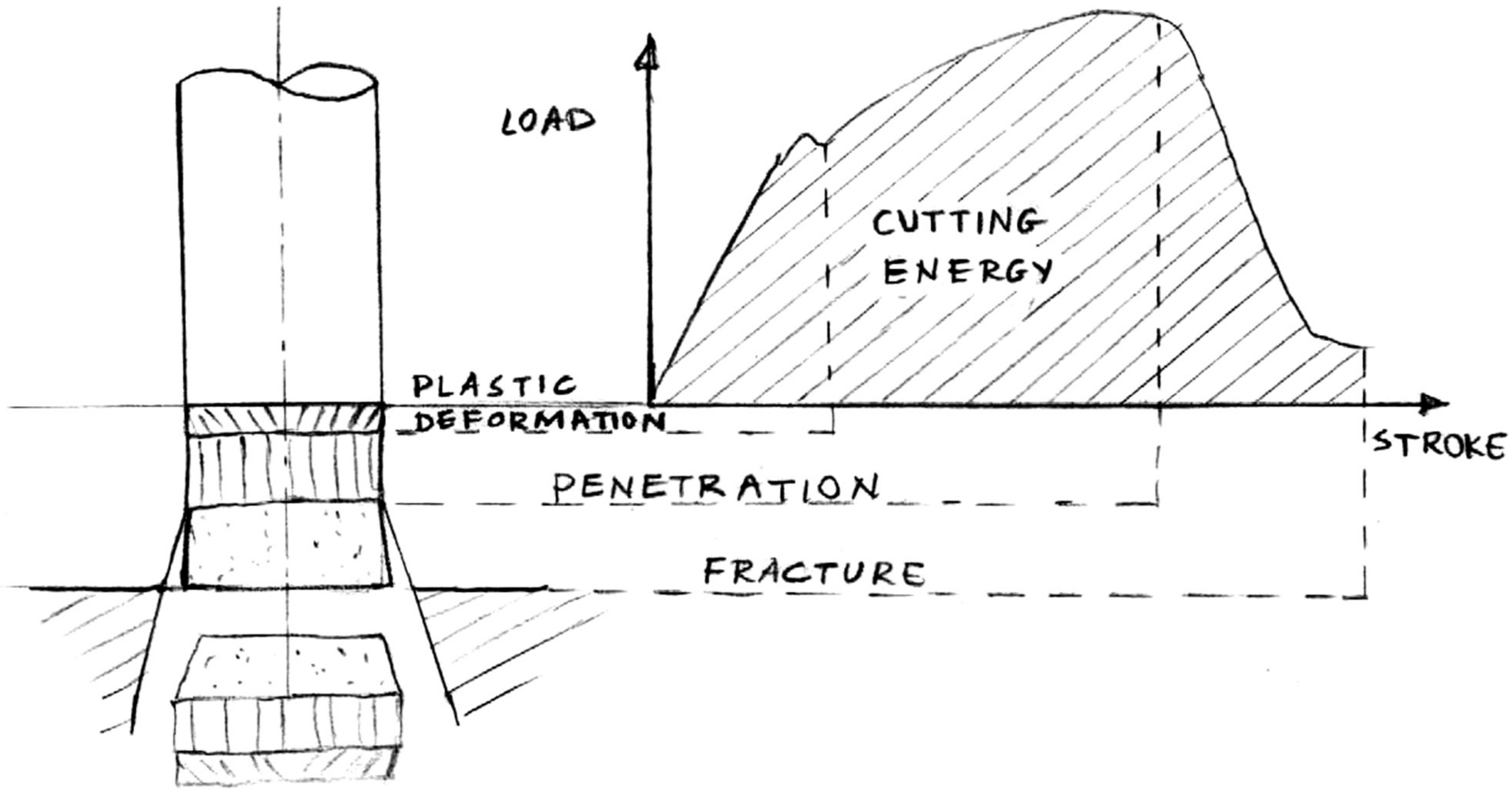
(2) Punch pushes into work, causing plastic deformation

(3) Punch penetrates into work, causing smooth cut surface

(4) Fracture is initiated at opposing cutting edges to separate the sheet

t : stock thickness c : clearance

- Cutting of metal between die components is shearing process in which the metal is stressed in shear between two cutting edges to point of fracture, or beyond its ultimate strength.
- Metal is subjected to **both tensile and compressive stresses**; stretching beyond the elastic limit occurs; then, plastic deformation and reduction in area take place; and finally, fracturing starts and becomes complete.

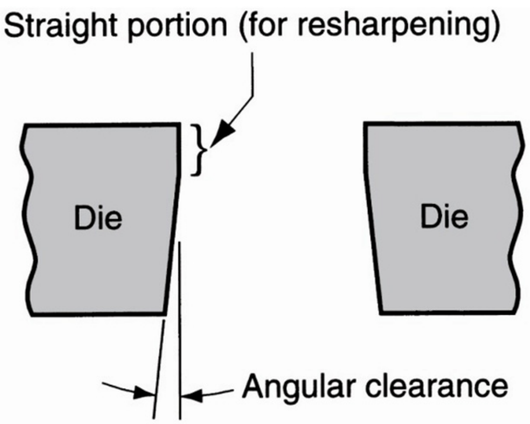


Clearances

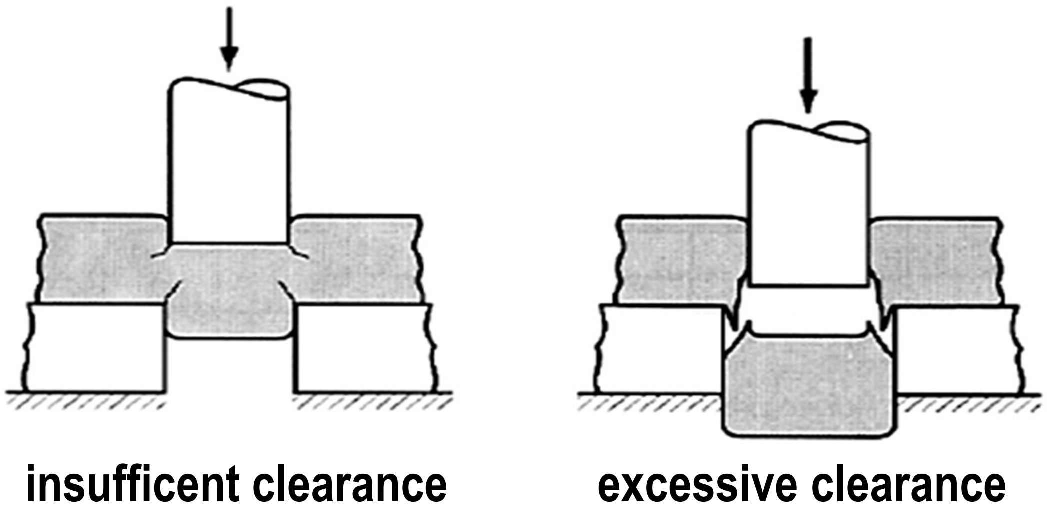
- **Clearance** is the space between the mating members *(i.e. punch and die)* of a die set.
- For optimum finish of cut edge, proper clearance is necessary which is a function of type, thickness, and hardness of the work material:

$$c = a * t \qquad t: \text{stock thickness} \qquad a: \text{allowance } (0.075 \text{ for steels}, 0.06 \text{ for Al alloys})$$

- Most die clearances are **linear** *(usually 2-5% of the material thickness)*.
- **Angular clearance** is given to the hole in the die, such that the material will easily be removed *(usually 0.25-1.5° per side)*.



- ***Insufficient clearance*** causes excessive forces & improper fracture, while ***excessive clearance*** causes oversized burr.



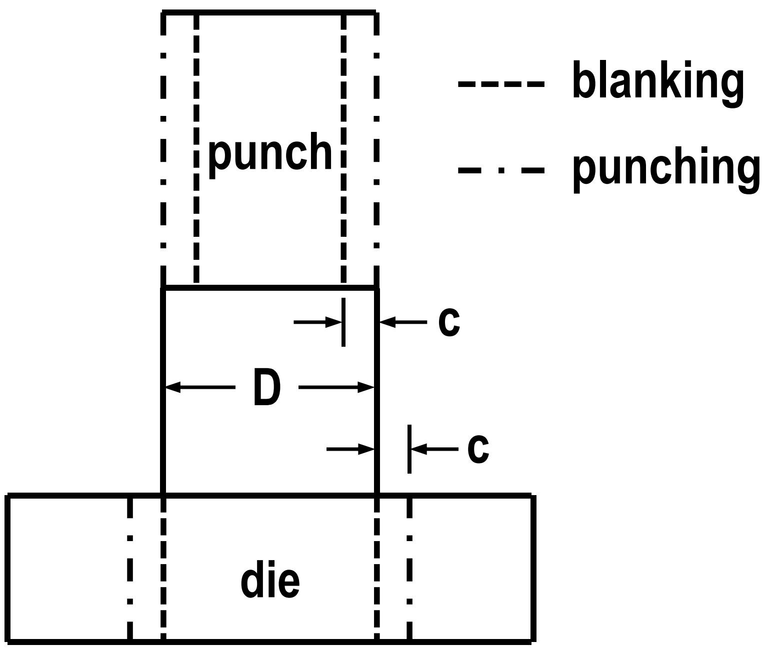
- The calculated clearance must be **subtracted** from blanking die diameter **for blanking operations** whereas it must be **added** to punching die diameter for **punching operations**:

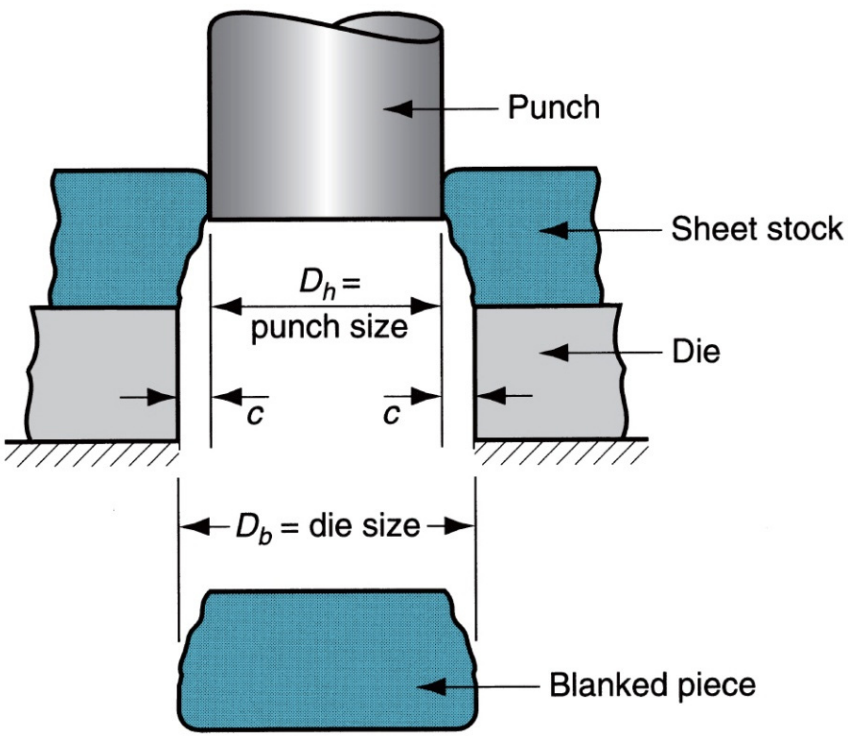
$$Blanking\ die\ diameter = D_b$$

$$Hole\ punch\ diameter = D_h$$

$$Blanking\ punch\ diameter = D_b - 2c$$

$$Hole\ die\ diameter = D_h + 2c$$





Cutting Force

- **Pressure (stress)** required to cut (shear) work material is:

$$P = S * t * L \ (for\ any\ contour)$$

$$P = S * t * (\pi D) \ (for\ round\ hole)$$

S : shear strength of material (kg/mm^2)

t : material thickness (mm)

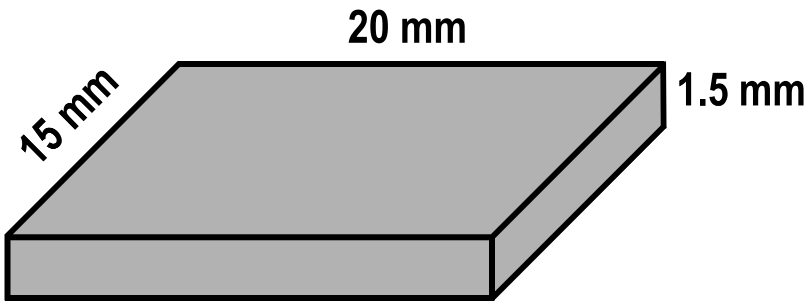
L : shear length (mm)

D : hole diameter (mm)

Example:

- Calculate the force to produce a pocket (20 mm x 15 mm) within a material (1.5 mm thick) having shear strength of 40 kg/mm^2.

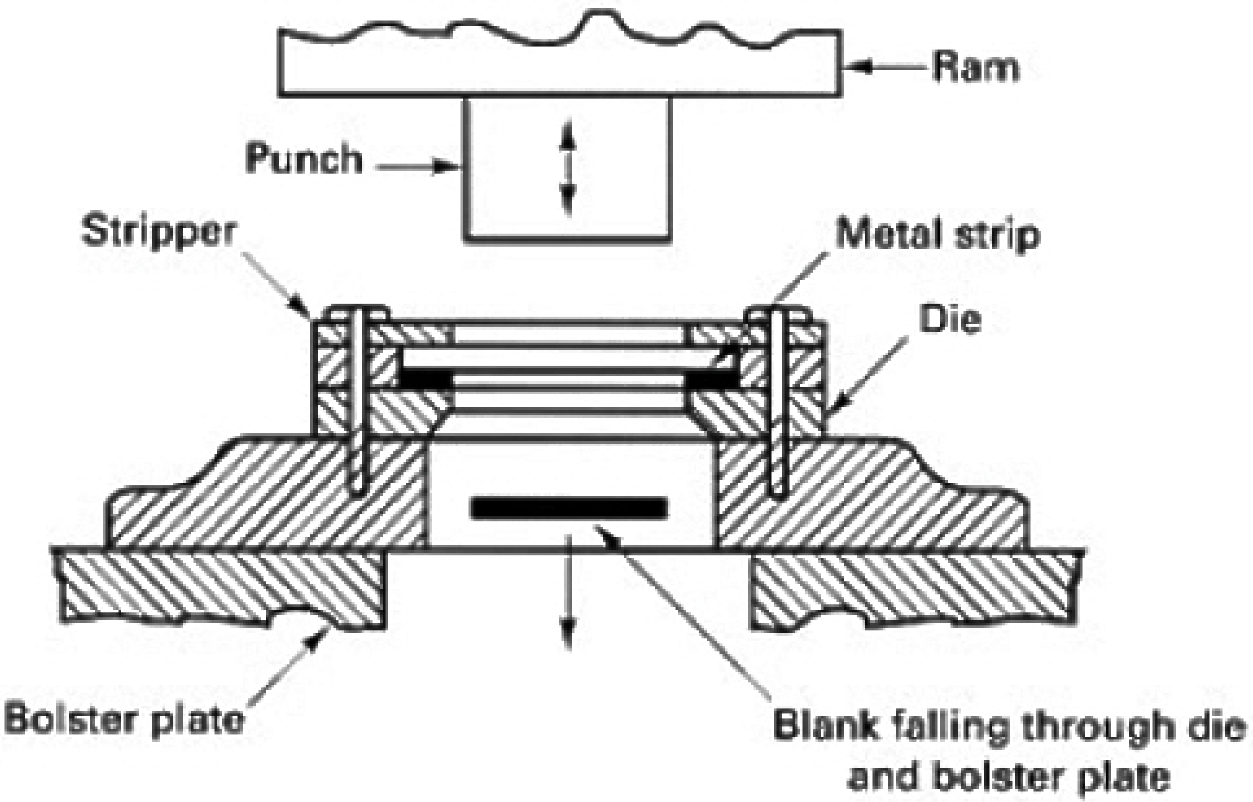
Solution:



- $L = (2*15 + 2*20)\,mm = 70\ mm$
- $P = (40\ kg/mm^2)*(1.5\ mm)*(70\ mm) = 4200\ kg$

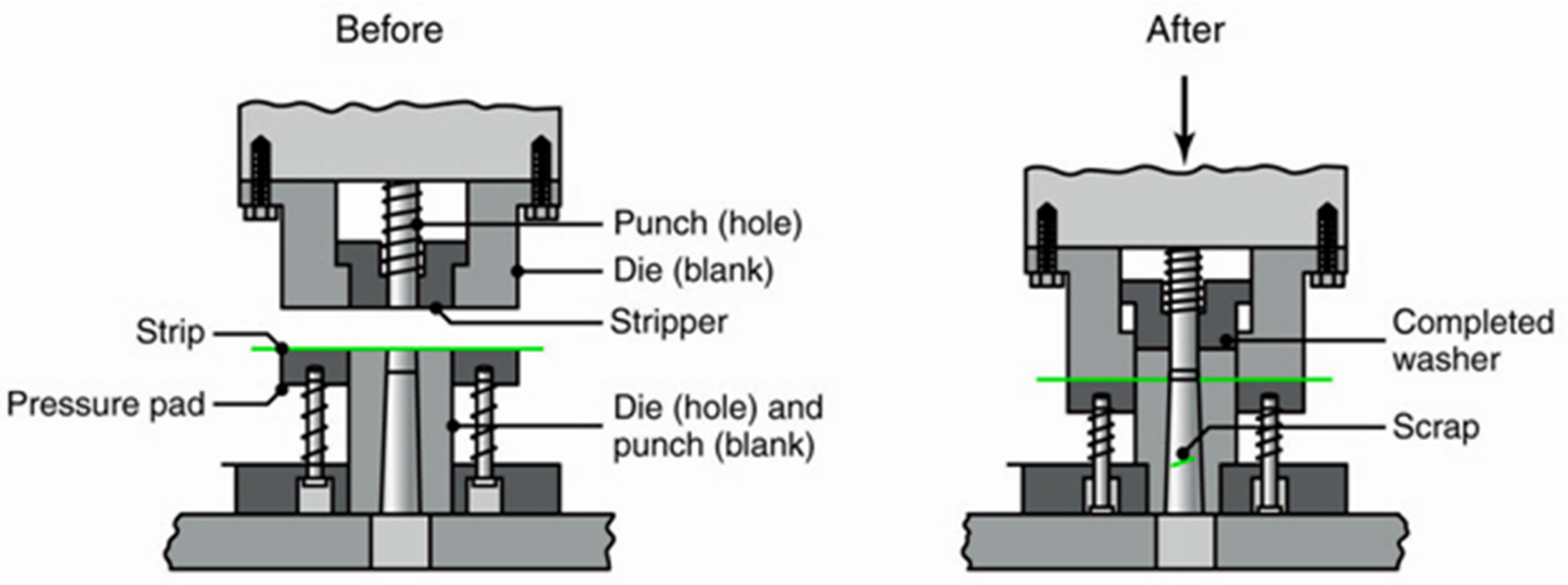
Tools and Dies

- **Simple dies:** Designed to perform **a single operation** (e.g. cutting, blanking, or punching) with each stroke of the press.



Tools and Dies

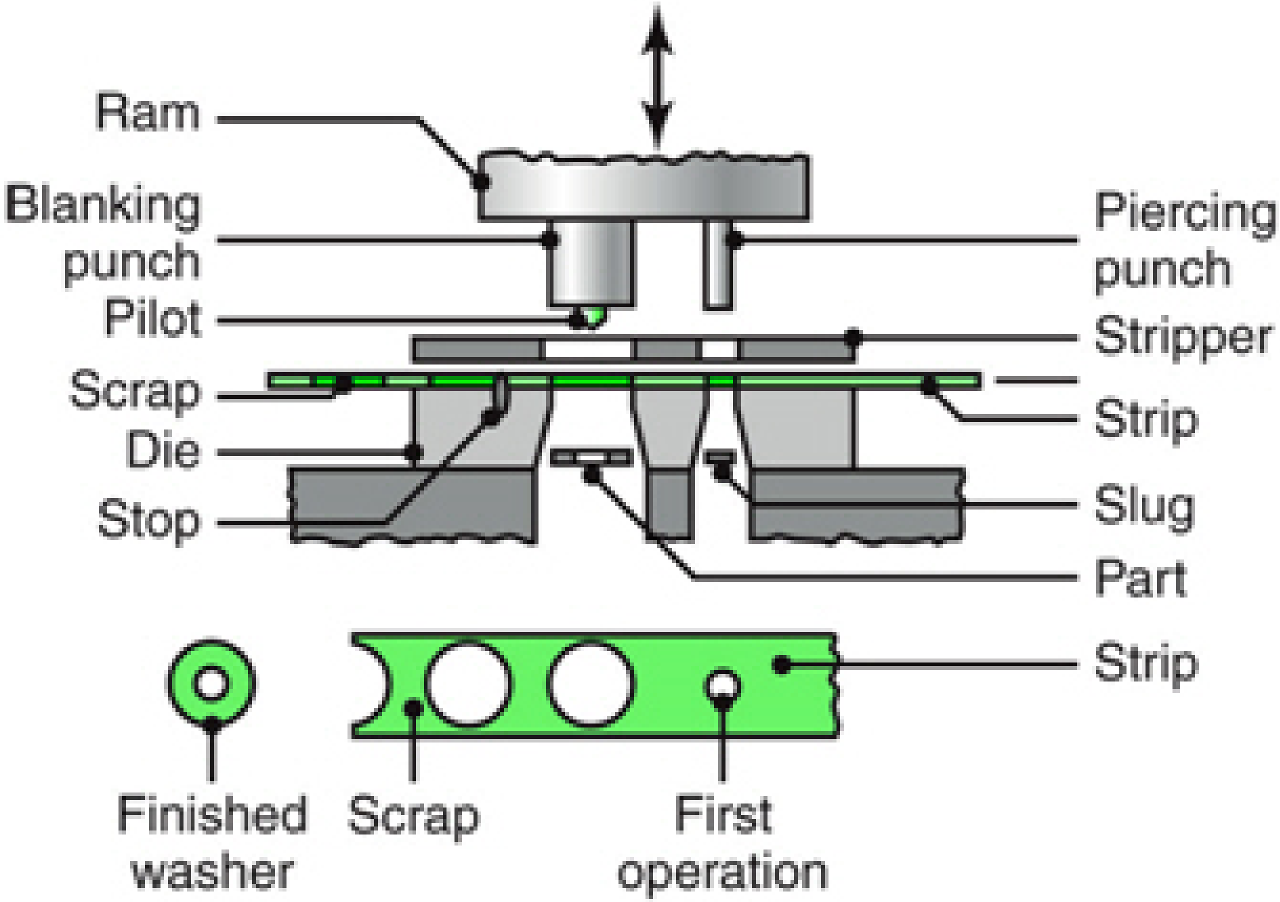
- **Multi-operational dies:** More complicated press working dies for **multi operations**:
  - ***Compound die:*** to perform two or more operations *at a single position* of metal strip.



Method of making a simple washer in a compound blanking and punching die

Tools and Dies

- **Multi-operational dies:** More complicated press working dies for **multi operations**:
  - ***Progressive die:*** to perform two or more operations *at two or more positions* of metal strip.



Progressive blanking and punching die for making a washer

Center of Pressure

- When sheet metal part to be blanked is of **irregular shape**, summation of shearing forces on one side of the center of ram may greatly exceed forces on the other side. This results in bending and undesirable deflections.
- **Center of pressure** is a point at which the summation of shearing forces will be symmetrical. In other words, it is ***the center of gravity of the perimeter of blank*** (*NOT the area of blank*).

- **Procedure to find center of pressure:**

– divide cutting edges into line elements ***(1,2,3, …)***

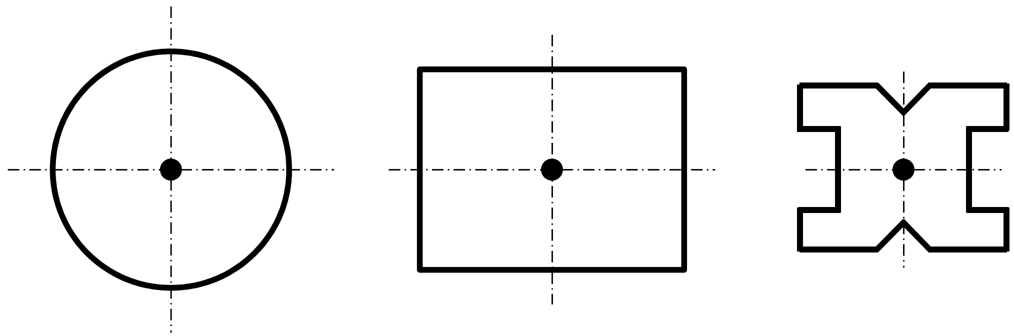
– find length of each element ***(l_1, l_2, l_3, …)***

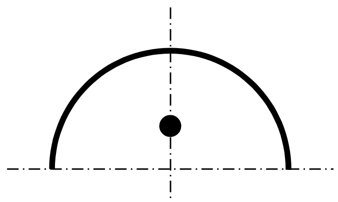
– find center of gravity of each element ***(x_1, … & y_1, …)***

– calculate the center of pressure from given formulas:

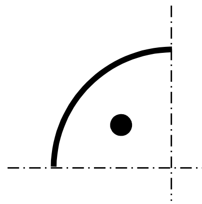
$$x = \frac{l_1 x_1 + l_2 x_2 + l_3 x_3 + \dots}{l_1 + l_2 + l_3 + \dots} = \frac{\sum lx}{\sum l}$$

$$y = \frac{l_1 y_1 + l_2 y_2 + l_3 y_3 + \dots}{l_1 + l_2 + l_3 + \dots} = \frac{\sum ly}{\sum l}$$

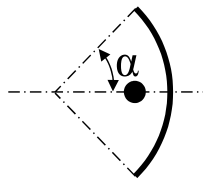




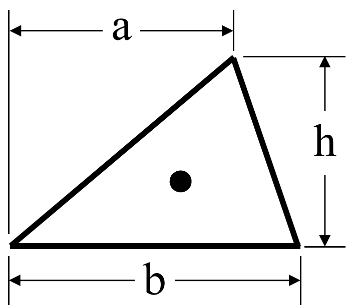
$$y = \frac{2r}{\pi}$$



$$x = y = \frac{2r}{\pi}$$



$$x = \frac{r \sin \alpha}{\alpha}$$



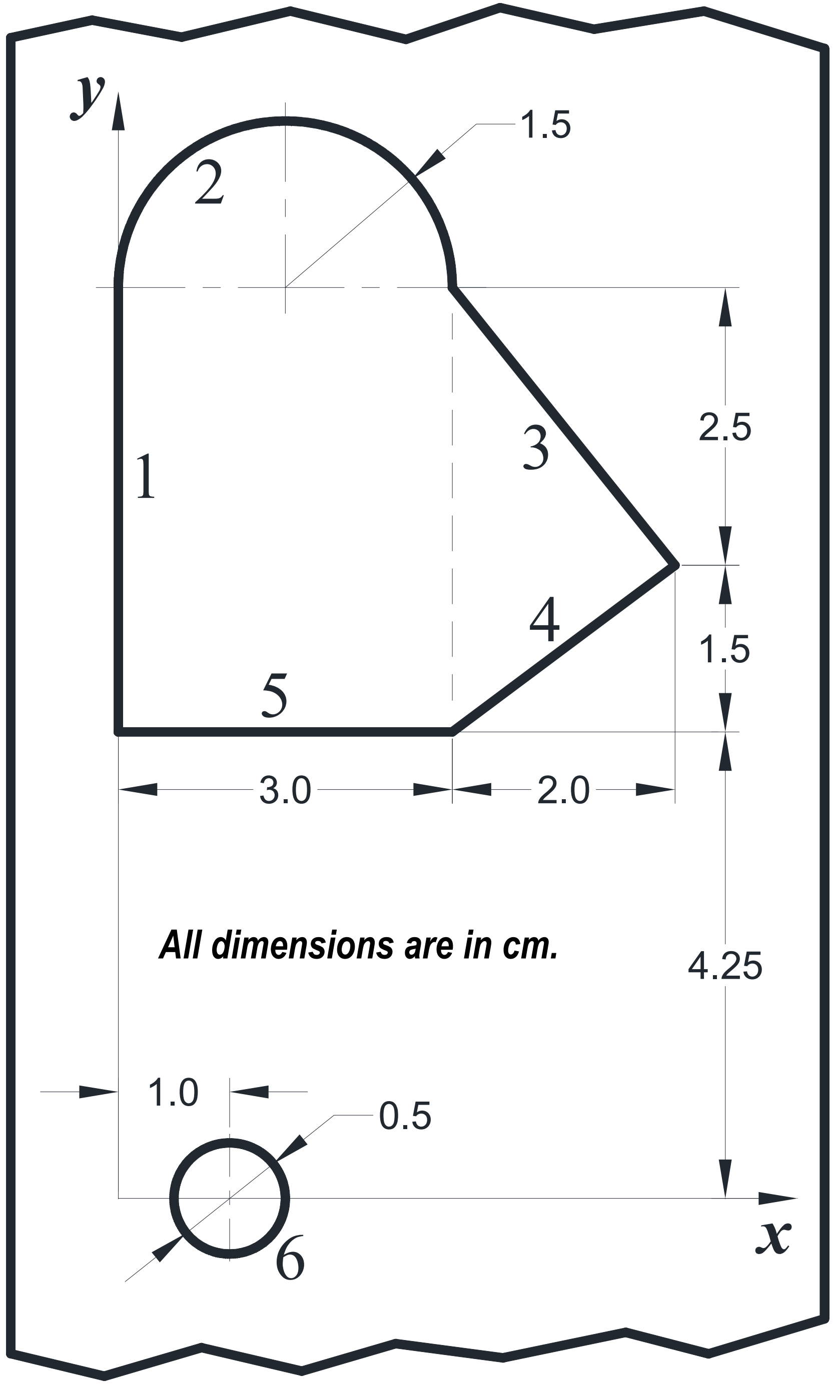
$$x = \frac{a+b}{3} \; \& \; y = \frac{h}{3}$$

Example:

Find center of pressure and required cutting force for the given blank (**S = 40 kg/mm² and t = 2 mm**).

Solution:

Element	*l*	*x*	*y*	*l * x*	*l * y*
1	4.00	0.00	6.25	0.00	25.00
2	4.71	1.50	9.20	7.05	43.33
3	3.20	4.00	7.00	12.80	22.40
4	2.50	4.00	5.00	10.00	12.50
5	3.00	1.50	4.25	4.50	12.75
6	1.57	1.00	0.00	1.57	0.00
Σ	**18.98**			**35.92**	**115.98**



➤ **Center of pressure:**

$$\bar{x} = \frac{35.92}{18.98} = 1.89\ cm$$

$$\bar{y} = \frac{115.98}{18.98} = 6.10\ cm$$

➤ **Cutting force:**

$$P = S * t * L$$

$$\Downarrow$$

$$P = \left(40\, kg/mm^2\right) * \left(2\ mm\right) * \left(189.8\ mm\right) = 15184\ kg$$

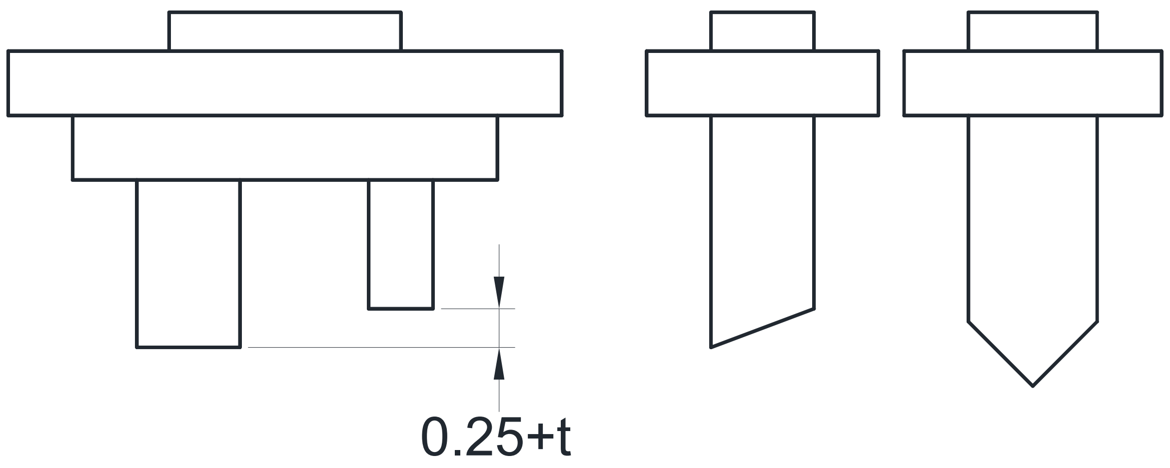
Reducing Cutting Forces

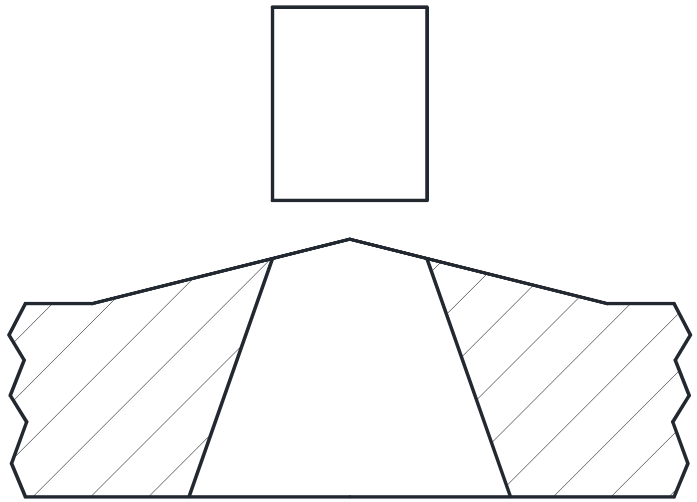
- Since cutting operations are characterized by very high forces exerted over very short periods of time, it is sometimes desirable to reduce the force and spread it over a longer portion of the ram stroke.

- Two methods are often used to reduce cutting forces and to smooth out the heavy loads:

1. Step the punch lengths: the load may be *reduced approximately 50%*.

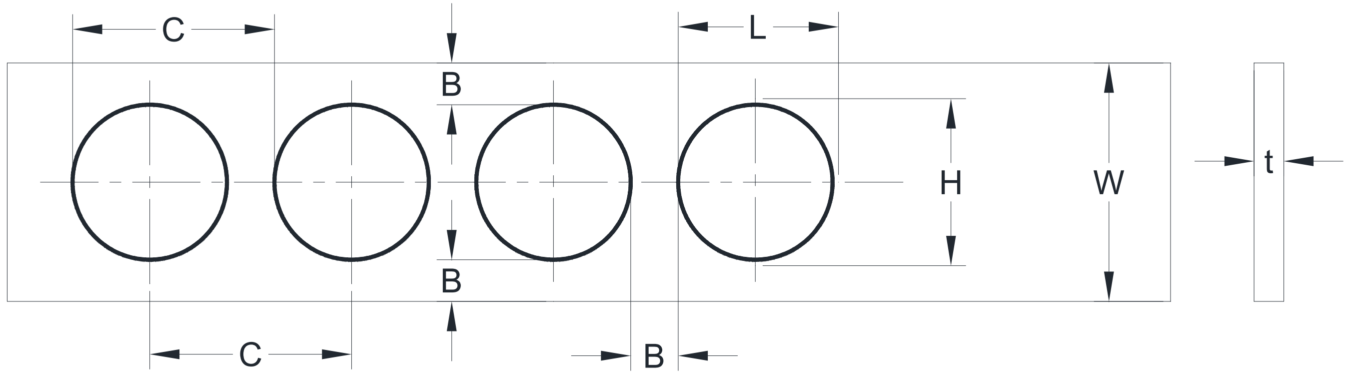
2. Taper the punch: grind the face of punch or die at a small shear angle with the horizontal. This has the effect of reducing area in shear at any time, and may *reduce cutting force up to 50%*. The taper angle should provide a change in punch length of *about 1.5 times material thickness*. It is usually preferable to double cut to prevent setup of lateral force components.





Scrap-Strip Layout for Blanking

- In designing parts to be blanked from strip material, it is very important to achieve economical strip utilization (**at least 75%**):

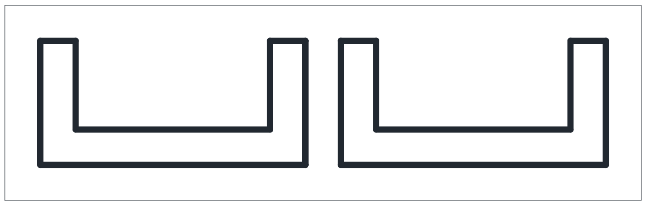


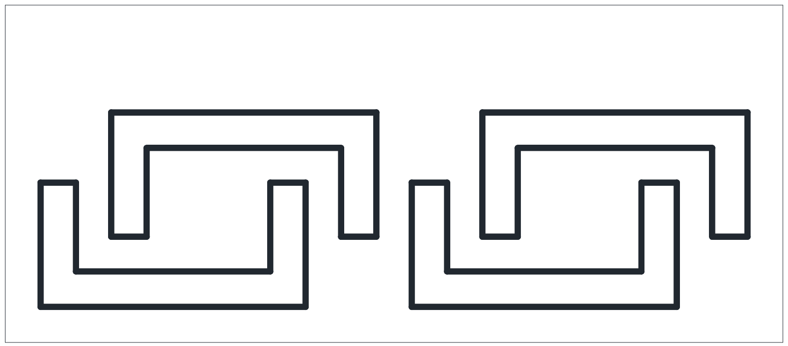
$$Scrap\ (\%) = \frac{Scrap}{Total} * 100$$

$$Utilization\ (\%) = \frac{Util.}{Total} * 100$$

t : thickness of stock
W : width of stock
B : space btw part and edge of stock ***(1.5t)***
C : lead of die ***(L + B)***
L & H : dimensions of part

- Thus, ***locating the part for maximum economy*** must be accomplished by trying various configurations.

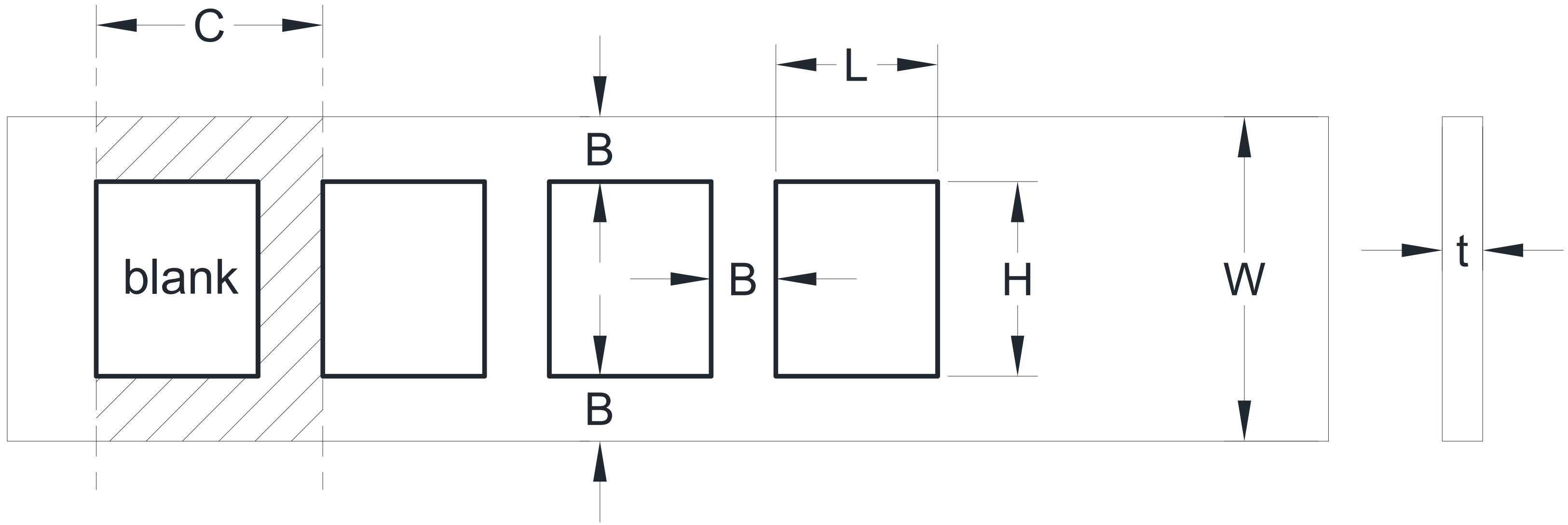




Example:

Calculate **scrap & strip utilization (in percentage)** for a rectangular blank (10 x 20 mm) to be produced from a strip (width of 25 mm and thickness of 1 mm).

Solution:



➤ Given dimensions:

$$L = 10\ mm$$

$$H = 20\ mm$$

$$W = 25\ mm$$

$$t = 1\ mm$$

➤ Calculated dimensions:

$$B = 1.5 * t = 1.5\ mm$$

$$C = L + B = 11.5\ mm$$

➤ Areas of blank & strip:

$$A_{blank} = L * H = 200\ mm^2$$

$$A_{strip} = C * W = 287.5\ mm^2$$

➤ **Strip utilization:**

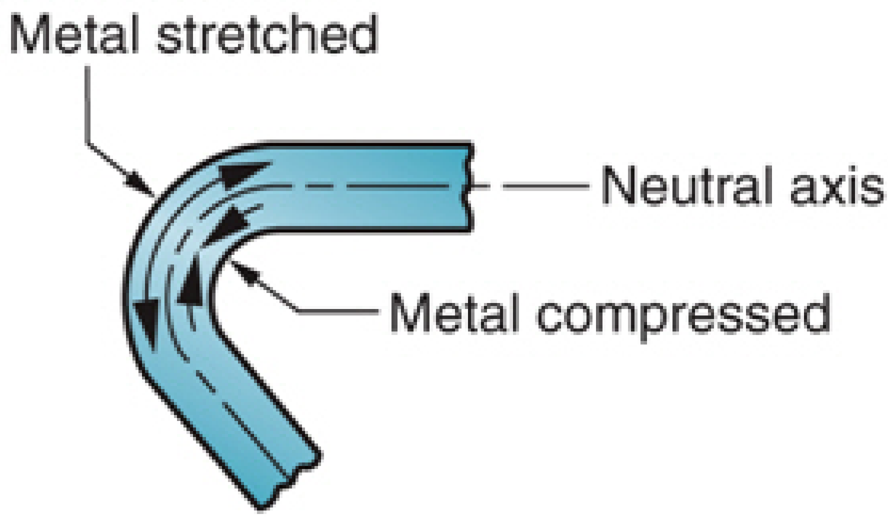
$$Utilization\ (\%) = \frac{A_{blank}}{A_{strip}} * 100 = 69.6$$

➤ **Scrap:**

$$Scrap\ (\%) = \frac{A_{scrap}}{A_{strip}} * 100 = \frac{A_{strip} - A_{blank}}{A_{strip}} * 100 = 30.4$$

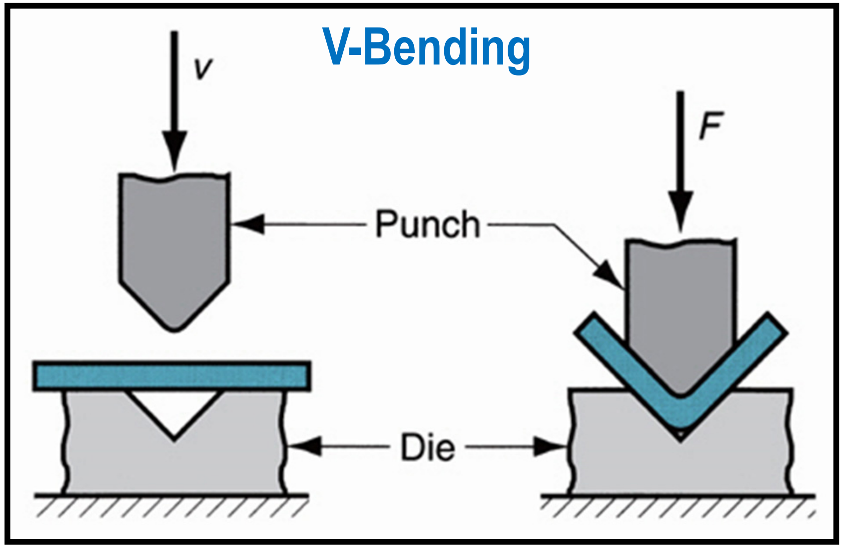
- Bending is defined as the straining of sheet metal around a straight edge (i.e. *a straight length is transformed into a curved length*).

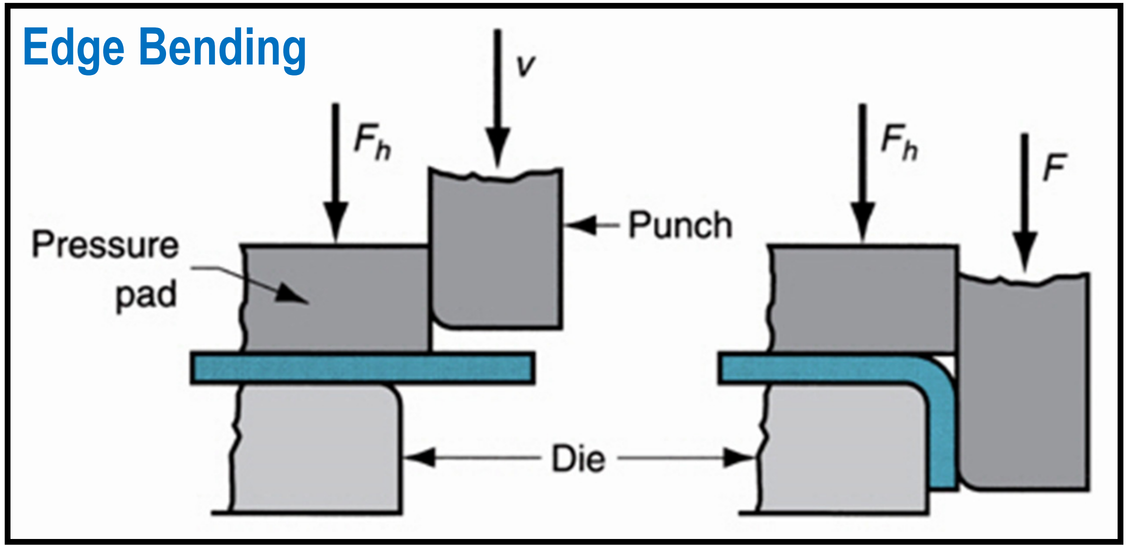
- It is a very common forming process for changing sheets and plates into **channels**, **tanks**, etc.



- There are two types of bending:

1. **V-Bending:** Sheet metal is bent along a straight line **between a V-shape punch and die**.
2. **Edge Bending:** Bending of the cantilever part of sheet **around the die edge**.

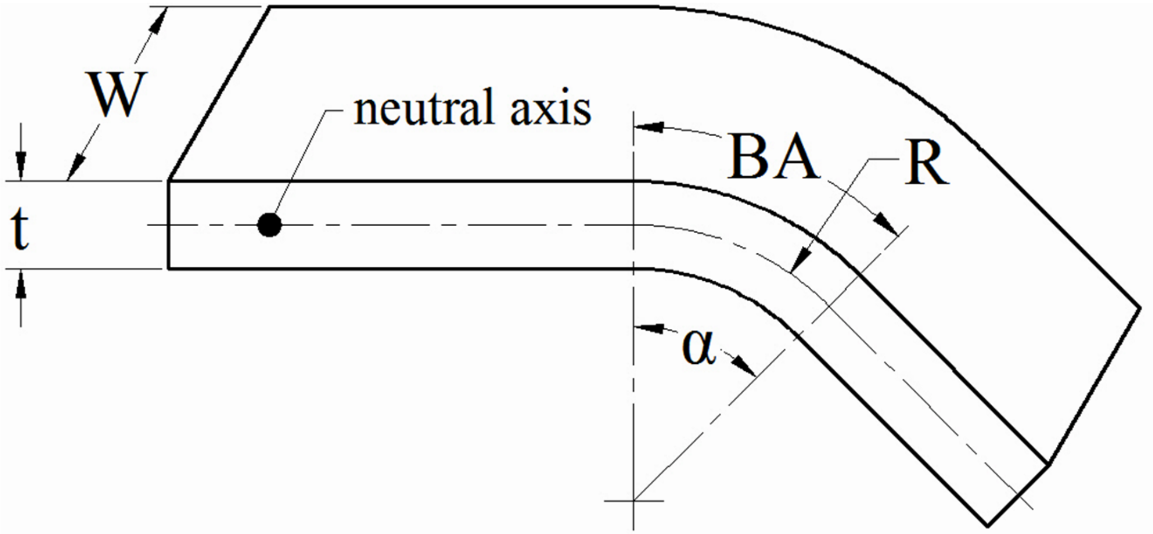




Bend Radius

- For a given bending operation, **bend radius (*R*)** cannot be made smaller than a certain value; otherwise the metal will crack on the outer tensile surface. Thus, **the minimum bend radius (R_{min})** must be used for a safe bending operation.
- In practice, it *cannot be less than 1 mm*, and expressed in multiples of sheet thickness. (*for high strength alloys:* $R_{min} \geq 5t$)
- R_{min} can also be predicted from **reduction of area (A_r)** measured by tension test:

$$A_r = \frac{A_o - A_f}{A_o} \Rightarrow \frac{R_{\min}}{t} = \frac{1}{2A_r} - 1 \quad (for\ A_r < 0.2) \qquad \frac{R_{\min}}{t} = \frac{(1-A_r)^2}{2A_r - A_r^2} - 1 \quad (for\ A_r \geq 0.2)$$

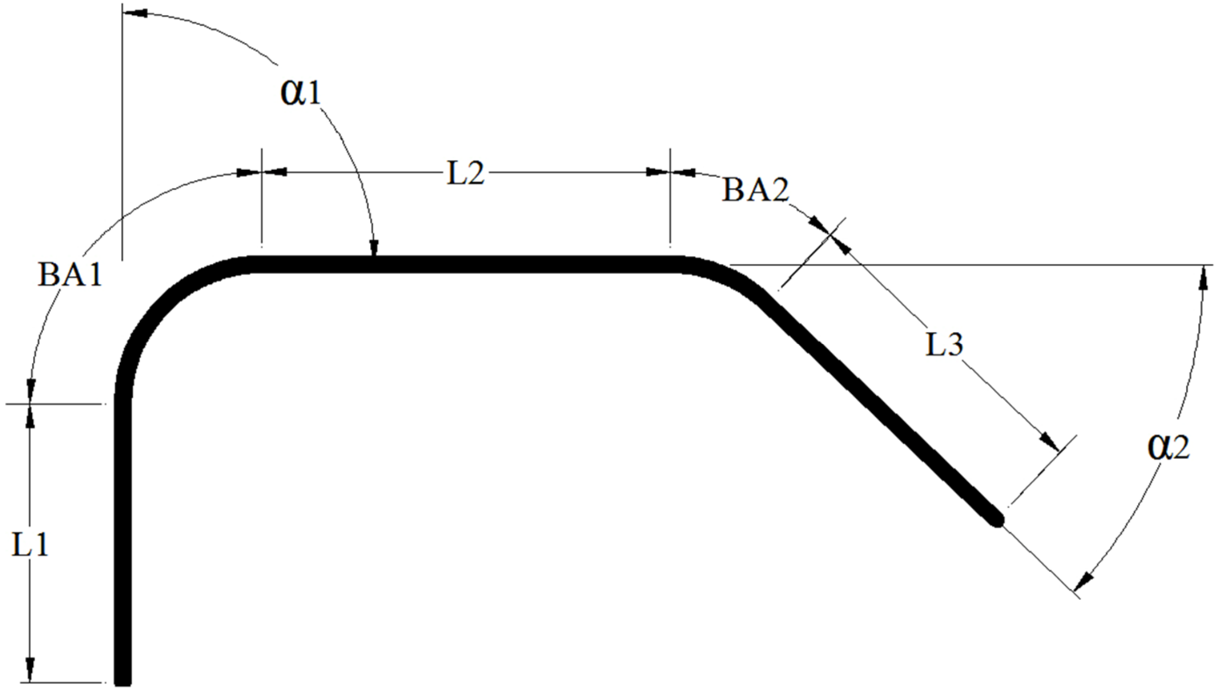


t	: thickness of sheet metal
W	: width of sheet metal
R	: bending radius
α	: bend angle
BA	: bend allowance

Length of Blank

- **Final length of blank (L_b)** can be determined based on summation of **length of stratight sections (L)** and **bend allowances (BA)**:

$$L_b = \sum L + \sum BA$$



Bend Allowance

- **Bend allowance (BA)** can be calculated based on **bend angle (α)**, **sheet thickness (t)**, and **stretching factor (K_{ba})**:

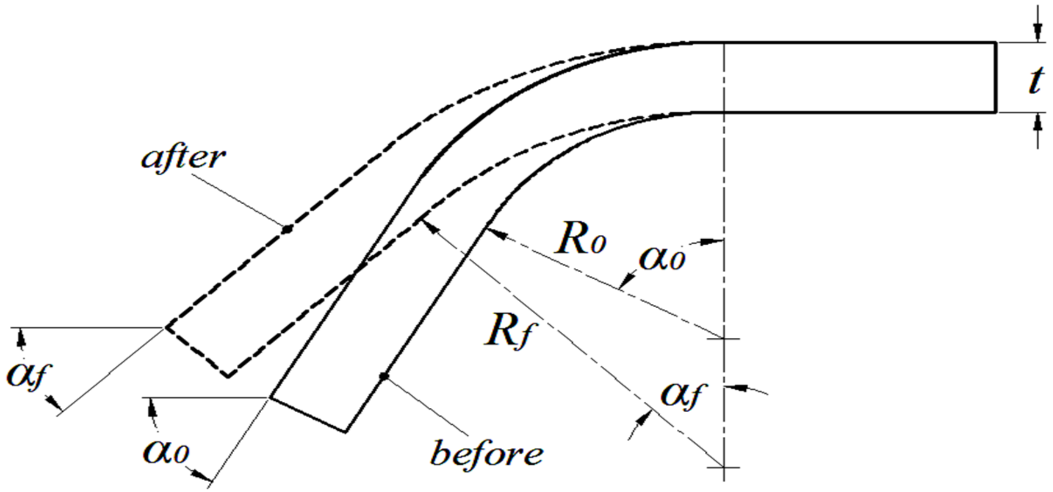
$$K_{ba} = 0.33 \quad (for\ R < 2t)$$
$$K_{ba} = 0.50 \quad (for\ R \geq 2t)$$

$$\Rightarrow \quad BA = 2\pi \frac{\alpha}{360}\left(R + K_{ba} * t\right)$$

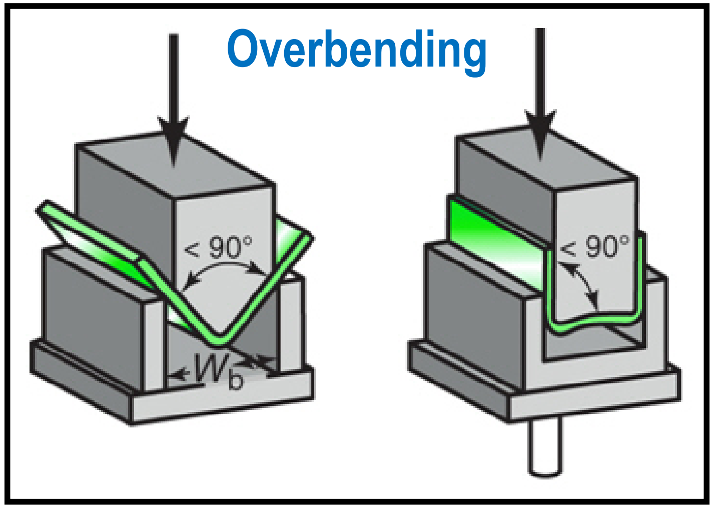
Springback

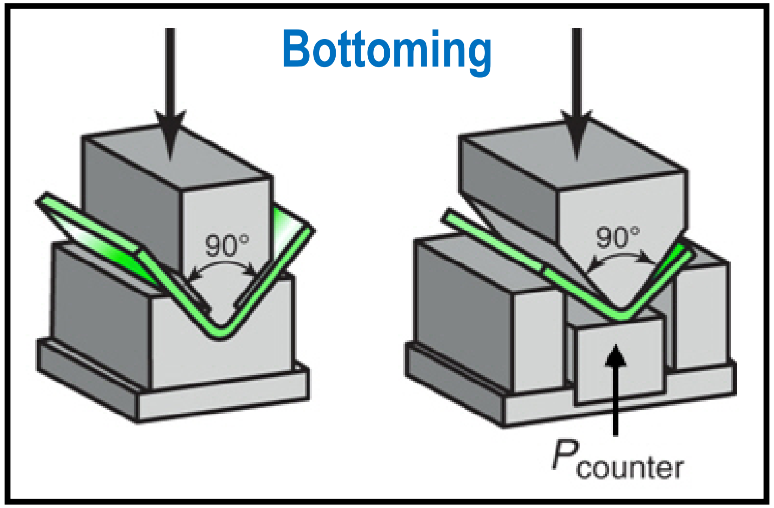
- It is the elastic recovery leading to dimensional change in the metal after pressure is removed. It is expressed by **springback ratio (K_s)**:

$$K_s = \frac{\alpha_f}{\alpha_o} = \frac{R_o + (t/2)}{R_f + (t/2)}$$



- Springback can be compensated by bending the part to a smaller radius of curvature than desired so that the part will have the proper radius after springback. This is done in two ways:
  – **Overbending:** using smaller punch angle and radius
  – **Bottoming:** squeezing the part at the end of stroke





Bending Force

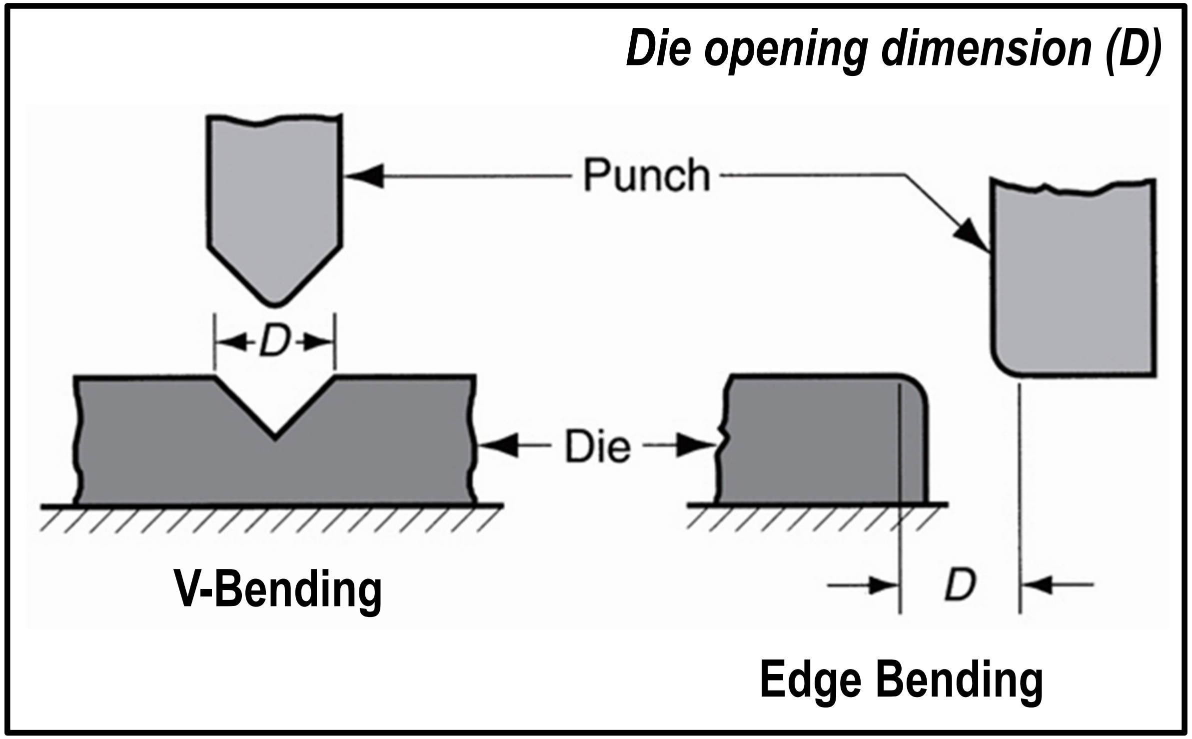
- The force required for bending **a length (*L*)** about **a radius (*R*)** may be estimated based on **mean flow stress ($\overline{\sigma_o}$)**, **angle of bending (α)**, and **sheet thickness (*t*)**:

$$P = \frac{\overline{\sigma_o} * L * t^2}{2\left[R + (t/2)\right]} \tan(\alpha/2)$$

- **The maximum bending force** is:

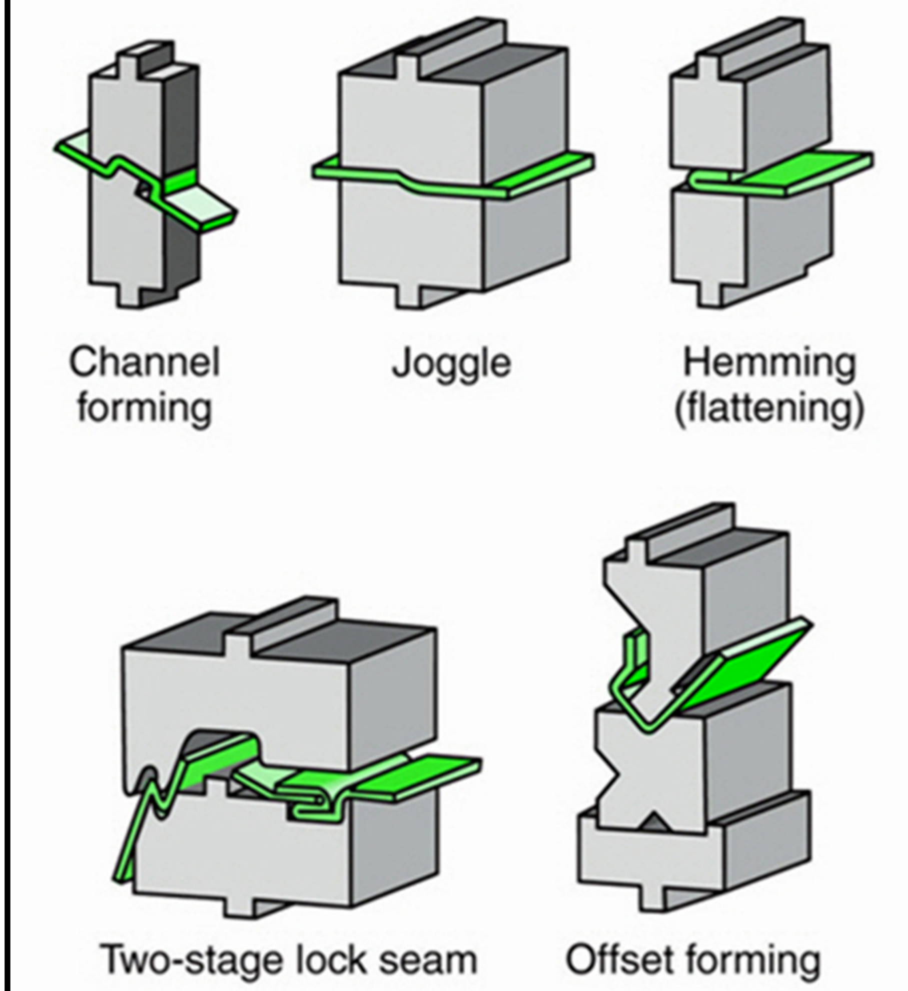
$$P_{\max} = \frac{K_{bf} * S_{ut} * W * t^2}{D}$$

t : thickness of sheet metal
W : width of sheet metal
S_{ut} : tensile strength of material
D : die opening dimension
K_{bf} : force coefficient
1.33 *(for V - bending)*
0.33 *(for edge bending)*

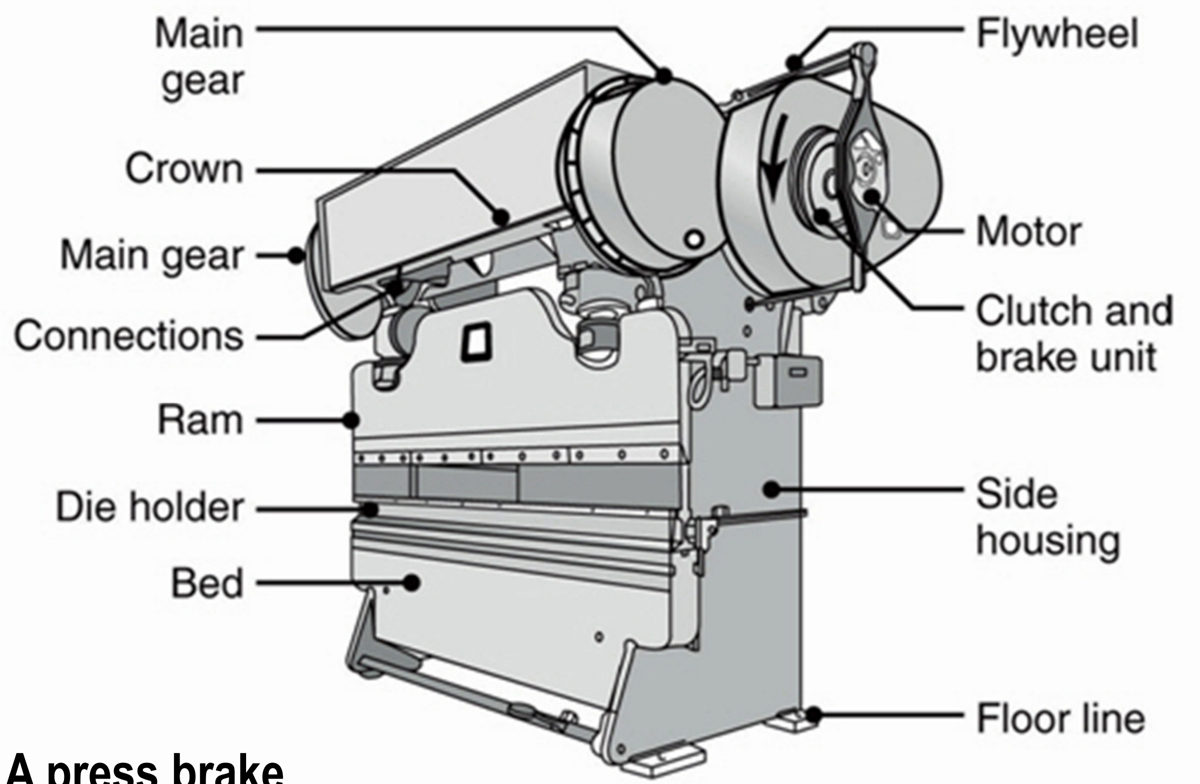


Bending Equipment

➤ Various bending operations can be performed in **a press brake**:

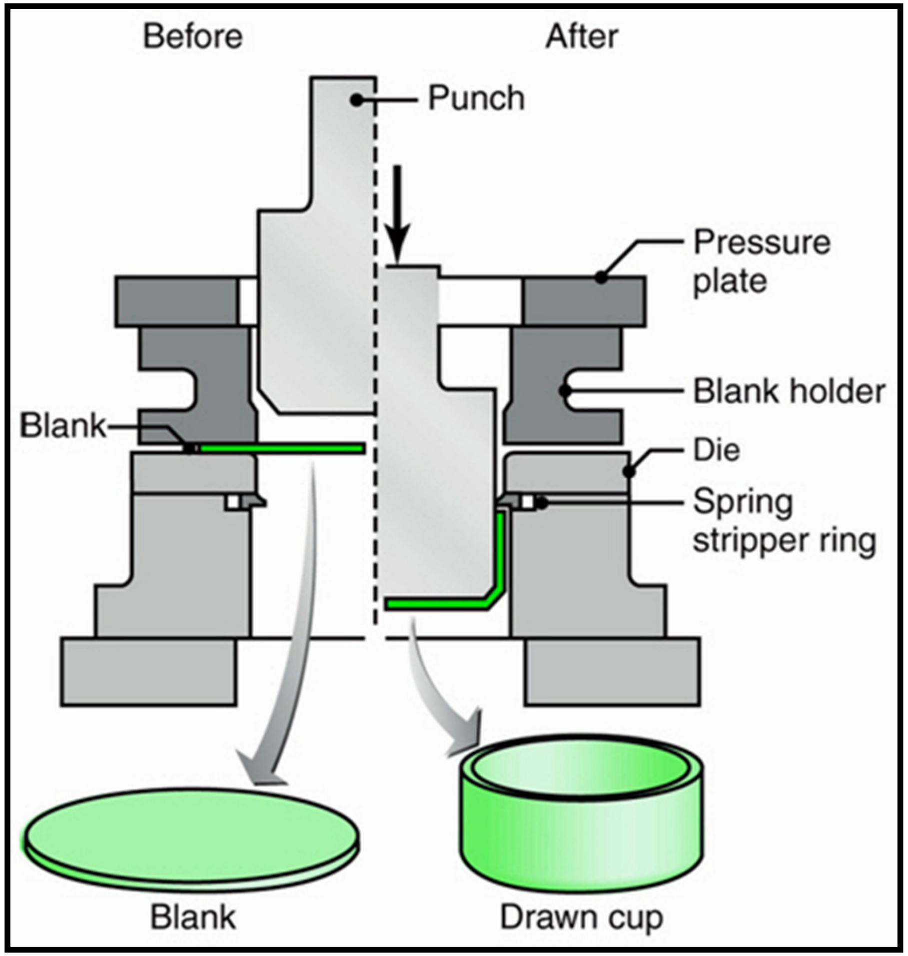


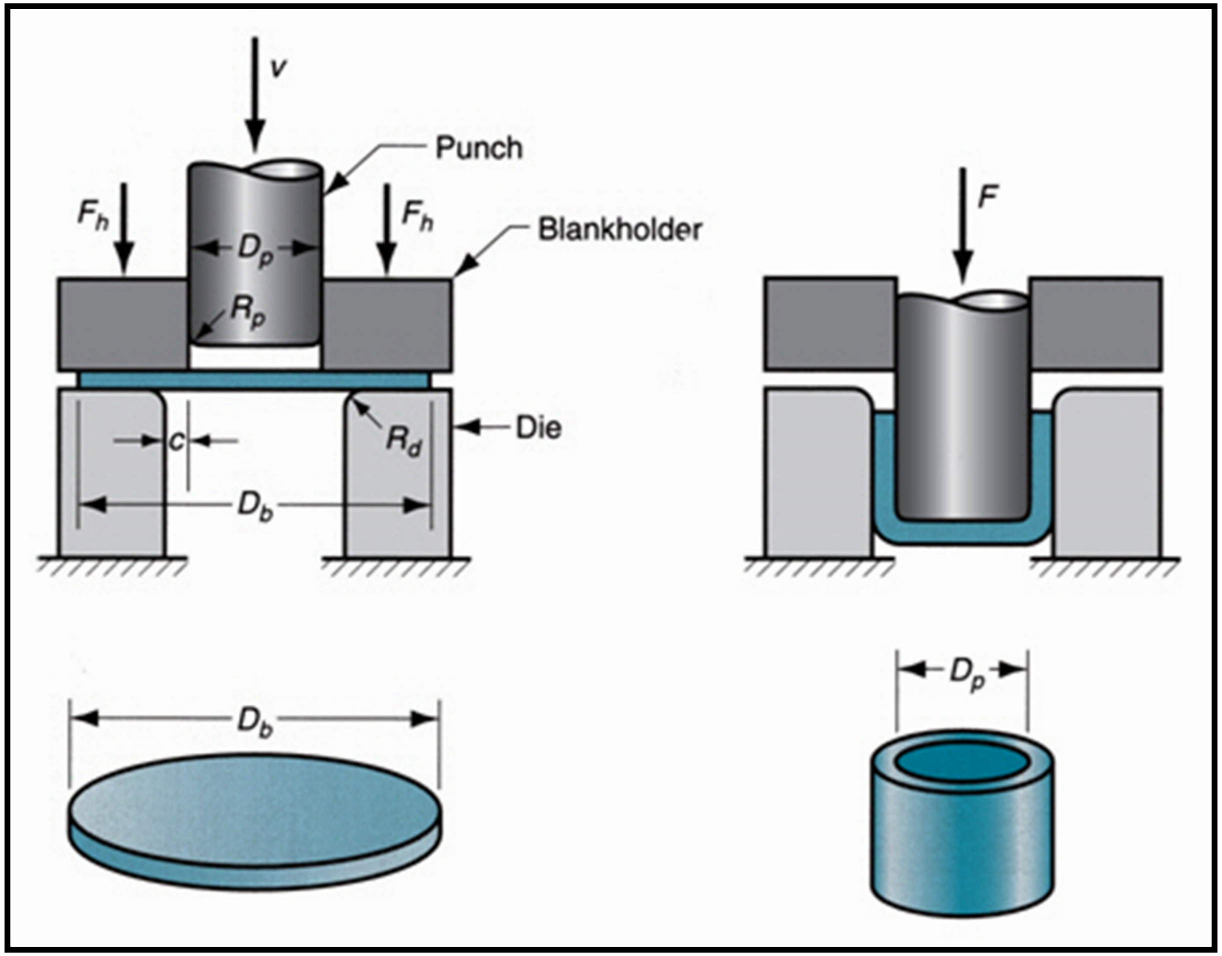
Various bending operations



A press brake

- Deep drawing is used for shaping flat sheets into cup-shaped products such as *bathtubs, shell cases, and automobile fenders*.
- In general, **a pressure (hold-down) pad** is required to press the blank against the die to prevent wrinkling. Optional pressure pad from the bottom may also be used.





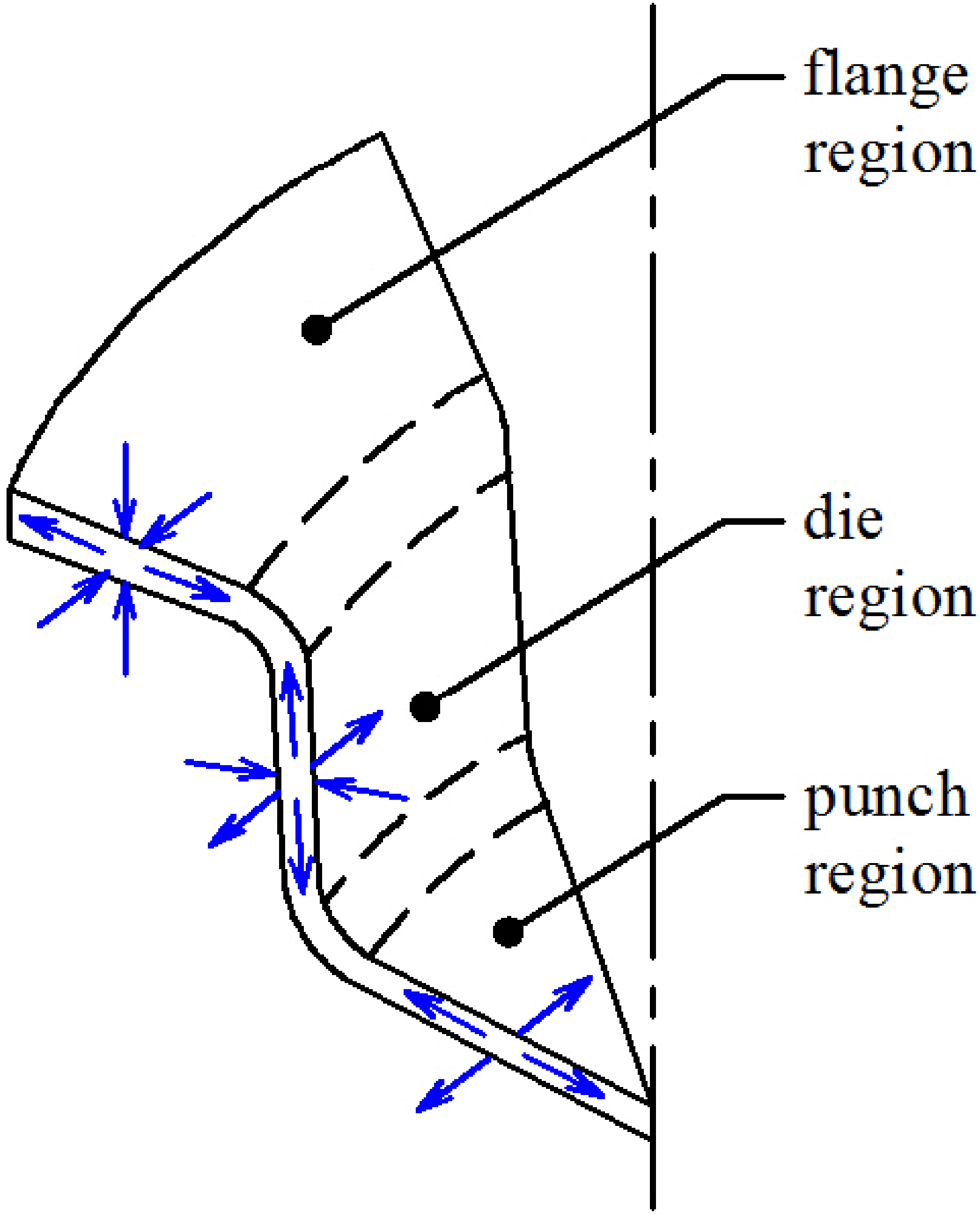
Engineering Analysis

- During deep drawing of a cup, the metal is subjected to different types of deformations:

– **Flange region:** As the metal is being drawn, the original circumference of blank (***πD_b***) will continuously decrease to the circumference of finish cup (***πD_p***). Due to tensile strain in radial direction and compressive (hoop) strain in circumferencial direction, increase in thickness occurs as the metal moves inward.

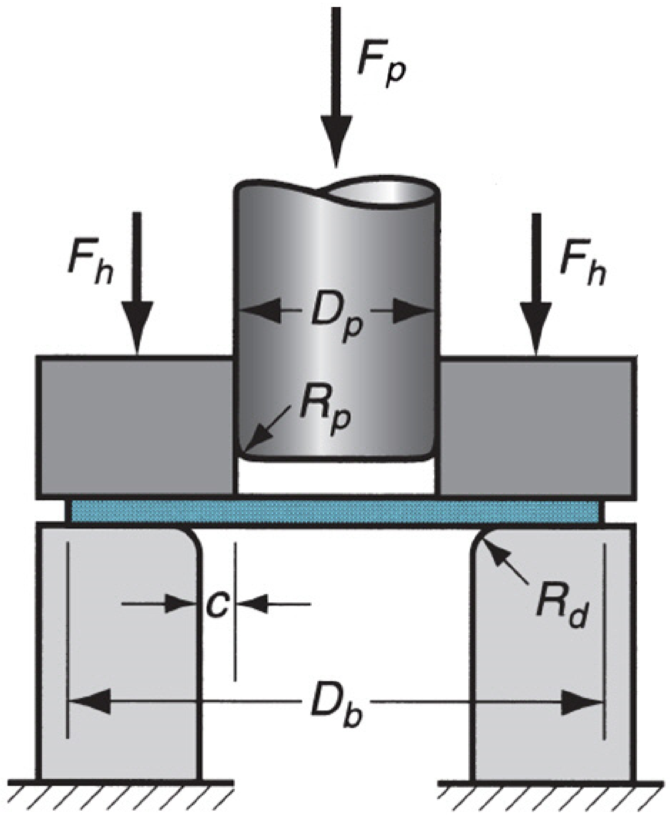
– **Die (wall) region:** The metal is first bent and then straightened as it is subjected to tensile stress. This plastic bending under tension results in considerable thinning.

– **Punch region:** Very low tensile stresses act in radial and circumferencial directions.



Clearance

- It is the distance between punch and die: $c = 1.1(t)$
- If it is less than the thickness produced by thicknening, the metal will be ***sequeezed (ironed)*** between punch and die to produce a uniform wall thickness.



c : clearance

F_h : holding force

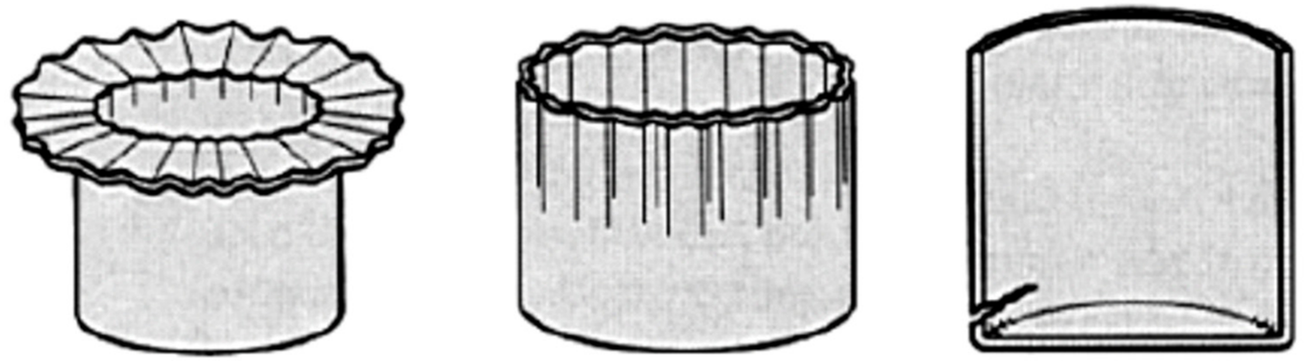
F_p : drawing force

D_p : punch diameter

D_b : blank diameter

Holding Force

- The improper application of holding force would cause ***severe defects*** in the drawn parts:
  - **wrinkling** (if holding force is underestimated)
  - **tearing** (if holding force is overestimated)



Flange wrinkling **Wall wrinkling** **Corner tearing**

Drawing (Punching) Force

- The force to produce a cup is summation of **ideal force of deformation**, **frictional forces**, and **the force required for ironing**. Appproximate calculation of drawing force is as follows:

$$F_p = \left[\pi D_p t \left(1.1\overline{\sigma_o}\right) * \ln\left(\frac{D_b}{D_p}\right) + \mu\left(2F_h \frac{D_p}{D_b}\right)\right] e^{(\mu\pi/2)} + F_b$$

$\overline{\sigma_o}$: mean flow stress
F_h : holding force
F_b : force for bending
μ : friction coefficient
D_b : blank diameter
D_p : punch (cup) diameter

- For practical purposes, this force may be calculated based on ***Limiting Drawing Ratio (LDR)***:

$$F_p = \overline{\sigma_o} \pi D_p t \quad (for\ LDR \approx 2)$$

Limiting Drawing Ratio (LDR)

- **The drawability of a metal** is defined by ***Limiting Drawing Ratio (LDR)***, which represents *the largest blank that can be drawn through a die without tearing*.
- **LDR** is the ratio of blank diameter to cup diameter, which is related to ***efficiency term (η)***:

$$LDR \approx \frac{D_b}{D_p} \approx e^{\eta}$$

⇨

η = 1.0 ⇨ ***no frictional loss (for ideal conditions)*** ⇨ ***LDR ≈ 2.7***

η = 0.7 ⇨ ***frictional loss accounted (for practical purposes)*** ⇨ ***LDR ≈ 2.0***

Estimating Blank Diameter

- The blank diameter (***D_b***) required to draw a given cup (***D_p***) can be estimated by equating surface areas *(**h** is the height of cup)*:

$$A_{blank} = A_{cup\ (punch)} \Rightarrow \frac{\pi D_b^2}{4} = \frac{\pi D_p^2}{4} + \pi D_p h \Rightarrow D_b = \sqrt{D_p^2 + 4D_p h}$$

Practical Considerations for Drawability

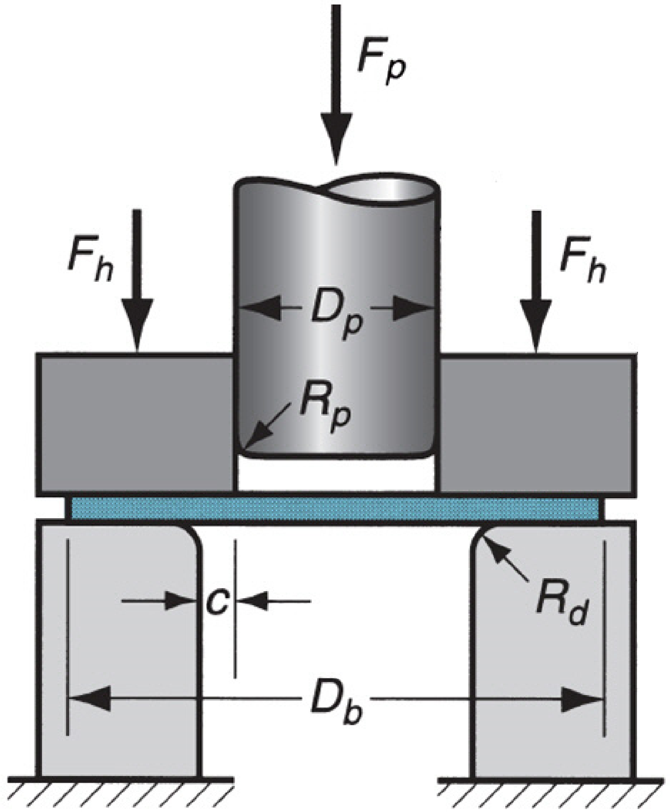
– **Die allowance (R_d)** ≈ 10(**t**)

– **Punch allowance (R_p)** must be sufficient to prevent tearing.

– **Clearance (c)** ≈ 1.2(**t**) to 1.4(**t**)

– **Holding force (F_h)** ≈ 0.2($\overline{\sigma_o}$)

– Die walls should be **lubricated**.



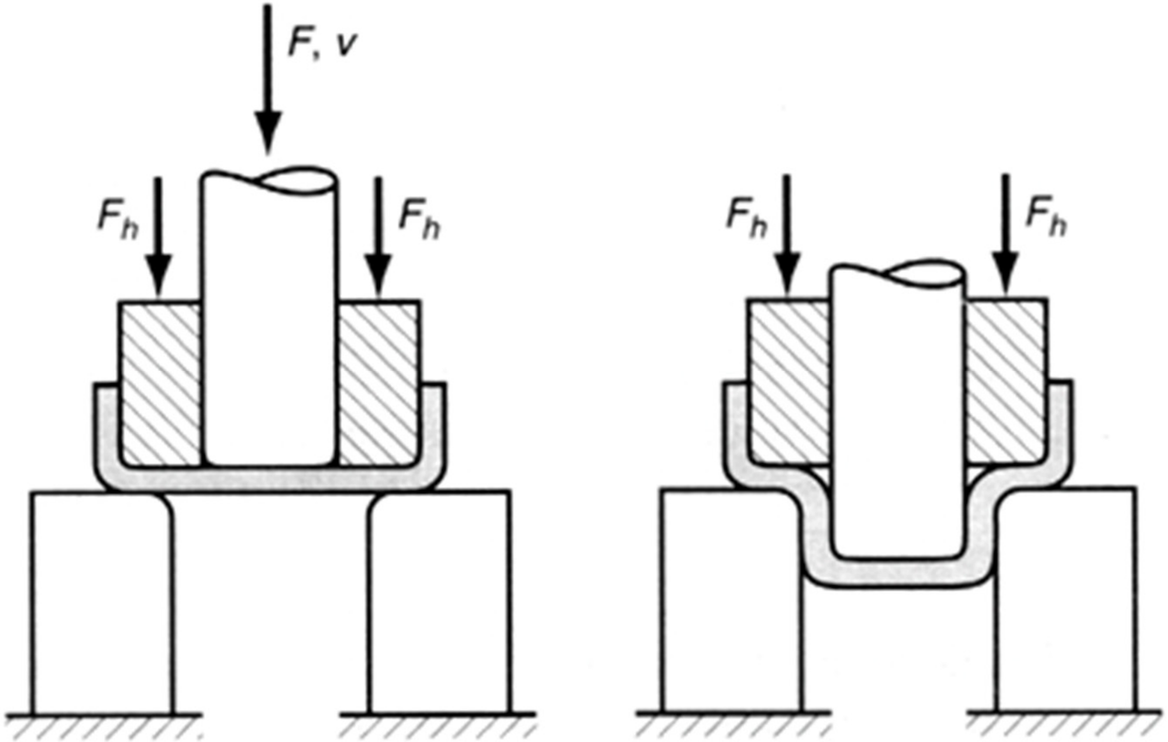
Redrawing

- If **the required change in shape of drawn part** is too severe (i.e. *LDR is too high or not sufficient to form the desired cup*), then the complete forming of part will require more than one drawing step. The second drawing step (and any further drawing steps if needed) are referred to as **redrawing**.

- Redrawing is done in decreasing ratios as given below (*where the throat angle is 10-15°*):

	Redrawing Steps					
	1st	2nd	3rd	4th	5th	6th
D_b / D_p	1.43	1.33	1.25	1.19	1.14	1.11

- If these steps are not enough to reach the required cup diameter, **annealing** is required, and then redrawing can be performed.



Example:

A Ø200 mm blank is to be drawn to a Ø50 mm cup. Estimate the minimum number of draws required for this operation using the given drawing ratios.

Step	1st	2nd	3rd	4th	5th	6th
Ratio	1.43	1.33	1.25	1.19	1.14	1.11

Solution:

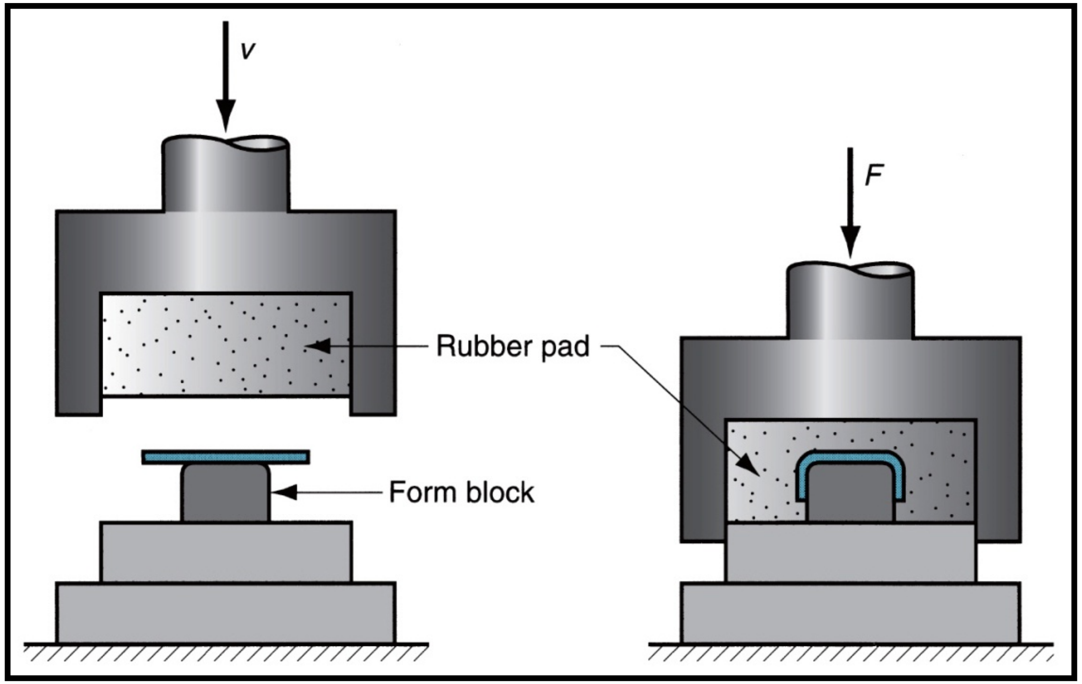
- Determine if redrawing is required: $\frac{D_b}{D_p} = \frac{200}{50} = 4 > LDR = 2$ ⇨ *Redrawing is necessary*

- Step 1: $\frac{D_b}{D_1} = 1.43$ ⇨ $D_1 = \frac{200}{1.43} = 139.86$
- Step 2: $\frac{D_1}{D_2} = 1.33$ ⇨ $D_2 = \frac{139.86}{1.33} = 105.16$
- Step 3: $\frac{D_2}{D_3} = 1.25$ ⇨ $D_3 = \frac{105.16}{1.25} = 84.13$
- Step 4: $\frac{D_3}{D_4} = 1.19$ ⇨ $D_4 = \frac{84.13}{1.19} = 70.69$
- Step 5: $\frac{D_4}{D_5} = 1.14$ ⇨ $D_5 = \frac{70.69}{1.14} = 62.01$
- Step 6: $\frac{D_5}{D_6} = 1.11$ ⇨ $D_6 = \frac{62.01}{1.11} = 55.86$

- Desired diameter still cannot be achieved after 6th step. Thus, **annealing must be applied**.
- It might be better to **anneal the blank before 6th draw** to reduce number of redraws.
- If annealing is performed **after 3rd draw**, the ratio to reach required cup diameter is: $\frac{84.13}{50} = 1.68 < LDR = 2$ ⇨ ***# of steps: 4***

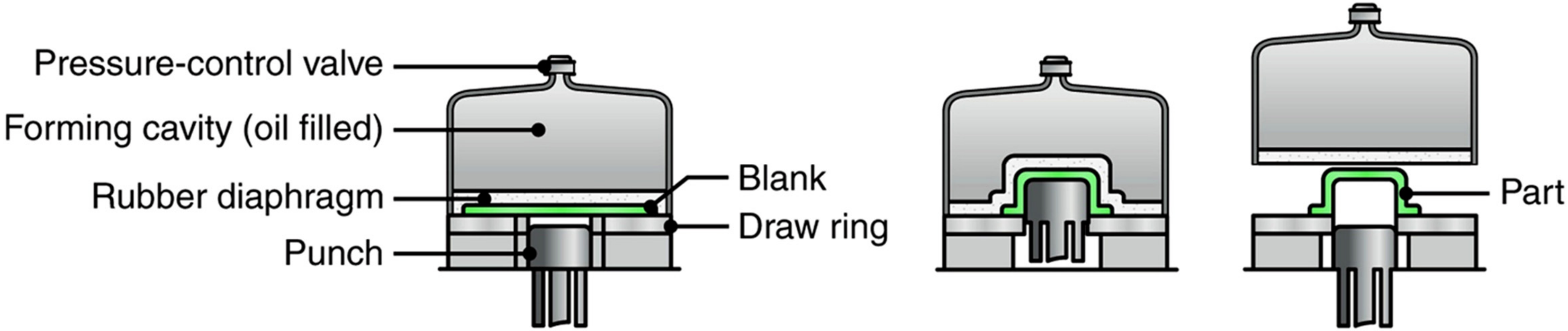
Guerin Process (Rubber Pad Forming)

- It involves the **use of a thick rubber pad** to form metal over a positive form block.
- Advantages: low tooling cost, using same rubber pad with different form blocks
- Limitations: for relatively shallow shapes
- Application area: small-quantity production



Hydroforming (Fluid Forming)

- Instead of a rubber pad in Guerin process, **a rubber diaphragm filled with fluid** is used.
- Advantages: low tooling cost
- Limitations: for simple shapes
- Application area: small-quantity production



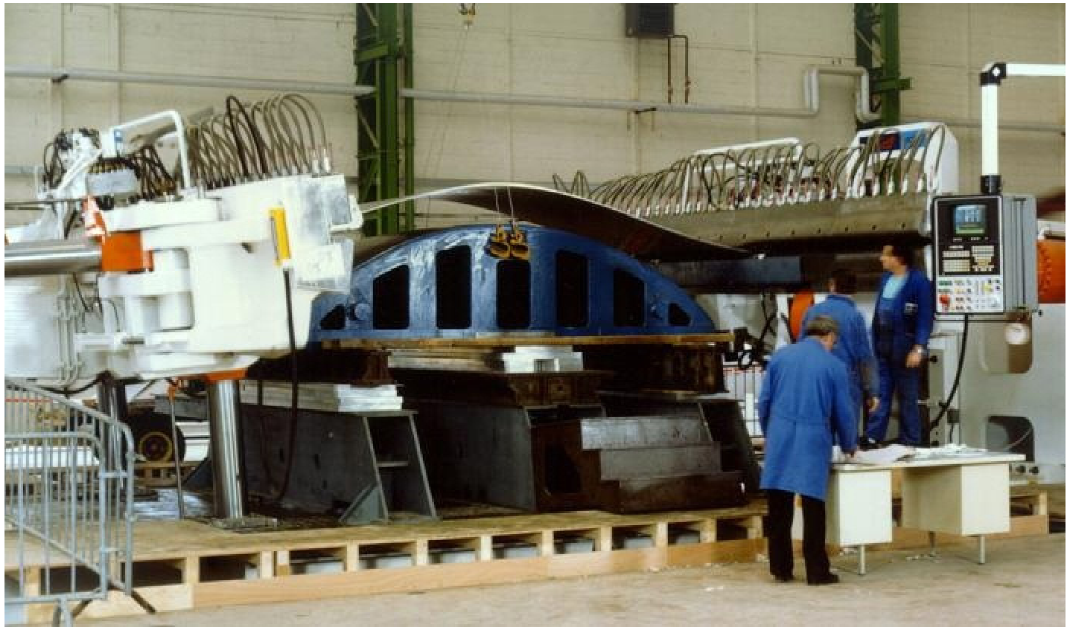
(1) Press closed and cavity pressurized with hydraulic fluid

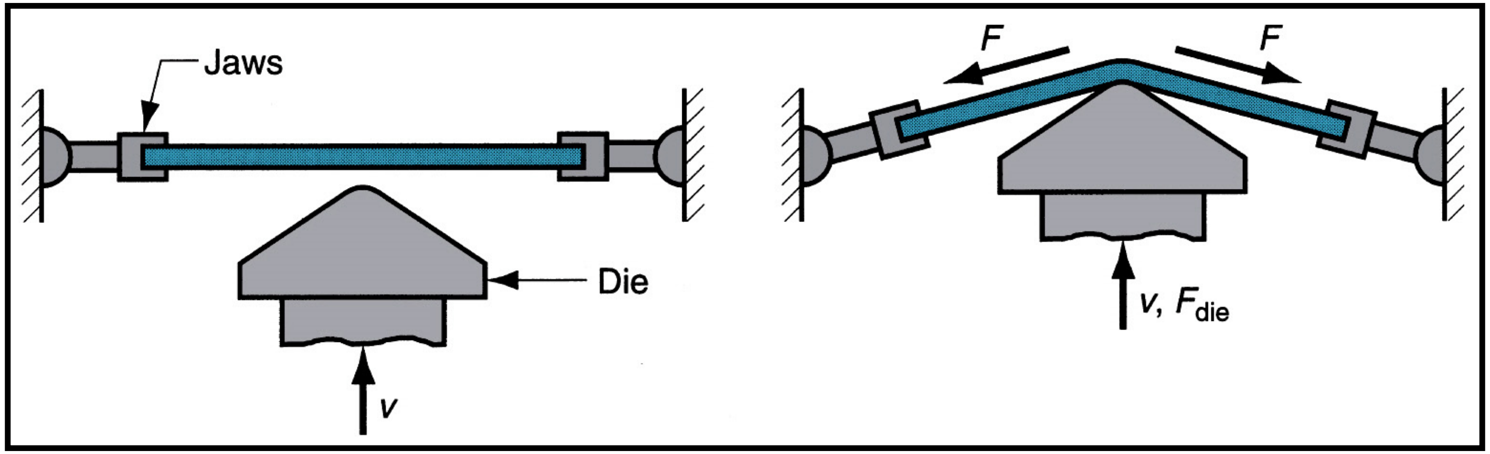
(2) Punch pressed into blank

(3) Punch and press pulled back and part produced

Stretch Forming

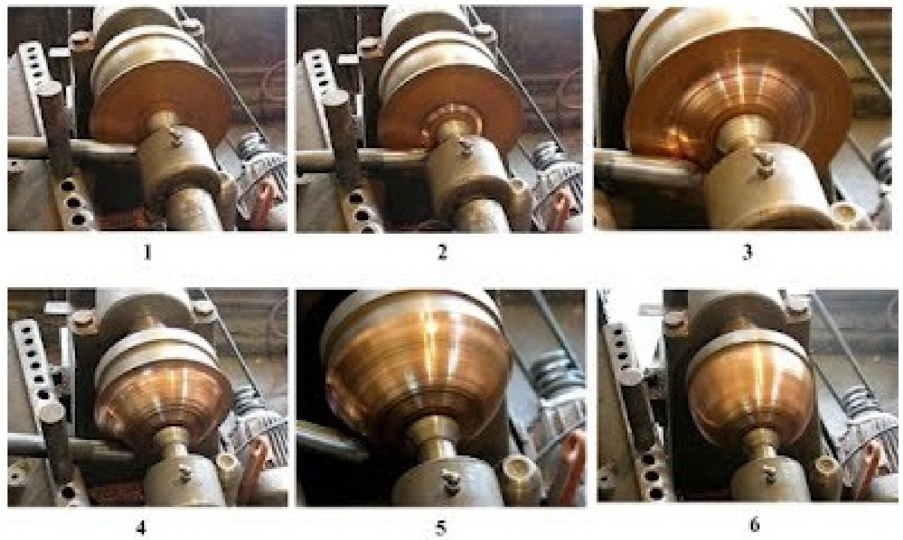
- The metal is **stretched and bent** to achieve the desired shape.
- Advantages: low tooling cost, production of large parts
- Limitations: for simple shapes
- Application area: small-quantity production

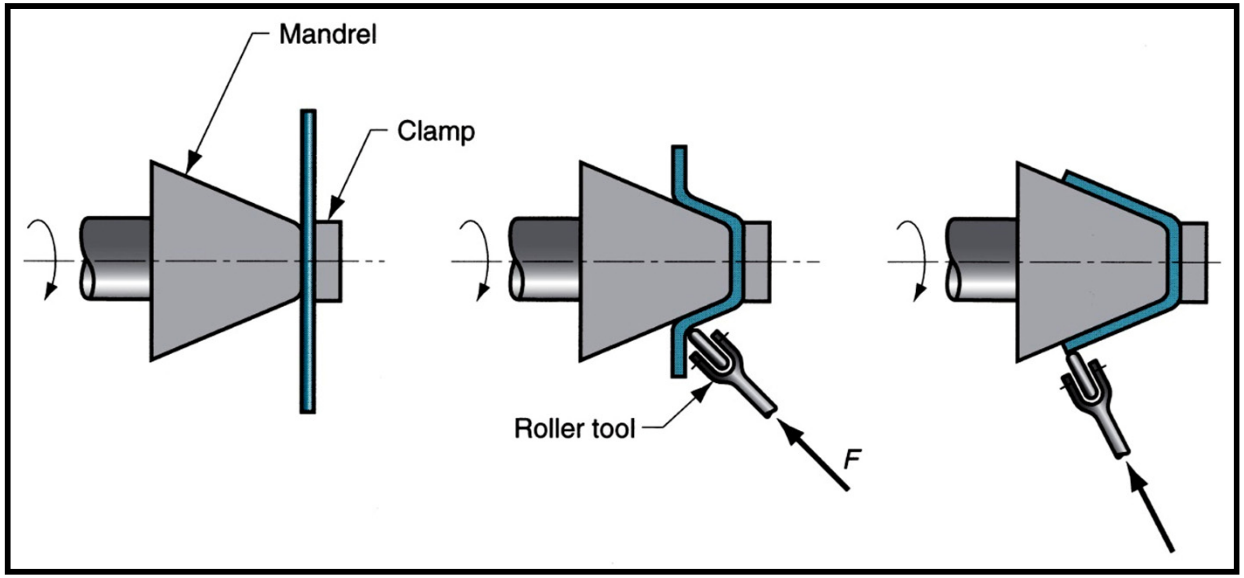




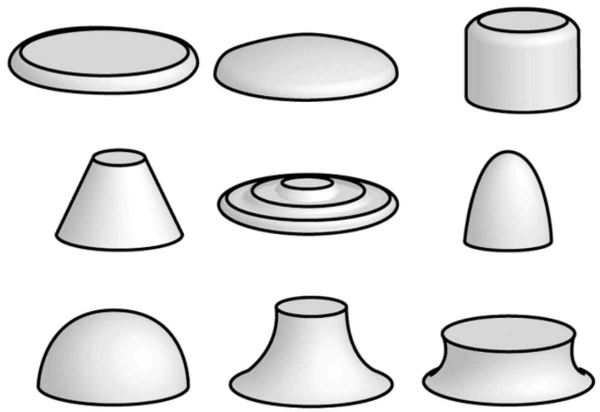
Spinning

- An axially symmetric part is **gradually shaped over a mandrel** by means of a rounded tool or roller.
- Advantages: low tooling cost, production of large parts (up to diameter of 5 m)
- Limitations: only axially symmetric parts
- Application area: small-quantity production





In a lathe, tool is forced against a rotating disk, gradually forcing the metal over chuck to conform to its shape. Chucks and follow blocks are usually made of wood.

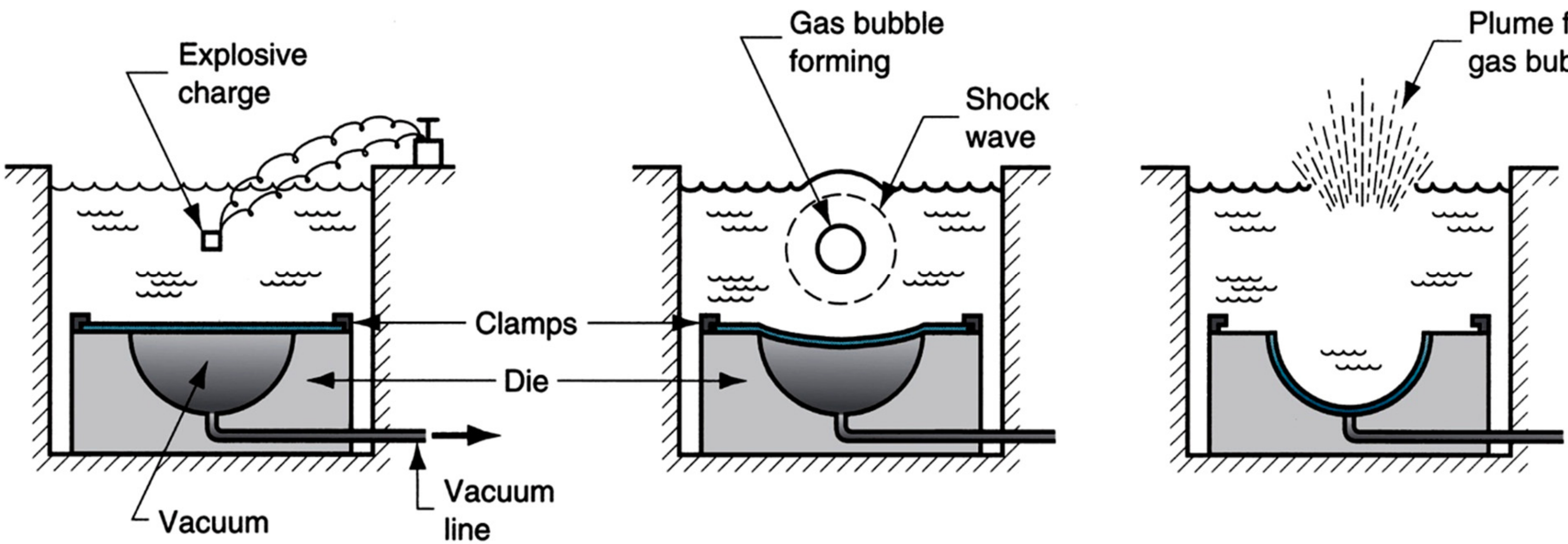


High Energy Rate Forming (HERF)

- These are forming processes in which large amount of energy is applied in a very short time:

Explosive Forming

- It involves use of **an explosive charge placed in water** to form sheet into the die cavity.
- Advantages: low tooling cost, large parts
- Limitations: skilled and experienced labour
- Application area: large parts in aerospace industry



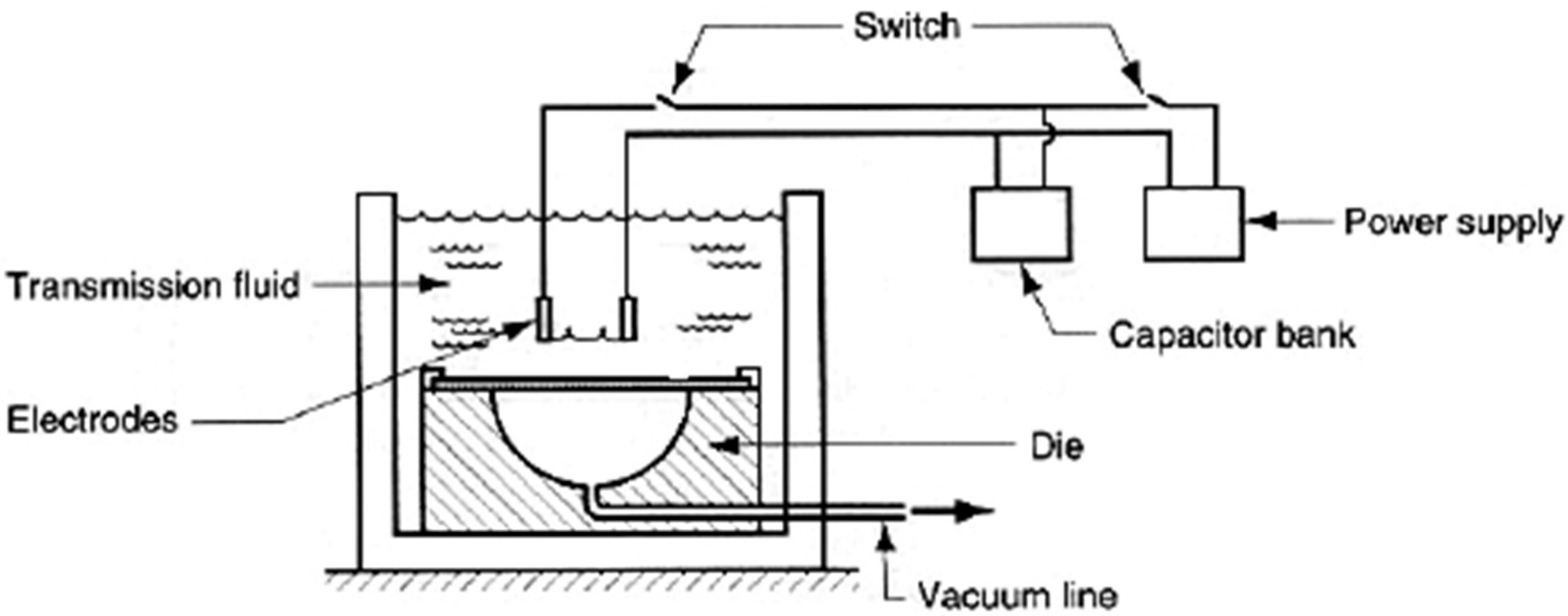
(1) Setup pf process

(2) Explosive detonated

(3) Part formed by shock waves

Electrohydraulic Forming

- The shock wave is generated by **discharge of electrical energy between two electrodes submerged in water**.
- Similar to explosive forming, but applied only to small part sizes.



Electromagnetic Forming

- The sheet metal is deformed by **the mechanical force of an electromagnetic field** induced in workpiece by a coil.
- Advantages: can produce shapes which cannot be produced easily by the other processes
- Limitations: suitable for magnetic materials
- Application area: most widely used HERF process to form tubular parts