ME5005/ME4002
DESIGN FOR MANUFACTURE
PRODUCTION ENGINEERING

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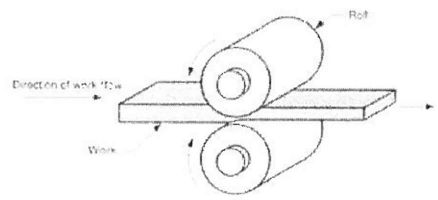
Lecture 14: Rolling and Extrusion

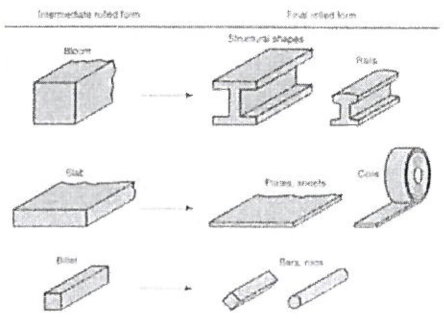
Rolling

- A deformation process in which the thickness of the workpiece is reduced by compressive forces between two opposing rolls
- The rolls pull the workpiece along and simultaneously squeeze it
- Two main types:
  - Flat rolling
    - Reduction in thickness of a rectangular cross-section
  - Shape rolling
    - I-beams, tubing
- Expensive plant required
  - High volume production of standard items
- Steel rolling most common
  - Aluminium sheets



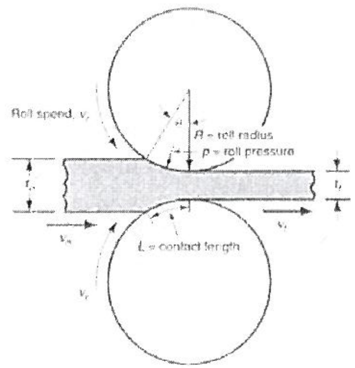
Standard rolled products

- *Hot rolling*
  - Largest deformation
  - Free of residual stress
  - Isotropic properties
  - Accuracy difficult
  - Surface oxide/scale
  - Steel is thermally soaked until temperature is uniform (1200°C typically)
  - Cast *ingots* rolled into *blooms* (large square cross-section), *slabs* (large rectangular cross-section) and *billets* (small square cross-section)
- *Cold rolling*
  - Greater accuracy
  - Metal strengthened (work hardened)
  - No surface oxide/scale



Flat rolling analysis

- Change in thickness is called draft
  $d = t_0 - t_f$
- Ratio to starting thickness t_0 is the reduction:
  $r = d / t_0$
- Material *spreads* as the thickness reduce (conservation of volume):
  $t_0 w_0 L_0 = t_f w_f L_f$
- Initial and final material velocities also linked:
  $t_0 w_0 v_0 = t_f w_f v_f$
- Rolls are in contact with the workpiece along the *contact length*, arc $L = R\theta$
- Roll speed v_r is between the input and output workpiece velocities v_0 and v_f
  - Workpiece velocity varies gradually along the arc length
- Roll speed equals workpiece velocity at the no-slip point



Maximum draft

- <u>Slipping</u> and <u>Friction</u> occur between roll and workpiece either side of the no-slip point:

$$s = \frac{V_f - V_r}{V_r}$$

- Coefficient of friction between rolls and workpiece is μ
  - Depends on lubrication, material and rolling temperature
  - <u>Sticking</u> between roll and workpiece can occur ($\mu \sim 0.7$)
  - Stuck surface moves at <u>roller</u> speed
- Frictional *FORCE* varies with the *compression force* along the contact length and is *greater* on the input side
  - Net force pulls the workpiece through the rolls
- Maximum possible draft is given by:

$$d_{max} = \mu^2 R$$

Process	Typical μ
Cold	0.1
Warm	0.2
Hot	0.4

Rolling force, torque and power

- <u>True</u> strain in rolling is:

$$\varepsilon = \ln \frac{t_0}{t_f}$$

- The average <u>flow</u> stress in the material is:

$$\overline{Y}_f = \frac{K\varepsilon^n}{1+n}$$

- Approximate roll force:

$$F = \overline{Y}_f wL$$

- Approximate contact length:

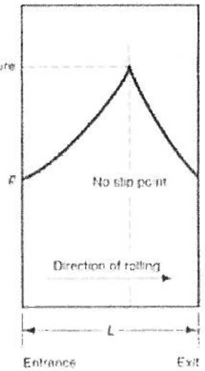
$$L = \sqrt{R(t_0 - t_f)}$$

- Approximate torque for each roll is:

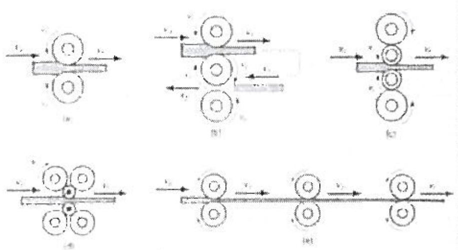
$$T = 0.5FL$$

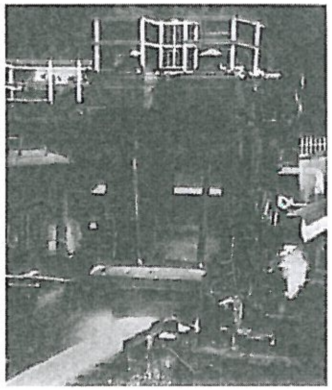
- Rolling mill power (2 rolls) with rotational speed N revs/sec:

$$P = 2\pi NFL$$



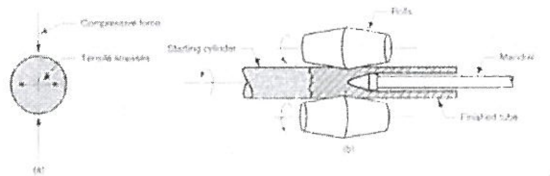
Rolling mill configurations



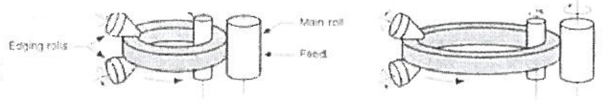


a) <u>Two</u> -high
b) <u>Three</u> -high
c) <u>Four</u> -high
d) Cluster
e) Tandem

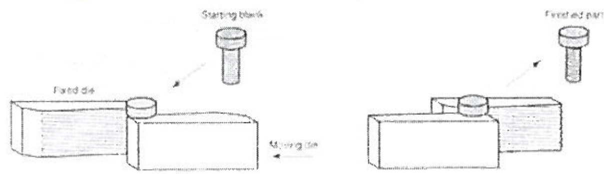
Other rolling operations



Roll piercing and seamless tubing

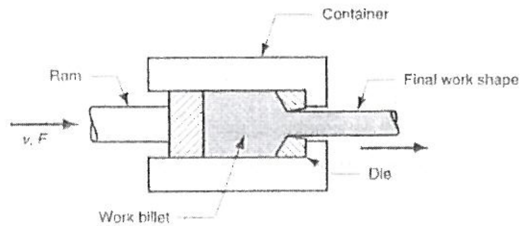


<u>Ring</u> rolling



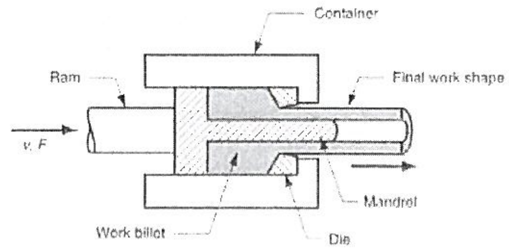
<u>Thread</u> rolling

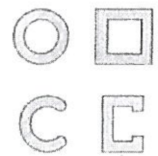
Direct extrusion



- A ram compresses a metal billet forcing it through a die
- A small portion of the billet will be left behind (the '*butt*')
  - Post-machining required for butt removal
- Significant friction exists between workpiece surface and container
  - More powerful ram required
  - Increases with temperature
- Smaller diameter dummy block used between ram and billet
  - Reduces friction
  - Leaves behind narrow ring of metal, containing mostly surface oxides

Hollow extrusion

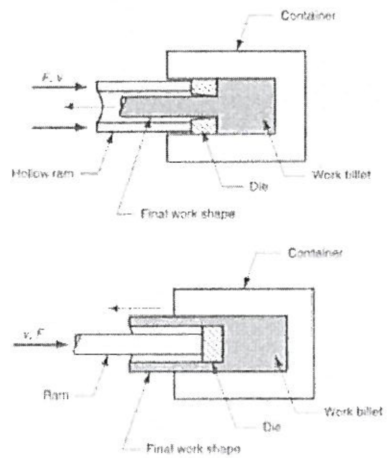




- Starting billet prepared with through hole
- Ram or dummy block has a material
- Material is forced to flow through the gap between the mandrel and the die
- Extruded sections may be hollow or semi-hollow
- Starting billet is usually round
- Final shape determined by die opening, may be complex
  - I-sections, Heat sinks/fins

Indirect extrusion

- Die is mounted on the ____ rather than the ____________
- As ram penetrates into the workpiece, material is forced to flow through the clearance gap
- Indirect extrusion direction __________ to ram motion
- Friction greatly reduced as billet does not move along the container
- Hollow rams less rigid
- Extruded product leaving the die difficult to support
- Hollow indirect extrusion possible
- Material flows in cup-shape around a smaller diameter ram
- Ram support difficult as extruded workpiece length increases

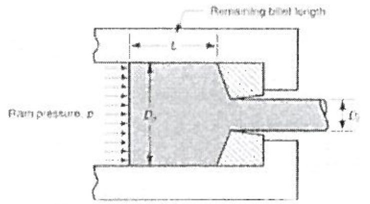


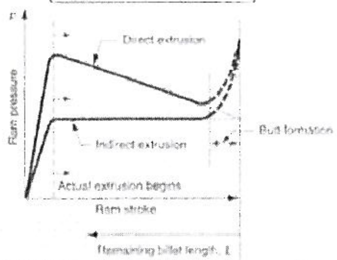
Extrusion temperature

- Extrusion may be *hot* or *cold* depending on the metal to be extruded and the required amount of deformation or strain
- Typically extruded metals are
- Hot extrusion:
  - Typically Al, Cu, Zn, Sn (+ alloys) and most steels
  - Billet heated to above its recrystallisation temperature
  - Reduces billet strength and increases ductility
  - Reduces ram force
  - Billet cooling at the container walls may be problematic
  - Lubrication critical
    - Molten glass – reduces friction plus acts as thermal insulator
- Cold extrusion:
  - Al, Cu, Zn, Sn (+ alloys) and ductile low-C steels
  - Increased strength due to strain hardening
  - Closer tolerances, better surface finishes (no oxides)
  - Faster production rates (no billet heating required)

Analysis of extrusion

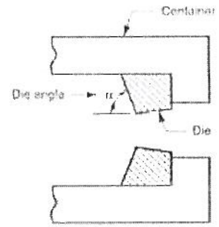
- Reduction ratio:
  $$r_x = \frac{A_0}{A_f}$$
- Extrusion strain:
  $$\varepsilon_x = a + b\ln r_x$$
- Ram pressure:
  $$p = \overline{Y}_f \varepsilon_x$$
- Additional pressure is required to overcome friction:
  $$p = \overline{Y}_f\left(\varepsilon_x + \frac{2L}{D_0}\right)$$
- Ram force:
  $$F = pA_0$$
- Ram power:
  $$P = Fv$$
- Higher die angles produce steeper pressure build-ups

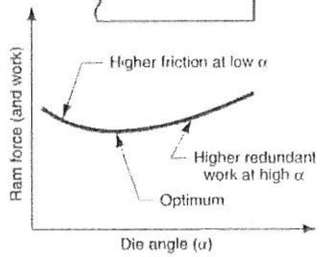




Extrusion dies

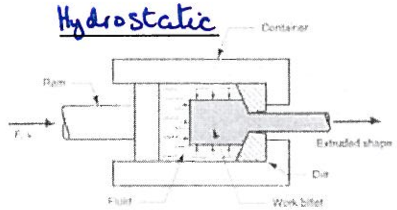
- An optimum die angle exists:
  - Too low, die surface area too large, increased friction
  - Too high, turbulence in metal flow, increase in ram force
- Depends on many factors (e.g. lubrication), difficult to calculate
- Shape factor K_x based on the perimeter ratio of the extruded product C_x to an equivalent area circle C_c should also be included:
  $$K_x = 0.98 + 0.02\left(\frac{C_x}{C_c}\right)^{2.25}$$
  $$p = K_x \overline{Y}_f\left(\varepsilon_x + \frac{2L}{D_0}\right)$$
- Die materials are usually extremely hard alloy steels with high thermal conductivity and wear resistance

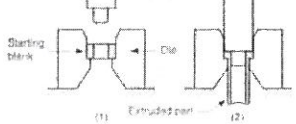




Other extrusion methods

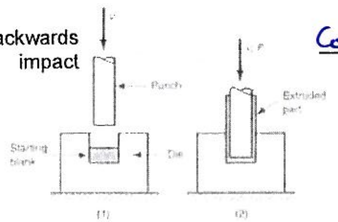
Hydrostatic



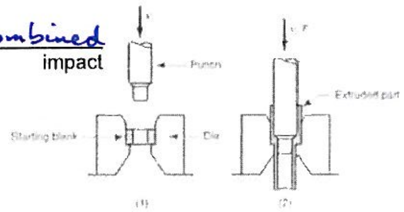


Forward impact

Backwards impact

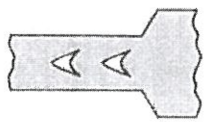


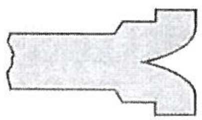
Combined impact



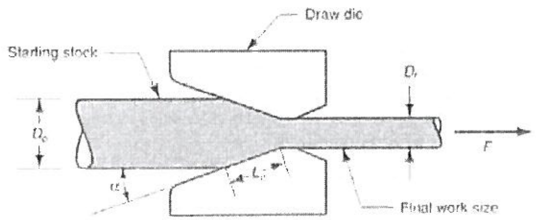
Extrusion defects

- Centreburst:
  - Internal crack produced by tensile stresses along the centre line
  - Produced where large deformation occurs away from the central axis
  - High die angles
  - Low extrusion ratios
  - Impurities in the metal
  - Difficult to detect
- Piping:
  - Sink hole in direct extrusion
  - May be prevented with a dummy block
- Surface cracking:
  - High workpiece temperatures
  - High extrusion velocity
  - High friction
  - Surface chilling





Drawing of wire and bar

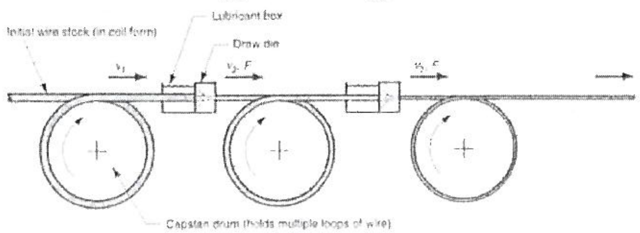


- Similar to extrusion but workpiece pulled through die rather than pushed
- Combination of longitudinal tensile stresses and lateral compressive stresses
- Bars are usually a single straight length drawn through a single die
- Wires are drawn through several (typically 4-12) dies to produce long coils
  - Wires as small as 0.03 mm in diameter may be drawn
  - Process may be continuous as coils may be welded together to produce one long length

Analysis of drawing

- Reduction in area r:
$$r = \frac{A_0 - A_f}{A_0}$$
- True strain ε:
$$\varepsilon = \ln\frac{A_0}{A_f} = \ln\frac{1}{1-r}$$
- Ideal stress σ:
$$\sigma = \overline{Y}_f \varepsilon = \overline{Y}_f \ln\frac{A_0}{A_f}$$
- Draw stress σ_d:
$$\sigma_d = \overline{Y}_f\left(1 + \frac{\mu}{\tan\alpha}\right)\phi \ln\frac{A_0}{A_f}$$
  - This accounts for friction and inhomogeneous deformation
- Inhomogeneity factor ϕ:
$$\phi = 0.88 + 0.12\frac{D}{L_c}$$
- Average workpiece diameter D:
$$D = \frac{D_0 + D_f}{2}$$
- Contact length L_c:
$$L_c = \frac{D_0 - D_f}{2\sin\alpha}$$
- Draw force F:
$$F = A_f \sigma_d = A_f \overline{Y}_f\left(1 + \frac{\mu}{\tan\alpha}\right)\phi \ln\frac{A_0}{A_f}$$

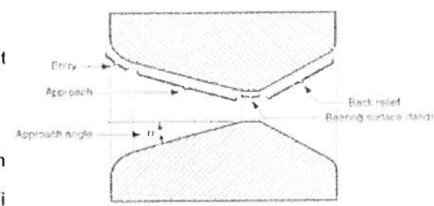
Drawing configuration



- Bars are normally drawn on a hydraulic bench that pulls the workpiece through the dies, sometimes several bars in parallel
- Wire is drawn through a number of dies and wound on motor powered drums or capstans
  - Each capstan rotates at a different speed to ensure the correct draw force is applied at each die stage
  - Maintains tension in the wire between each stage
  - Wire is coated with lubricant before each die, may also be annealed
- Continuous process
- Often wire coating or insulating process (polymer extrusion) included

Drawing dies

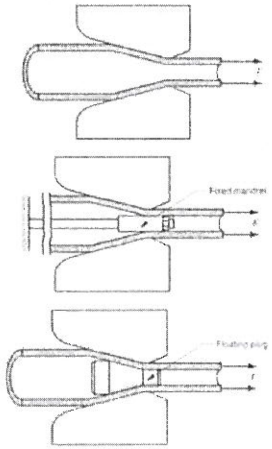
- Four main regions to each die:
- Entry:
  - A smooth bell-shaped 'mouth' t does not touch the workpiece
  - Funnels lubricant into the die, prevents scratching
- Approach:
  - Cone-shaped surface where th drawing process occurs
  - Half-angle of 6° to 20° dependi on workpiece material
- *Bearing surface* or land
  - Determines final size of the workpiece
- Back Relief
  - Exit zone
  - Half-angle of about 30°
  - Does not touch workpiece



- Workpiece must also be:
  - Annealed
  - Cleaned
  - Pointed

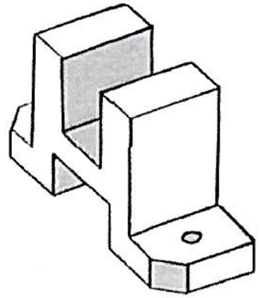
Drawing tubing

- Combined with extrusion to produce seamless tubes and pipes
- Simplest form just reduces the diameter
  - Poor control over the inside dimensions and surface finish
- A fixed *mandrel* may be used to control the inside tolerances
  - Tube length limit determined by length of mandrel support
- A floating plug with a taper that sits correctly in the approach of the die may also be used
  - Good control over wall thickness still maintained
  - Semi-continuous process possible



Design exercise - Plate bracket

- Machined prototype from mild steel
- Top slot holds edge of a large rectangular plate in a specific position
- Base slot fits over a guide rail
- May be mounted horizontally or vertically
- No movement allowed between plate and clamp in *any* direction
  - Shaded surfaces critical
- Bolt hole locations and chamfered corners locate with other geometry
- No cosmetic surfaces
- Redesign for extrusion from an aluminium alloy (assume $a = 0.8$ and $b = 1.5$ for ε_x), and calculate the ram force



Bracket dimensions (mm)