





Four Important forming techniques are:

- Rolling
- Forging
- Extrusion
- Drawing

Terminology

Semi-finished product

- **Bloom:** is the product of first breakdown of ingot.
- **Billet:** is the product obtained from a further reduction by hot rolling (cross sectional area $> 40 \times 40 \text{ mm}^2$)
- **Slab:** is the hot rolled ingot (cross sectional area $> 100 \text{ cm}^2$ and with a width $\geq 2 \times$ thickness)



Contd.

Terminology

Mill product

- **Plate** is the product with thickness $> 5 \text{ mm}$
- **Sheet** is the product with thickness $< 5 \text{ mm}$ and width $> 600 \text{ mm}$
- **Strip** is the product with a thickness $< 5 \text{ mm}$ and width $< 600 \text{ mm}$



Plastic Deformation

- Deformation beyond elastic limits.
- Due to slip, grain fragmentation, movement of atoms and lattice distortion.

Recrystallisation Temperature (R_x)

- "The minimum temperature at which the completed recrystallisation of a cold worked metal occurs within a specified period of approximately one hour".
- R_x decreases strength and increases ductility.
- If working above R_x , hot-working process whereas working below are cold-working process.
- It involves replacement of cold-worked structure by a new set of strain-free, approximately equi-axed grains to replace all the deformed crystals.

Contd.

- Rx depends on the amount of cold work a material has already received. The higher the cold work, the lower would be the Rx.
- Rx varies between $1/3$ to $1/2$ melting point.
- **$Rx = 0.4 \times \text{Melting temp. (Kelvin)}$.**
- Rx of lead and Tin is below room temp.
- Rx of Cadmium and Zinc is room temp.
- Rx of Iron is 450°C and for steels around 1000°C
- Finer is the initial grain size; lower will be the Rx

Contd.

Grain growth

- Grain growth follows complete crystallization if the materials left at elevated temperatures.
- Grain growth does not need to be preceded by recovery and recrystallization; it may occur in all polycrystalline materials.
- In contrary to recovery and recrystallization, driving force for this process is reduction in grain boundary energy.
- In practical applications, grain growth is not desirable.
- Incorporation of impurity atoms and insoluble second phase particles are effective in retarding grain growth.
- Grain growth is very strongly dependent on temperature.

Strain Hardening

- When metal is formed in cold state, there is no recrystallization of grains and thus recovery from grain distortion or fragmentation does not take place.
- As grain deformation proceeds, greater resistance to this action results in increased hardness and strength i.e. strain hardening.

Malleability

- Malleability is the property of a material whereby it can be shaped when cold by hammering or rolling.
- A malleable material is capable of undergoing plastic deformation without fracture.
- A malleable material should be plastic but it is not essential to be so strong.
- Lead, soft steel, wrought iron, copper and aluminium are some materials in order of diminishing malleability.



Cold Working

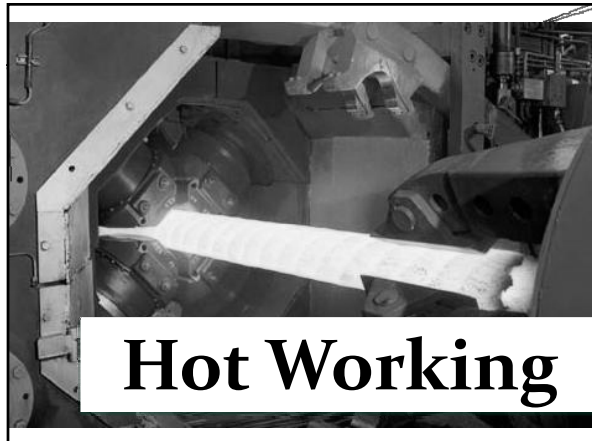
- Working below recrystallization temp.

Advantages of Cold Working

1. Better accuracy, closer tolerances
2. Better surface finish
3. Strain hardening increases strength and hardness
4. Grain flow during deformation can cause desirable directional properties in product
5. No heating of work required (less total energy)

Disadvantages of Cold Working

1. Equipment of higher forces and power required
2. Surfaces of starting work piece must be free of scale and dirt
3. Ductility and strain hardening limit the amount of forming that can be done
4. In some operations, metal must be annealed to allow further deformation
5. Some metals are simply not ductile enough to be cold worked.



- Working above recrystallization temp.

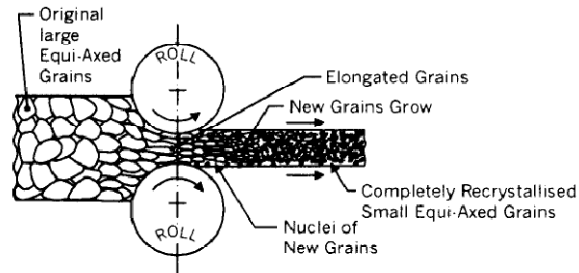
Advantages of Hot Working

1. The porosity of the metal is largely eliminated.
2. The grain structure of the metal is refined.
3. The impurities like slag are squeezed into fibers and distributed throughout the metal.
4. The mechanical properties such as toughness, ductility, percentage elongation, percentage reduction in area, and resistance to shock and vibration are improved due to the refinement of grains.

Dis-advantages of Hot Working

1. It requires expensive tools.
2. It produces poor surface finish, due to the rapid oxidation and scale formation on the metal surface.
3. Due to the poor surface finish, close tolerance cannot be maintained.

Micro-Structural Changes in a Hot Working Process (Rolling)



Annealing

- Annealing relieves the stresses from cold working – three stages: recovery, recrystallization and grain growth.
- During recovery, physical properties of the cold-worked material are restored without any observable change in microstructure.

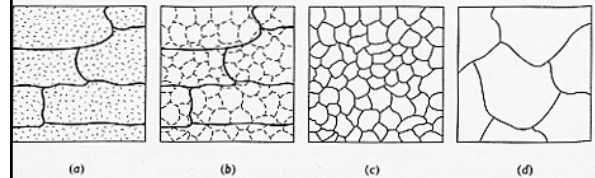


FIGURE 7-16 The effect of annealing temperature on the microstructure of cold-worked metals: (a) cold worked, (b) after recovery, (c) after recrystallization, and (d) after grain growth.

Warm Forming

- Deformation produced at temperatures intermediate to hot and cold forming is known as warm forming.
- Compared to cold forming, it reduces loads, increase material ductility.
- Compared to hot forming, it produce less scaling and decarburization, better dimensional precision and smoother surfaces.

Isothermal Forming

- During hot forming, cooler surfaces surround a hotter interior, and the variations in strength can result in non-uniform deformation and cracking of the surface.
- For temp.-sensitive materials deformation is performed under isothermal conditions.
- The dies or tooling must be heated to the workpiece temperature, sacrificing die life for product quality.
- Close tolerances, low residual stresses and uniform metal flow.

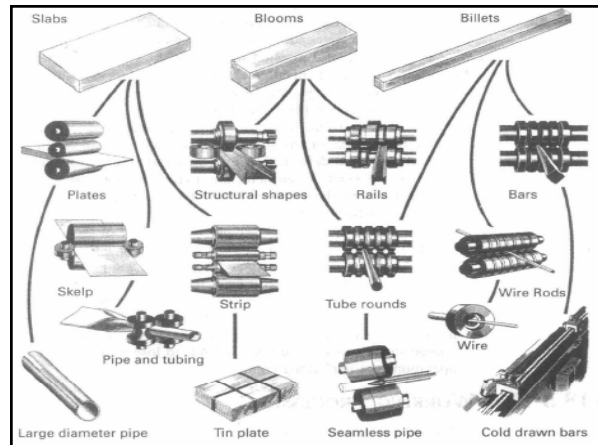
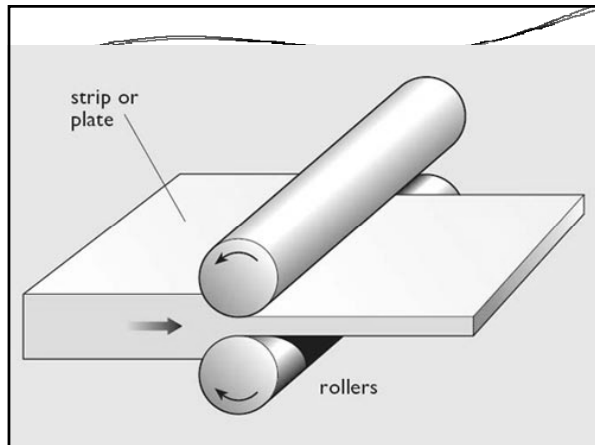
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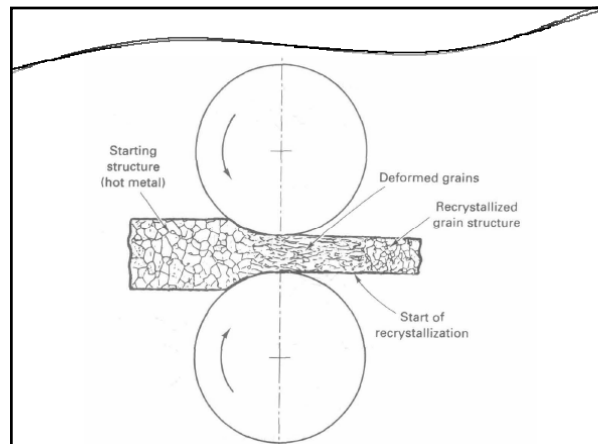
Rolling

- **Definition:** The process of plastically deforming metal by passing it between rolls.
- Most widely used, high production and close tolerance.
- Friction between the rolls and the metal surface produces high compressive stress.
- Hot-working (unless mentioned cold rolling).
- Metal will undergo bi-axial compression.



Hot Rolling

- Done above the recrystallization temp.
- Results fine grained structure.
- Surface quality and final dimensions are less accurate.
- Breakdown of ingots into blooms and billets is done by hot-rolling. This is followed by further hot-rolling into plate, sheet, rod, bar, pipe, rail.
- Hot rolling is terminated when the temp. falls to about (50 to 100°C) above the recrystallization temp.



Cold Rolling

- Done below the recrystallization temp..
- Products are sheet, strip, foil etc. with good surface finish and increased mechanical strength with close product dimensions.
- Performed on four-high or cluster-type rolling mills. (Due to high force and power)

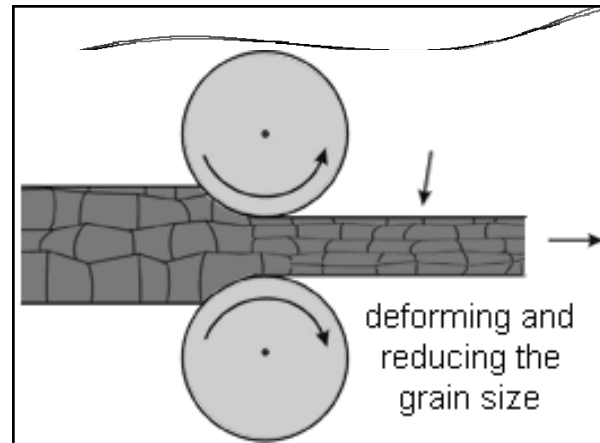
Cold Rolling

Contd..

- Skin-rolled metal is given only a 0.5% to 1% reduction to produce a smooth surface and uniform thickness, and to remove the yield-point phenomenon (i.e., prevent formation of Luders bands upon further forming). This material is well suited for subsequent cold-working operations where good ductility is required.
- Quarter-hard, half-hard, and full-hard sheet and strip have experienced greater amounts of cold reduction, up to 50%. Consequently, their yield points have been increased, properties have become directional, and ductility has decreased. Quarter-hard steel can be bent back on itself across the grain without breaking. Half-hard and full-hard can be bent back 90° and 45° respectively, about a radius equal to the material thickness.

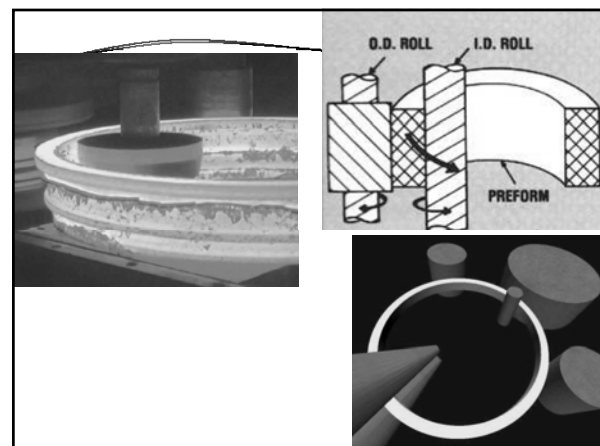
Assumptions of cold rolling

- Material is plastic.
- The arc of contact is circular with a radius greater than the radius of the roll.
- Coefficient of friction is constant over the arc of contact



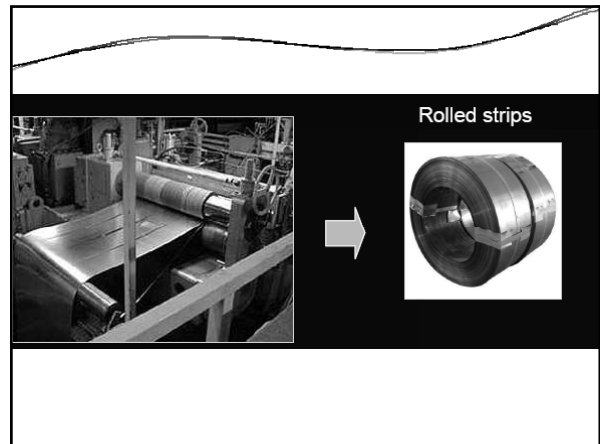
Ring Rolling

- Ring rolls are used for tube rolling, ring rolling.
- As the rolls squeeze and rotate, the wall thickness is reduced and the diameter of the ring increases.
- Shaped rolls can be used to produce a wide variety of cross-section profiles.
- Ring rolls are made of spheroidized graphite bainitic and pearlitic matrix or alloy cast steel base.

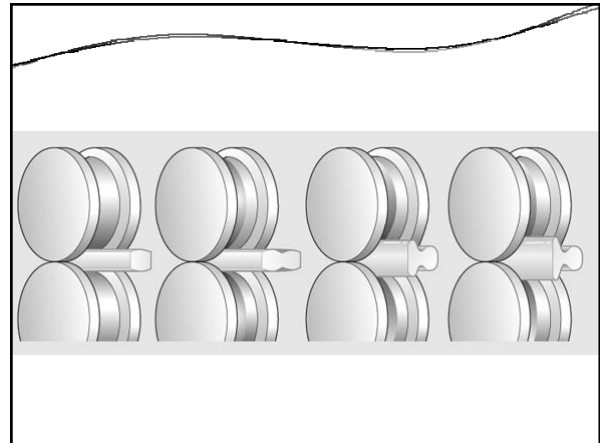
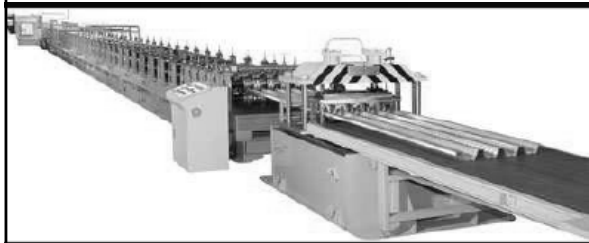


Sheet rolling

- In sheet rolling we are only attempting to reduce the cross section thickness of a material.

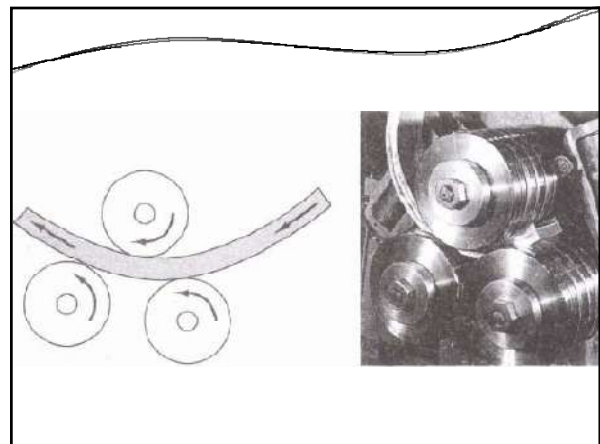


Roll Forming

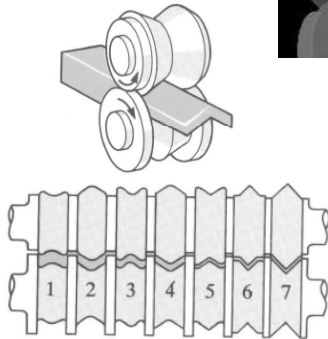


Roll Bending

- A continuous form of three-point bending is roll bending, where plates, sheets, and rolled shapes can be bent to a desired curvature on forming rolls.
- Upper roll being adjustable to control the degree of curvature.



Shape rolling



Pack rolling

- Pack rolling involves hot rolling multiple sheets of material at once, such as aluminium foil.
- A thin surface oxide film prevents their welding.

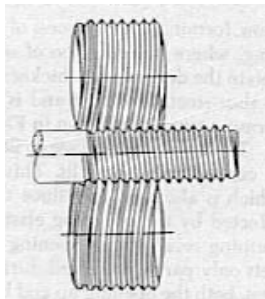
Thread rolling

- Used to produce threads in substantial quantities.
- This is a cold-forming process in which the threads are formed by rolling a thread blank between hardened dies that cause the metal to flow radially into the desired shape.
- No metal is removed, greater strength, smoother, harder, and more wear-resistant surface than cut threads.

Thread rolling

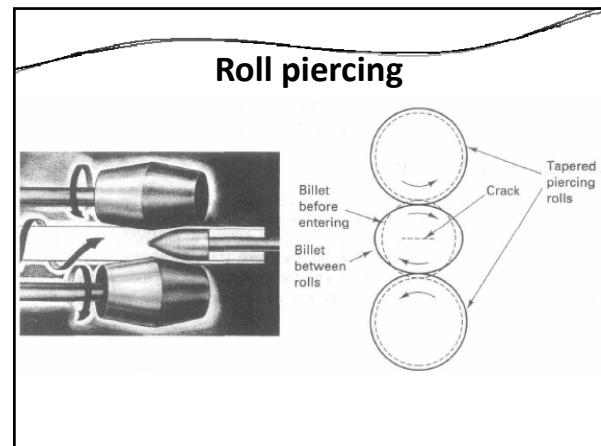
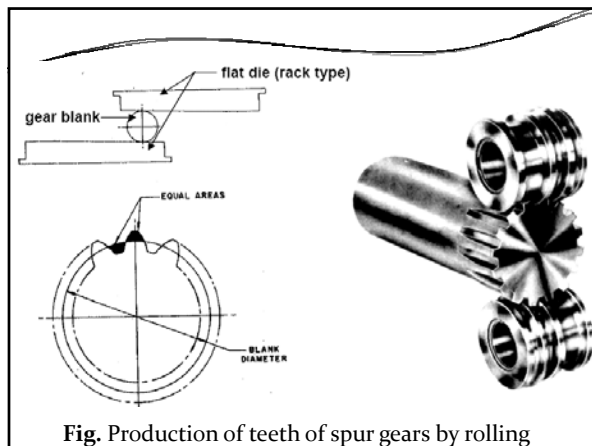
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- Major diameter is always greater than the diameter of the blank (
- Blank diameter is little larger than the pitch diameter of the thread.
- Restricted to ductile materials.

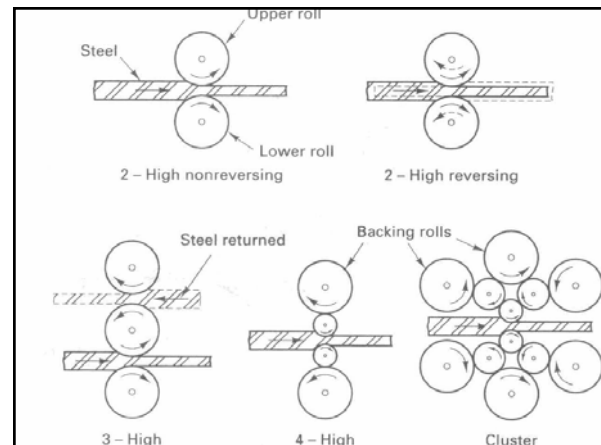


Manufacture of gears by rolling

- The straight and helical teeth of disc or rod type external steel gears of small to medium diameter and module are generated by cold rolling.
- High accuracy and surface integrity.
- Employed for high productivity and high quality. (costly machine)
- Larger size gears are formed by hot rolling and then finished by machining.

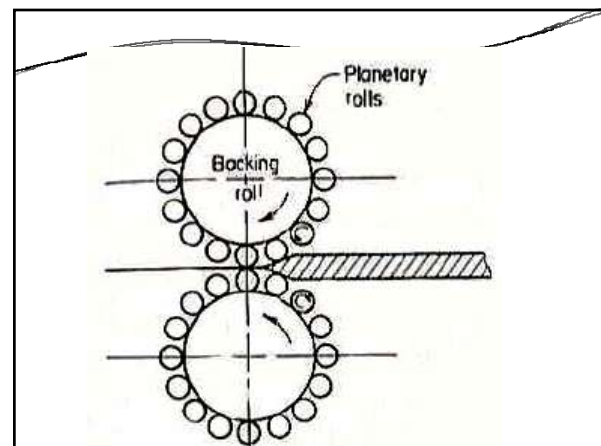


- It is a variation of rolling called roll piercing.
- The billet or round stock is rolled between two rolls, both of them rotating in the same direction with their axes at an angle of 4.5 to 6.5 degree.
- These rolls have a central cylindrical portion with the sides tapering slightly. There are two small side rolls, which help in guiding the metal.
- Because of the angle at which the roll meets the metal, it gets in addition to a rotary motion, an additional axial advance, which brings the metal into the rolls.
- This cross-rolling action makes the metal friable at the centre which is then easily pierced and given a cylindrical shape by the central-piercing mandrel.

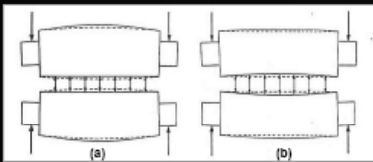


Planetary mill

- Consist of a pair of heavy backing rolls surrounded by a large number of planetary rolls.
- Each planetary roll gives an almost constant reduction to the slab as it sweeps out a circular path between the backing rolls and the slab.
- As each pair of planetary rolls ceases to have contact with the work piece, another pair of rolls makes contact and repeat that reduction.
- The overall reduction is the summation of a series of small reductions by each pair of rolls. Therefore, the planetary mill can not reduce a slab directly to strip in one pass through the mill.
- The operation requires feed rolls to introduce the slab into the mill, and a pair of planishing rolls on the exit to improve the surface finish.



Camber



(a) The use of cambered rolls to compensate for roll bending.

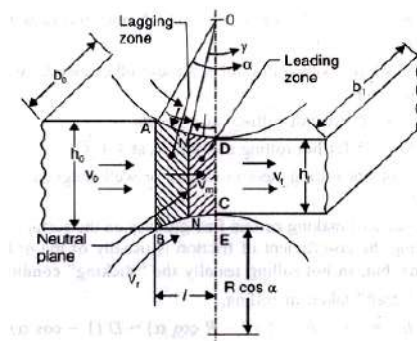
(b) Uncambered rolls give variation of thickness.

- Camber can be used to correct the roll deflection (at only one value of the roll force).

Lubrication for Rolling

- Hot rolling of ferrous metals is done without a lubricant.
- Hot rolling of non-ferrous metals a wide variety of compounded oils, emulsions and fatty acids are used.
- Cold rolling lubricants are water-soluble oils, low-viscosity lubricants, such as mineral oils, emulsions, paraffin and fatty acids.

Geometry of Rolling Process



Draft

- Total reduction or "draft" taken in rolling.

$$\Delta h = h_0 - h_f = 2(R - R \cos \alpha) = D(1 - \cos \alpha)$$

- Usually, the reduction in blooming mills is about 100 mm and in slabbing mills, about 50 to 60 mm.

Maximum Draft

$$(\Delta h)_{\max} = \mu^2 R$$

Assumption in Rolling

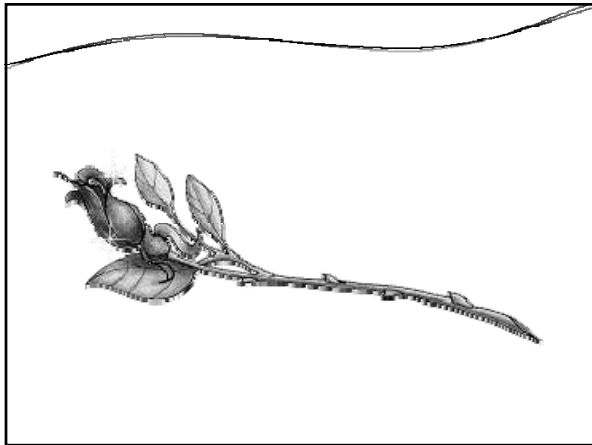
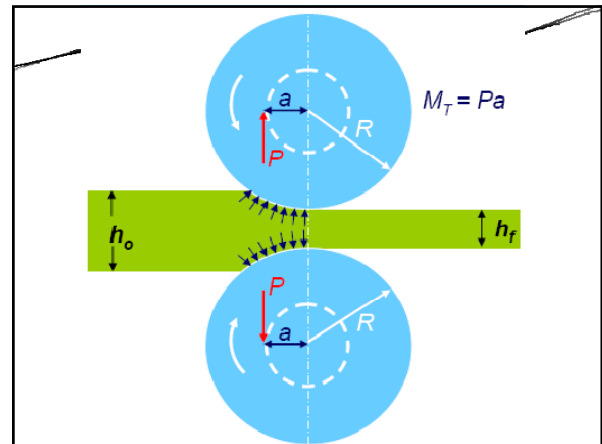
1. Rolls are straight, rigid cylinders.
2. Strip is wide compared with its thickness, so that no widening of strip occurs (plane strain conditions).
3. The material is rigid perfectly plastic (constant yield strength).
4. The co-efficient of friction is constant over the tool-work interface.

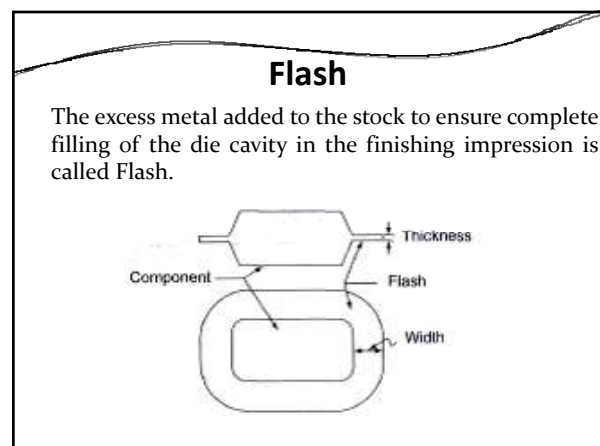
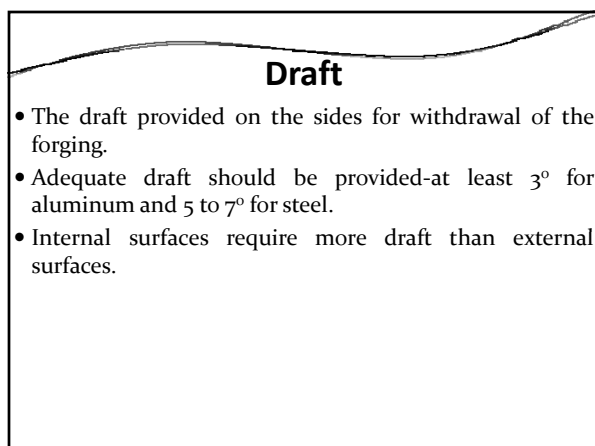
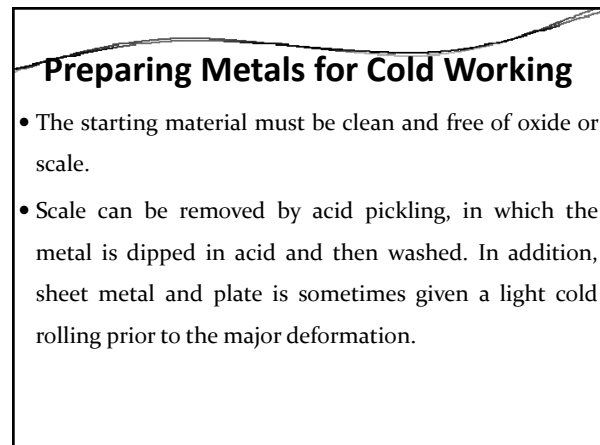
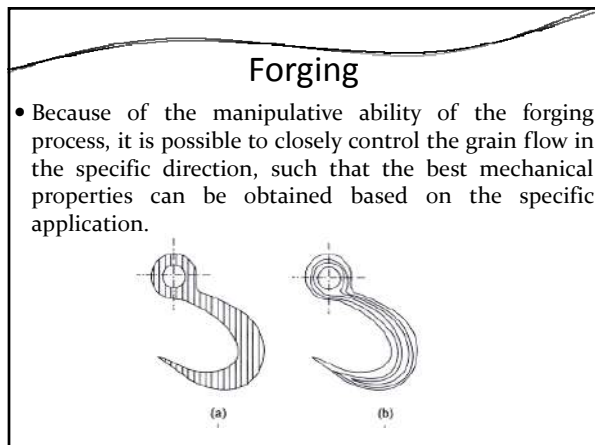
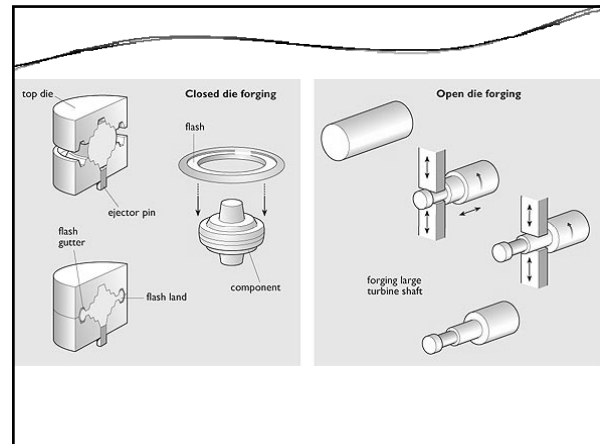
Torque and Power

The power is spent principally in four ways

- 1) The energy needed to deform the metal.
- 2) The energy needed to overcome the frictional force.
- 3) The power lost in the pinions and power-transmission system.
- 4) Electrical losses in the various motors and generators.

Remarks: Losses in the windup reel and uncoiler must also be considered.





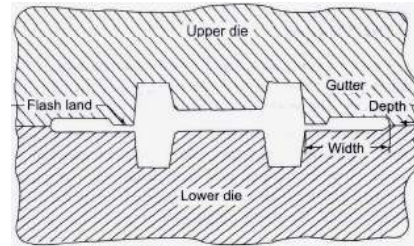
Flash

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- A flash acts as a cushion for impact blows from the finishing impression and also helps to restrict the outward flow of metal, thus helping in filling of thin ribs and bosses in the upper die.
- The amount of flash depends on the forging size and may vary from 10 to 50 per cent.
- The forging load can be decreased by increasing the flash thickness.

Gutter

- In addition to the flash, provision should be made in the die for additional space so that any excess metal can flow and help in the complete closing of the die. This is called gutter.



Gutter

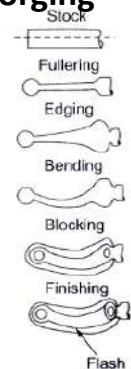
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- Without a gutter, a flash may become excessively thick, not allowing the dies to close completely.
- Gutter depth and width should be sufficient to accommodate the extra material.

Operations involved in forging

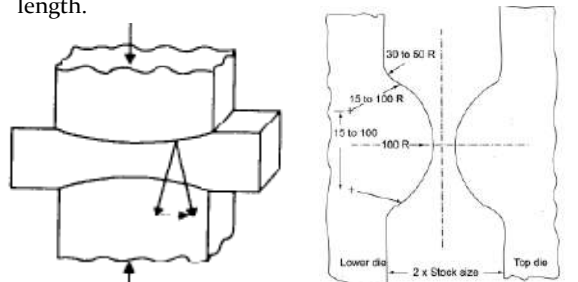
Steps involved in hammer forging

- Fullering or swaging
- Edging or rolling
- Bending
- Drawing or cogging
- Flattening
- Blocking
- Finishing operation
- Trimming or cut off



Fullering or swaging

- It is the operation of reducing the stock between the two ends of the stock at a central place, so as to increase its length.



Fullering or swaging

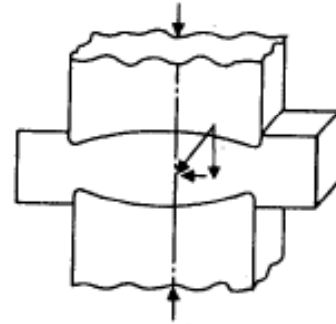
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- A forging method for reducing the diameter of a bar and in the process making it longer is termed as Fullering.

Edging or rolling

- Gathers the material as required in the final forging.
- The pre-form shape also helps in proper location of stock in the blocking impressions.
- The area at any cross section should be same as that of the corresponding section in the component and the flash allowance.

Edging or rolling Contd....



Bending

- Bending operation makes the longitudinal axis of the stock in two or more places. This operation is done after the stock has been edged or fullered and edged so that the stock is brought into a proper relation with the shape of the finishing impression.

Blocking

- Imparts to the forging its general but not exact or final shape. This operation is done just prior to finishing operation.

Flattening

- This operation is used to flatten the stock so that it fits properly into the finishing impression of a closed die.

Finishing

- The dimensions of the finishing impression are same as that of the final forging desired with the necessary allowances and tolerances.
- A gutter should be provided in the finishing impression.

Cut-off

- A pair of blades used to cut away a forging from the bar after the finishing blow.

Drop Forging

- The drop forging die consists of two halves. The lower half of the die is fixed to the anvil of the machine, while the upper half is fixed to the ram. The heated stock is kept in the lower die while the ram delivers four to five blows on the metal, in quick succession so that the metal spreads and completely fills the die cavity. When the two die halves close, the complete cavity is formed.
- Drop forging is used to produce **small components**.

Press Forging

- Force is a continuous squeezing type applied by the hydraulic presses.

Advantages of Press Forging over Drop Forging

- Press forging is faster than drop forging
- Alignment of the two die halves can be more easily maintained than with hammering.
- Structural quality of the product is superior to drop forging.
- With ejectors in the top and bottom dies, it is possible to handle reduced die drafts.

Machine Forging

- Unlike the drop or press forging where the material is drawn out, in machine forging, the material is only upset to get the desired shape.

Upset Forging

- Increasing the diameter of a material by compressing its length.
- Employs split dies that contain multiple positions or cavities.

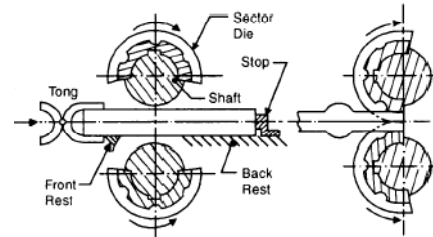
Roll Forging

- When the rolls are in the open position, the heated stock is advanced up to a stop. As the rolls rotate, they grip and roll down the stock. The stock is transferred to a second set of grooves. The rolls turn again and so on until the piece is finished.

Roll Forging

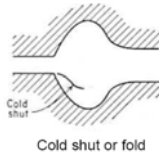
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- A rapid process.



Forging Defects

- **Unfilled Sections:** Die cavity is not completely filled, due to improper design of die
- **Cold Shut or fold:** A small crack at the corners of the forging. Cause: improper design of the die



Forging Defects

Contd....

- **Scale Pits:** Irregular depressions on the surface due to improper cleaning of the stock.
- **Die Shift:** Due to Misalignment of the two die halves or making the two halves of the forging to be of improper shape.
- **Flakes:** Internal ruptures caused by the improper cooling.
- **Improper Grain Flow:** This is caused by the improper design of the die, which makes the flow of metal not following the final intended directions.

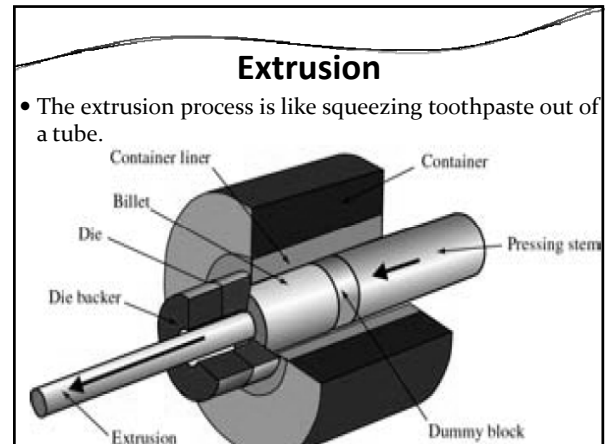
Forging Defects

Contd....

- **Forging Laps:** These are folds of metal squeezed together during forging. They have irregular contours and occur at right angles to the direction of metal flow.
- **Hot tears and thermal cracking:** These are surface cracks occurring due to non-uniform cooling from the forging stage or during heat treatment.

Lubrication for Forging

- Lubricants influence: friction, wear, deforming forces and flow of material in die-cavities, non-sticking, thermal barrier.
- For hot forging: graphite, MoS_2 and sometimes molten glass.
- For cold forging: mineral oil and soaps.
- In hot forging, the lubricant is applied to the dies, but in cold forging, it is applied to the workpiece.



- Metal is compressed and forced to flow through a suitably shaped die to form a product with reduced but constant cross section.
- Metal will undergo tri-axial compression.
- Hot extrusion is commonly employed.
- Lead, copper, aluminum, magnesium, and alloys of these metals are commonly extruded.

- Steels, stainless steels, and nickel-based alloys are difficult to extrude. (high yield strengths, welding with wall). Use **phosphate-based and molten glass lubricants**.

- ### Extrusion Ratio
- Ratio of the cross-sectional area of the billet to the cross-sectional area of the product.
 - about 40: 1 for hot extrusion of steel
 - 400: 1 for aluminium

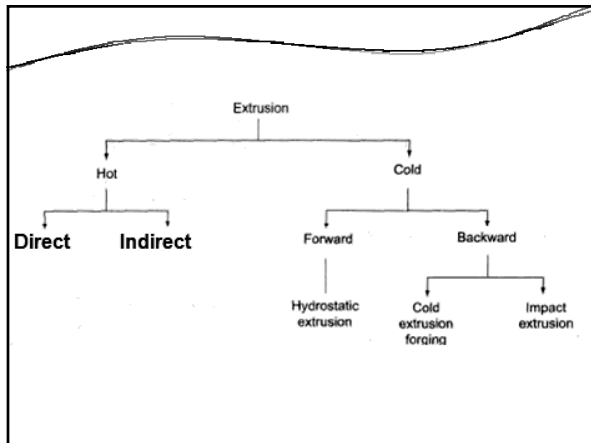
- ### Advantages of Extrusion
- Any cross-sectional shape can be extruded from the nonferrous metals.
 - Many shapes (than rolling)
 - No draft
 - Huge reduction in cross section.
 - Conversion from one product to another requires only a single die change
 - Good dimensional precision.

Limitation of Extrusion

- Cross section must be uniform for the entire length of the product.

Application

- Working of poorly plastic and non ferrous metals and alloys.
- Manufacture of sections and pipes of complex configuration.
- Medium and small batch production.
- Manufacture of parts of high dimensional accuracy.

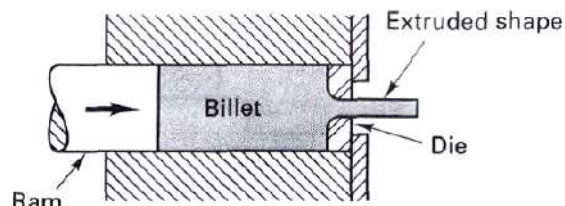


Hot Extrusion Process

- The temperature range for hot extrusion of aluminum is 430-480°C
- Used to produce curtain rods made of aluminum.
- Design of die is a problem.
- Either direct or indirect method used.

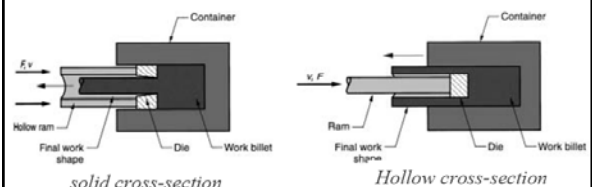
Direct Extrusion

- A solid ram drives the entire billet to and through a stationary die and must provide additional power to overcome the frictional resistance between the surface of the moving billet and the confining chamber.



Indirect Extrusion

- A hollow ram drives the die back through a stationary, confined billet.



- Since no relative motion, friction between the billet and the chamber is eliminated.

Indirect Extrusion Contd...

- Required force is lower (25 to 30% less)
- Low process waste.

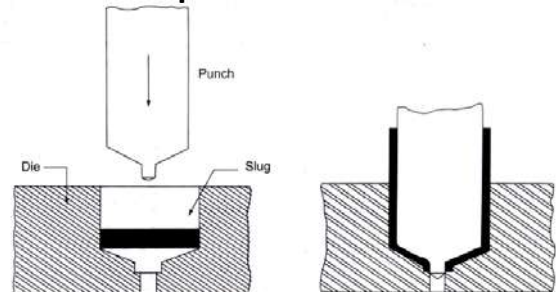
Cold Extrusion

- Used with low-strength metals such as lead, tin, zinc, and aluminum to produce collapsible tubes for toothpaste, medications, and other creams; small "cans" for shielding electronic components and larger cans for food and beverages.
- **Now-a-days** also been used for forming mild steel parts.

Backward cold extrusion

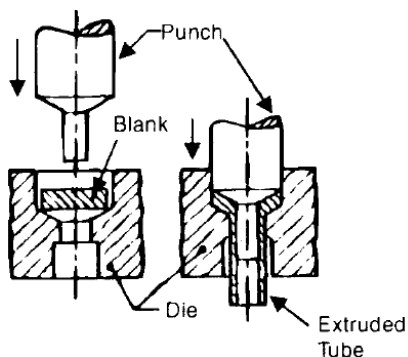
- The metal is extruded through the gap between the punch and die opposite to the punch movement.
- For softer materials such as aluminium and its alloys.
- Used for making collapsible tubes, cans for liquids and similar articles.

Impact Extrusion



- The extruded parts are stripped by the use of a stripper plate, because they tend to stick to the punch.

Hooker Method



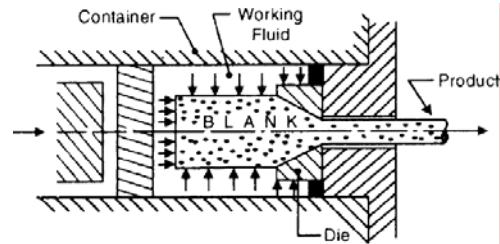
Hooker Method

- The ram/punch has a shoulder and acts as a mandrel.
- A flat blank of specified diameter and thickness is placed in a suitable die and is forced through the opening of the die with the punch.
- when the punch starts downward movement. Pressure is exerted by the shoulder of the punch, the metal being forced to flow through the restricted annular space between the punch and the opening in the bottom of the die.
- In place of a flat solid blank, a hollow slug can also be used.
- If the tube sticks to the punch on its upward stroke, a stripper will strip it from the punch.
- Small copper tubes and cartridge cases are extruded by this method.

Hydrostatic Extrusion

- Another type of cold extrusion process.
- High-pressure fluid applies the force to the workpiece through a die.
- It is forward extrusion, but the fluid pressure surrounding the billet prevents upsetting.
- Billet-chamber friction is eliminated, and the pressurized fluid acts as a lubricant between the billet and the die.

Hydrostatic Extrusion Contd....



Hydrostatic Extrusion Contd....

- Temperature is limited since the fluid acts as a heat sink and the common fluids (light hydrocarbons and oils) burn or decomposes at moderately low temperatures.
- The metal deformation is performed in a high-compression environment. Crack formation is suppressed, leading to a phenomenon known as pressure-induced ductility.
- Relatively brittle materials like cast iron, stainless steel, *molybdenum*, *tungsten* and various inter-metallic compounds can be plastically deformed without fracture, and materials with limited ductility become highly plastic.

Application

- Extrusion of nuclear reactor fuel rod
- Cladding of metals
- Making wires for less ductile materials

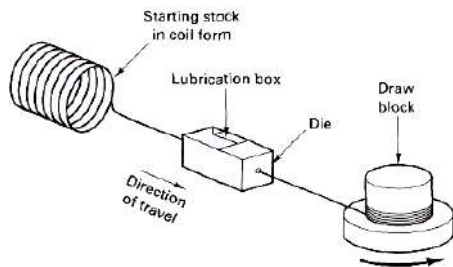
Lubrication for Extrusion

- For hot extrusion glass is an excellent lubricant with steels, stainless steels and high temperature metals and alloys.
- For cold extrusion, lubrication is critical, especially with steels, because of the possibility of sticking (seizure) between the workpiece and the tooling if the lubrication breaks down. Most effective lubricant is a phosphate conversion coating on the workpiece.

Wire Drawing

- A cold working process to obtain wires from rods of bigger diameters through a die.
- Same process as bar drawing except that it involves smaller-diameter material.
- At the start of wire drawing, the end of the rod or wire to be drawn is pointed (by swaging etc.) so that it freely enters the die orifice and sticks out behind the die.

Wire Drawing Contd....



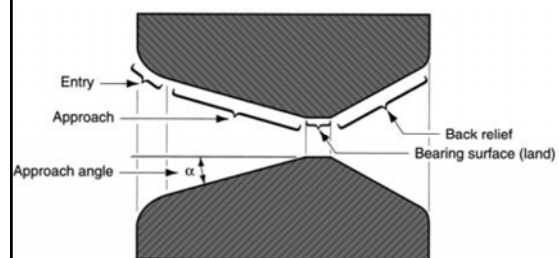
Wire Drawing Contd....

- Wire getting continuously wound on the reel.
- For fine wire, the material may be passed through a number of dies, receiving successive reductions in diameter, before being coiled.
- **The wire is subjected to tension only.** But when it is in contact with dies then a combination of tensile, compressive and shear stresses will be there in that portion only.

Cleaning and Lubrication in wire Drawing

- Cleaning is done to remove scale and rust by **acid pickling**.
- Lubrication boxes precede the individual dies to help reduce friction drag and prevent wear of the dies.
- **Sulling:** The wire is coated with a thin coat of ferrous hydroxide which when combined with lime acts as filler for the lubricant.
- **Phosphating:** A thin film of Mn, Fe or Zn phosphate is applied on the wire.
- **Electrolytic coating:** For very thin wires, electrolytic coating of copper is used to reduce friction.

Wire Drawing Die

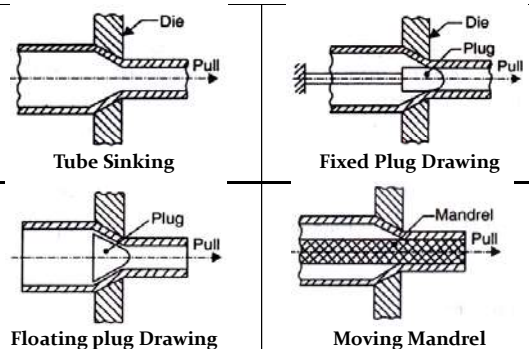


- **Die materials:** tool steels or tungsten carbides or polycrystalline diamond (for fine wire)

Rod and Tube Drawing

- Rod drawing is similar to wire drawing except for the fact that the dies are bigger because of the rod size being larger than the wire.
- The tubes are also first pointed and then entered through the die where the point is **gripped** in a similar way as the bar drawing and pulled through in the form desired along a straight line.
- When the final size is obtained, the tube may be annealed and straightened.
- The practice of drawing tubes without the help of an internal mandrel is called tube sinking.

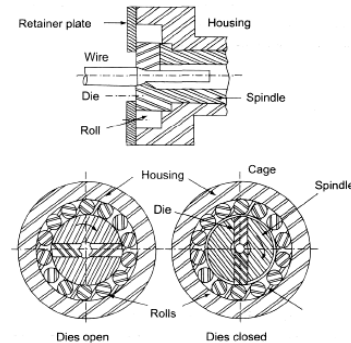
Rod and Tube Drawing Contd...



Swaging or kneading

- The hammering of a rod or tube to reduce its diameter where the die itself acts as the hammer.
- Repeated blows are delivered from various angles, causing the metal to flow inward and assume the shape of the die.
- It is cold working. The term swaging is also applied to processes where material is forced into a confining die to reduce its diameter.

Swaging or kneading Contd...



Extrusion Load

- Approximate method (Uniform deformation, no friction) "work - formula"

$$P = A_o \bar{\sigma} \ln \left(\frac{A_o}{A_f} \right)$$

- For real conditions

$$P = K A_o \ln \left(\frac{A_o}{A_f} \right)$$

K = extrusion constant.

Force required in Wire or Tube drawing

- Approximate method (Uniform deformation, no friction) "work - formula"

$$P = A_f \bar{\sigma} \ln \left(\frac{A_o}{A_f} \right)$$

Wire Drawing

$$\sigma_d = \frac{\sigma_o (1+B)}{B} \left[1 - \left(\frac{r_1}{r_o} \right)^{2B} \right] + \left(\frac{r_1}{r_o} \right)^{2B} \cdot \sigma_b$$

σ_o = yield strength of material

$B = \mu \cot \alpha$

μ = co-efficient of friction

α = half die-angle

r_1 = radius of work piece at exit

r_o = radius of work piece at entry.

Maximum Reduction per pass

With back stress, σ_b

$$\sigma_o = \frac{\sigma_o (1+B)}{B} \left[1 - \left(\frac{r_1}{r_o} \right)^{2B} \right] + \left(\frac{r_1}{r_o} \right)^{2B} \cdot \sigma_b$$

Without back stress, σ_b

$$\sigma_o = \frac{\sigma_o (1+B)}{B} \left[1 - \left(\frac{r_1}{r_o} \right)^{2B} \right]$$