

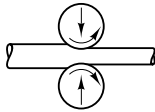
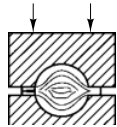
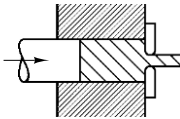
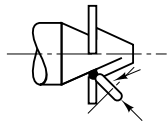
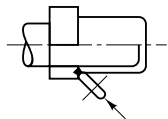
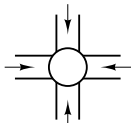
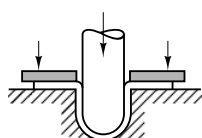
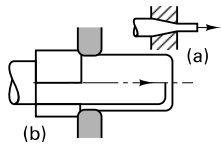
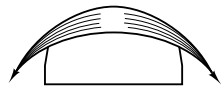
Basic classification of manufacturing processes

→ On the basis of physical state of the starting material

- Liquid state (casting processes)
- Solid state (forming and machining processes)
- Powders (powder metallurgy, Additive Manufacturing)

→ On the basis of the way the component is manufactured

- Forming processes (bulk and sheet)
- Subtractive processes (machining)
- Additive processes (Additive Manufacturing)

Process	Schematic Diagram
Rolling	
Forging	
Extrusion	
Shear spinning	
Tube spinning	
Swaging or kneading	
Deep drawing	
Wire and tube drawing	
Stretching	
Straight bending	

Forming processes

○ **Bulk**

○ **Sheet**

Independent variables

Starting material
Starting geometry
Tool geometry
Lubrication
Starting temperature
Speed of deformation
Amount of deformation

Links

-Experience-

-Experiment-

-Modeling-

Dependent variables

Force or power requirements
Product properties
Exit temperature
Surface finish
Dimensional precision
Material flow details



Spacer

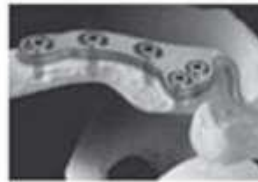


Plate and screw



Hip joint



Elbow joint



Knee joint



Hip screw



Finger joint



Ankle joint

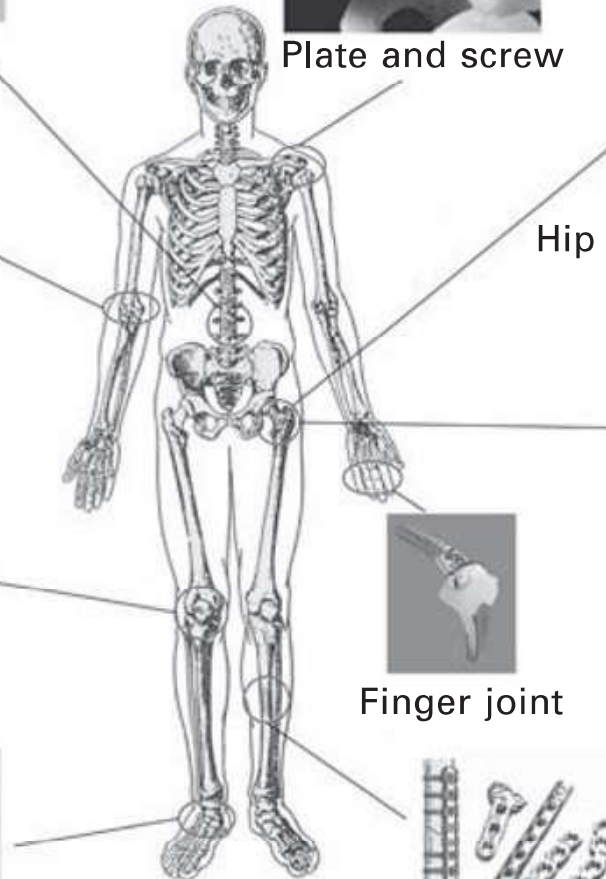
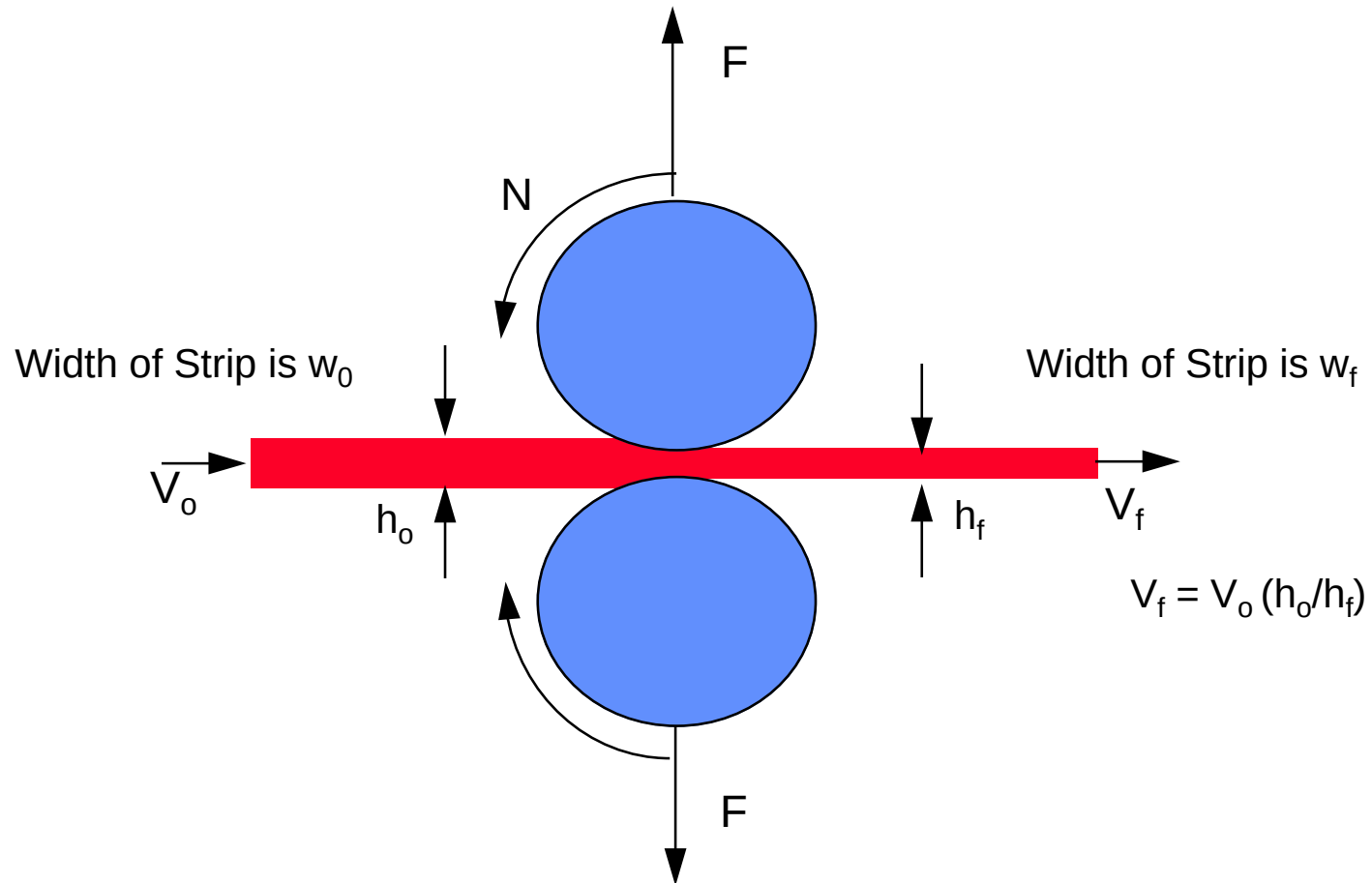


Plate and screw

Bulk Forming Processes

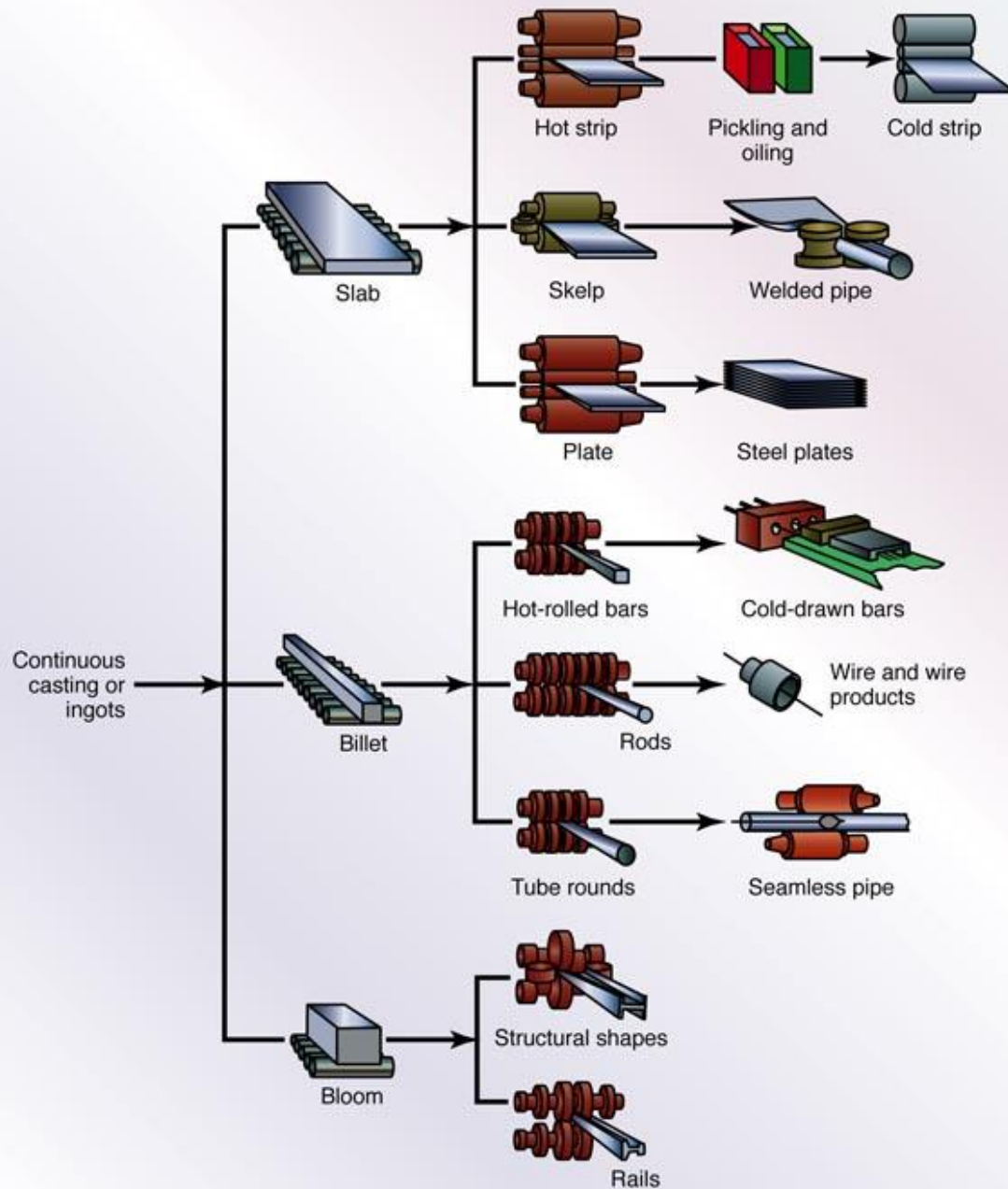
Chapter 6

Rolling process



Rotating rolls reduce the thickness of the incoming strip.

***Friction* is essential, otherwise the strip slips**



Rolling schemes

Sheet and plate rolling

- Continuous cast slab
- Scalp (not always)
- Reheat and homogenize
- Hot roll in reversing mill to ~4-5 mm thick
- Cut off ends (alligators)
- Warm roll to 0.2-4 mm thick
- Heat treat to recrystallize (sometimes)
- Cool
- Cold roll to finish thickness
- Heat treat (where appropriate)
- Results in material which must be further worked

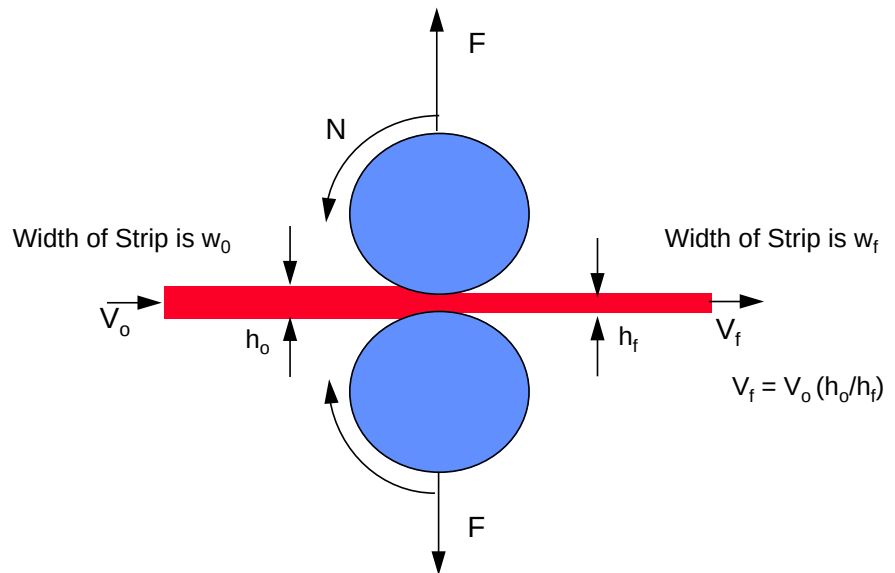
Process variables

Independent variables

- Roll speed and radius
- Draft (amount of thickness reduction) or roll gap
- Strip initial thickness
- Strip initial width
- Strip material
- Strip initial temperature
- Lubricant

Dependent variables

- Roll force
- Power
- Speed of exiting strip
- Final strip temperature
- Maximum draft
- Roll strip contact length
- Sheet or plate shape



Hot rolling

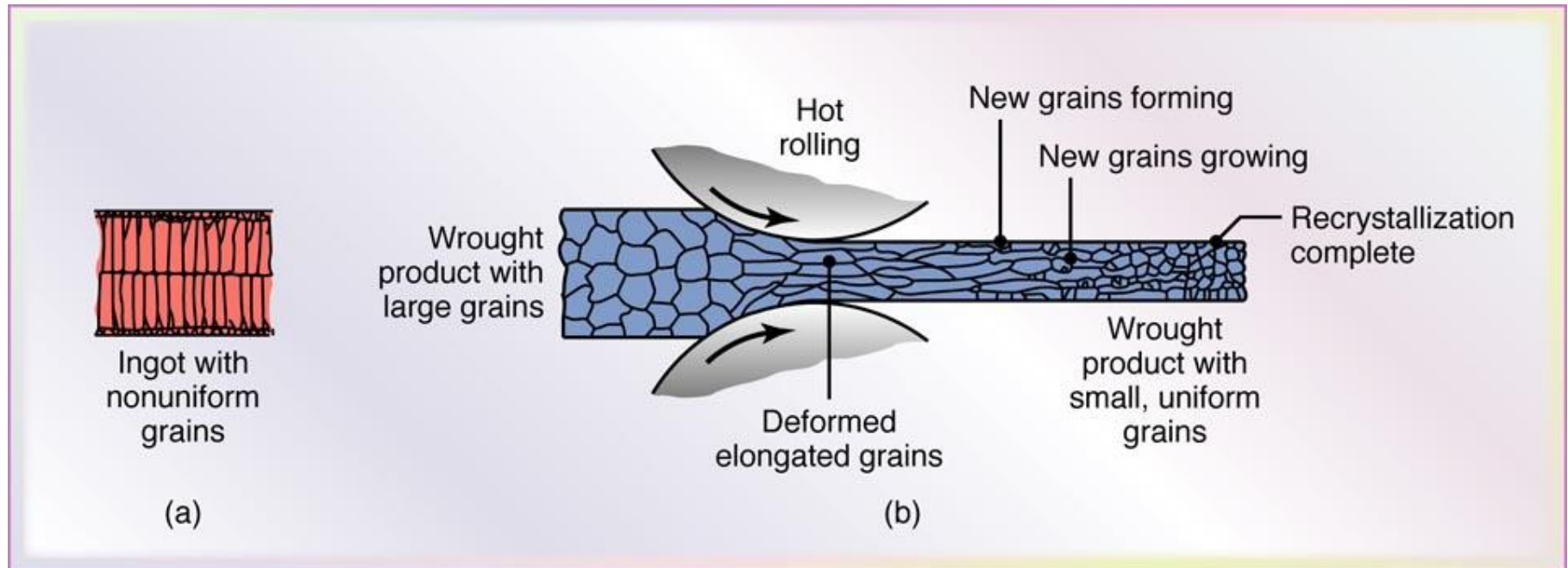
Advantages

- Stresses lower
- Forces smaller
- Power requirements less
- No work hardening
- Large deformations possible
- **Breaks up the cast structure into preferable forms**
- Closes porosity
- Sometimes the only way to create sheets

Disadvantages

- Higher friction
- Rolls need to be cooled
- Material handling difficult
- Personnel must be protected from heat

Microstructure in hot rolling



Cold rolling

Advantages

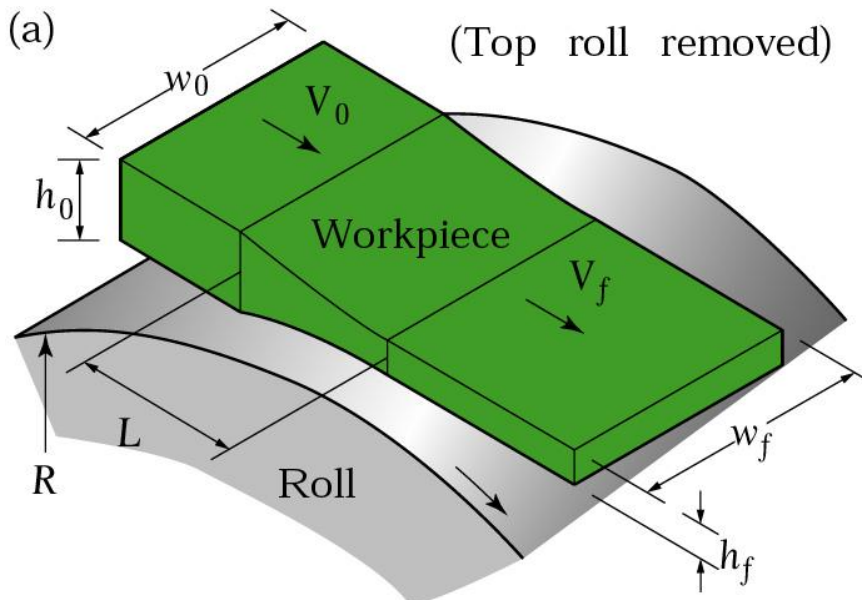
- Deformations of ~ 50 to 80%
- Work hardening increases strength
- Excellent surface finish
- Excellent tolerances on the thickness and shape

Disadvantages

- High forces
- Small reductions give rise to surface stresses and non-uniform stress distributions

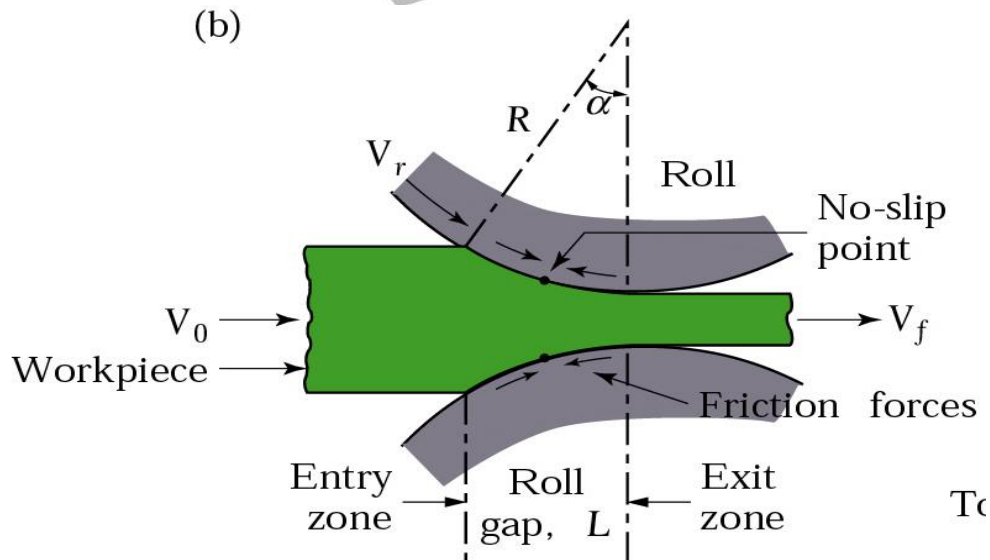
Mechanics of flat rolling – plane strain

12



To keep constant the volume rate of the material, the velocity of the strip must increase as it moves through the roll gap

$$V_f = V_0 \left(\frac{h_0}{h_f} \right)$$



NEUTRAL POINT:
point in the arc of contact where the roll velocity and the strip velocity are the same

Rolling force and power

R=roll radius

$$L = \sqrt{R\Delta h}$$

Δh =difference between the original and final thickness of the strip (draft)

$$F = Lw\overline{Yf'}\left(1 + \frac{mL}{2h_{av}}\right)$$

$\overline{Yf'}$ =average flow stress in plane strain of the material in the roll gap

Assume that the roll force acts in the middle of the arc of contact

$$T = \frac{FL}{2} \quad \text{Torque per roll}$$

$$\text{Power} = T\omega \quad \text{Power required per roll}$$

$$\text{Power} = \frac{\pi FLN}{60000} \quad (\text{kW})$$

Power required per roll

F (N)

L (m)

N (rpm)

Hot rolling force

- Proper estimation of the friction coefficient at elevated temperatures
- Strain-rate sensitivity of metals at high temperatures
- Calculation of the average flow stress considering the dependency from the strain rate

$$\mu = 0.2 \rightarrow 0.7$$

$$\bar{\dot{\varepsilon}} = \frac{V_r}{L} \ln \left(\frac{h_0}{h_f} \right)$$

Friction coefficient influence

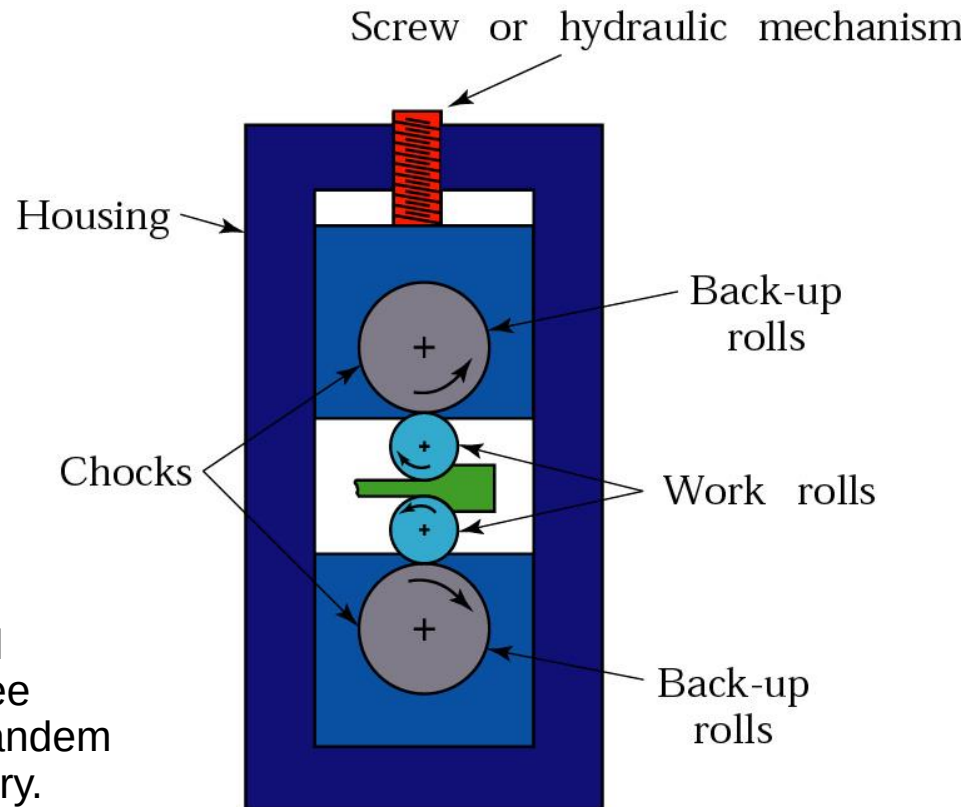
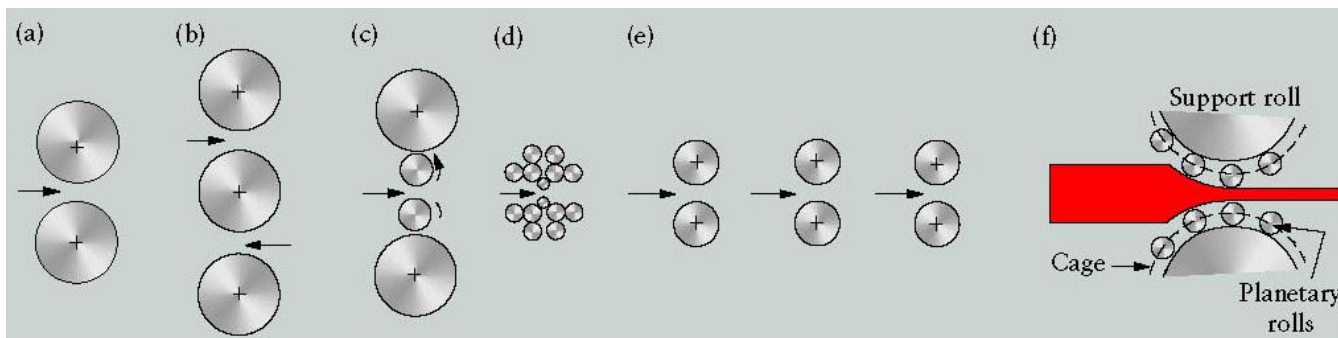
$$\Delta h_{\max} = \mu^2 R$$

Maximum draft

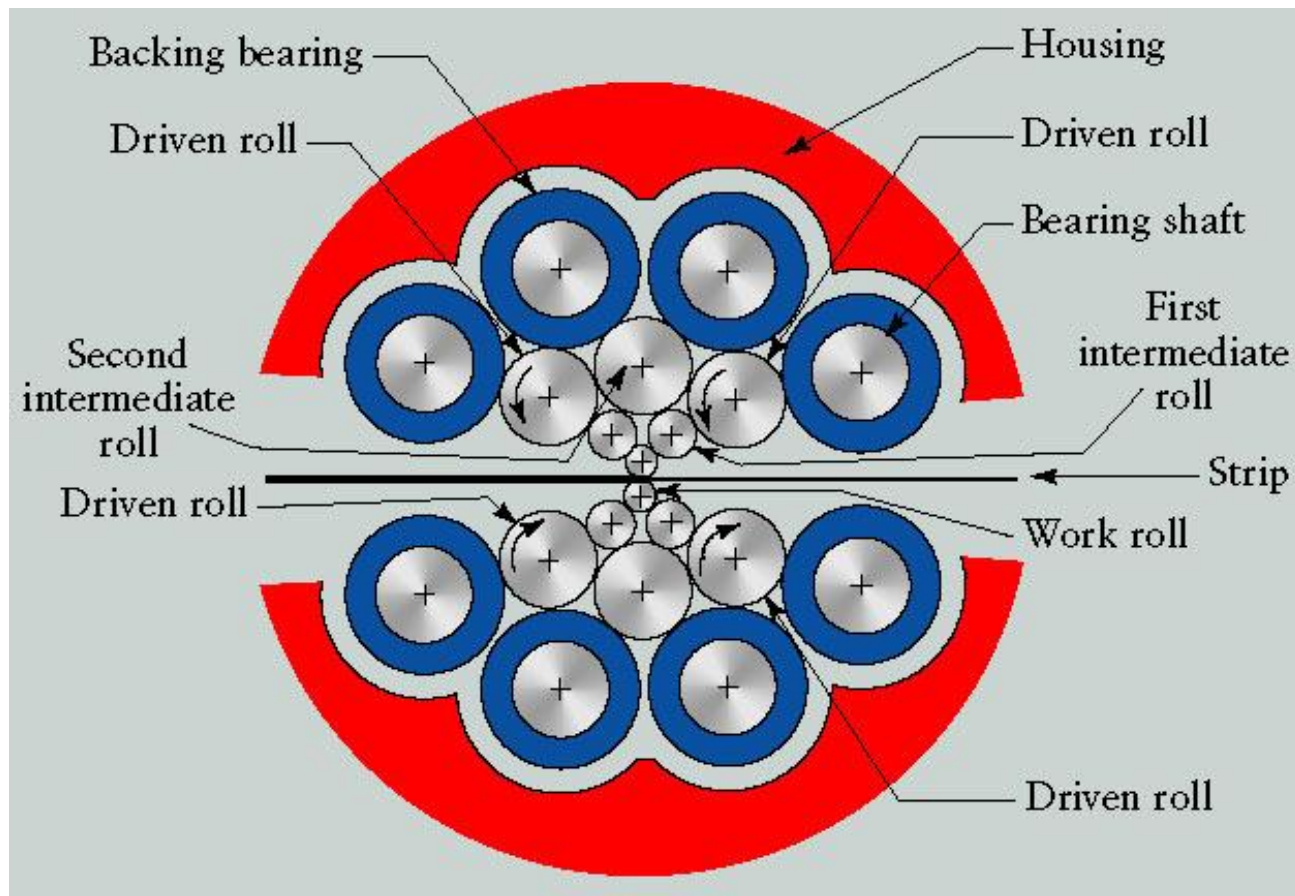
Rolling mills

- Most commercial mills are 4 high, reversible
 - Small rolls in contact
 - $F \propto L \propto R^{0.5}$
 - Large back up rolls provide stiffness

Schematic illustration of various roll arrangements: (a) two high; (b) three high; (c) four high; (d) cluster; (e) tandem rolling with three stands; (f) planetary.



Sendzimir rolling mill



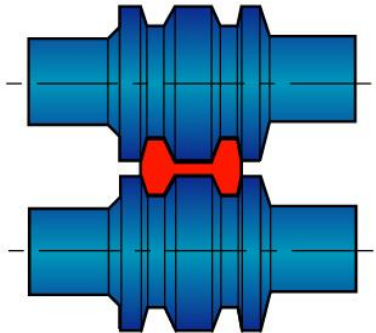
Schematic illustration of a cluster (Sendzimir) mill. These mills are very rigid and are used in cold rolling of thin sheets of high-strength metals, with good control of dimensions. Rolled products are as wide as 5000 mm and as thin as 0.0025 mm.

Shape rolling

- Non-flat shapes can be produced by using shaped rolls
 - **I-Beams**
 - **H-sections**
 - **Rails (trains)**
 - **Angle iron**
- Design of shaped rolls to provide the right amount of non-uniform deformation is critical

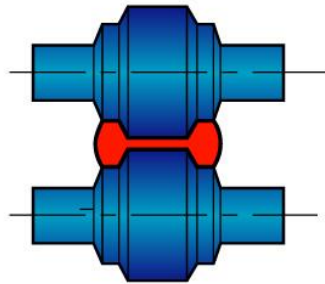
Sequence for shape rolling

Stage 1



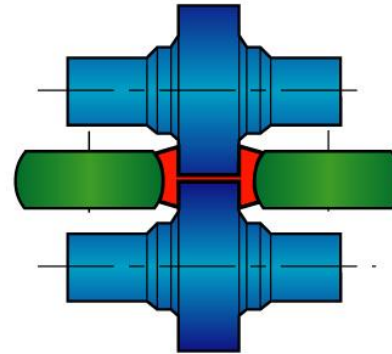
Blooming rolls

Stage 2



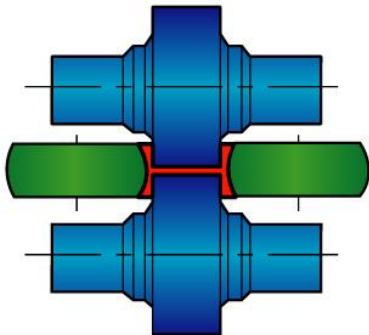
Edging rolls

Stage 3



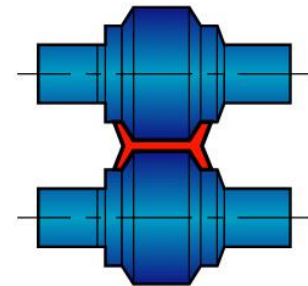
Roughing horizontal and vertical rolls

Stage 4



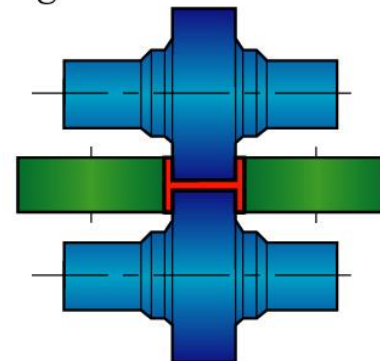
Intermediate horizontal and vertical rolls

Stage 5



Edging rolls

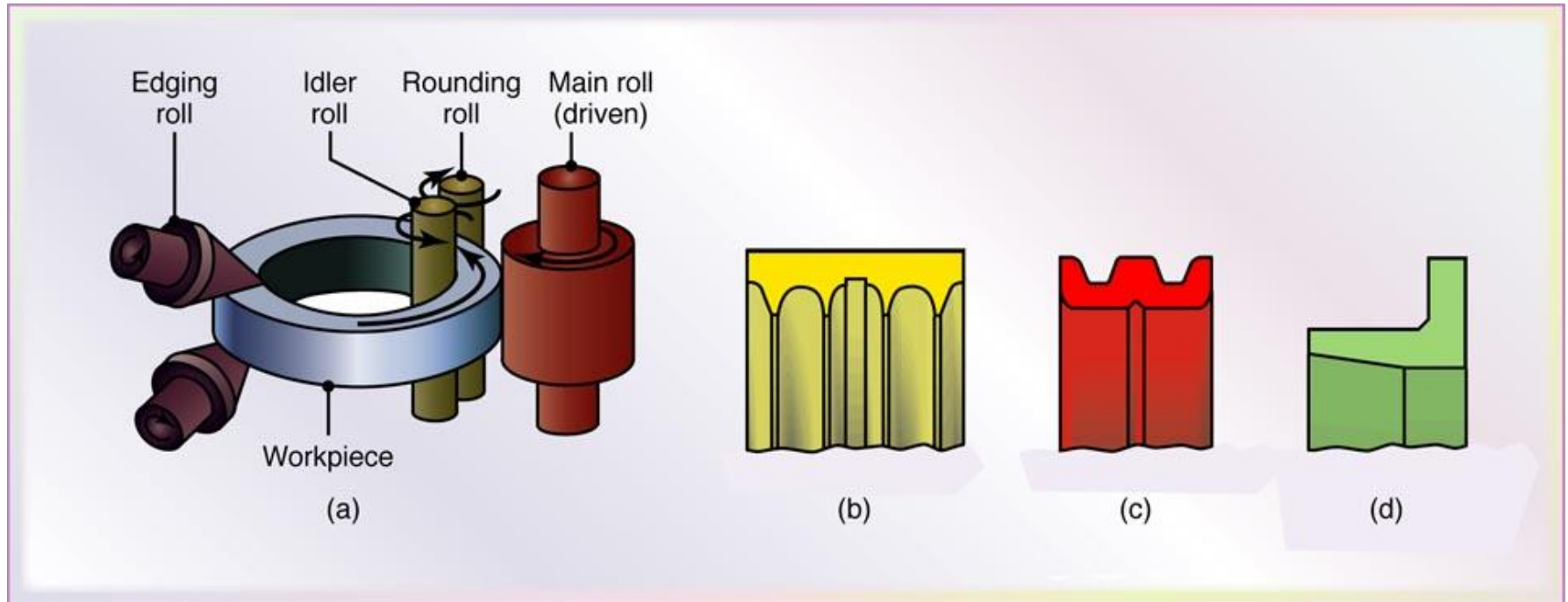
Stage 6



Finishing horizontal and vertical rolls

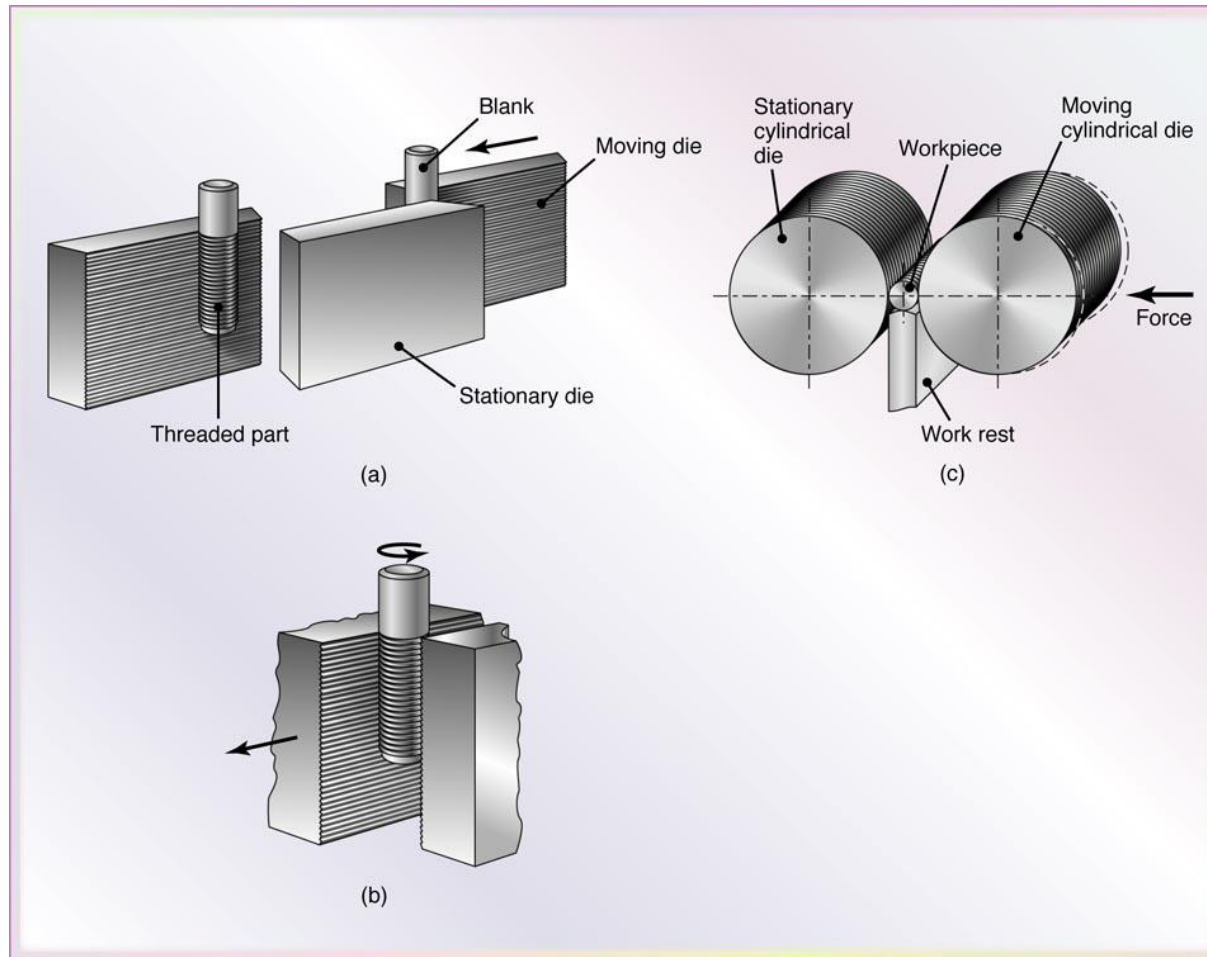
Stages in the shape rolling of an H-section part. Various other structural sections, such as channels and I-beams, are also rolled by this kind of process.

Ring rolling



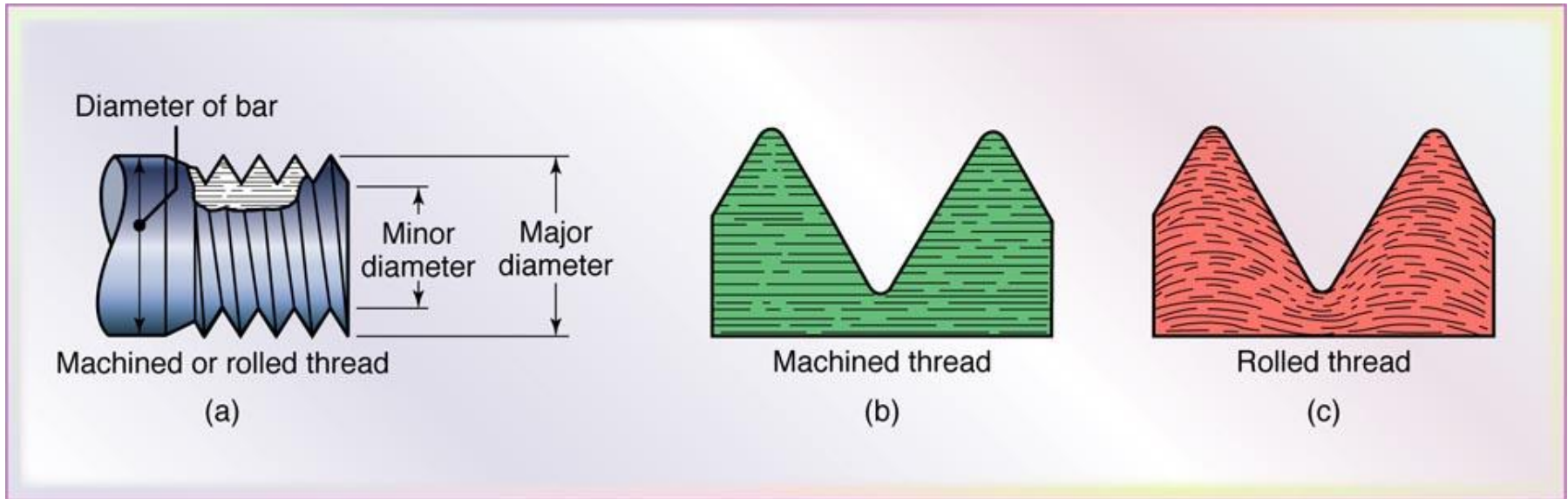
(a) Schematic illustration of a ring-rolling operation. Thickness reduction results in an increase in the part diameter. (b-d) Examples of cross-sections that can be formed by ring-rolling.

Thread rolling



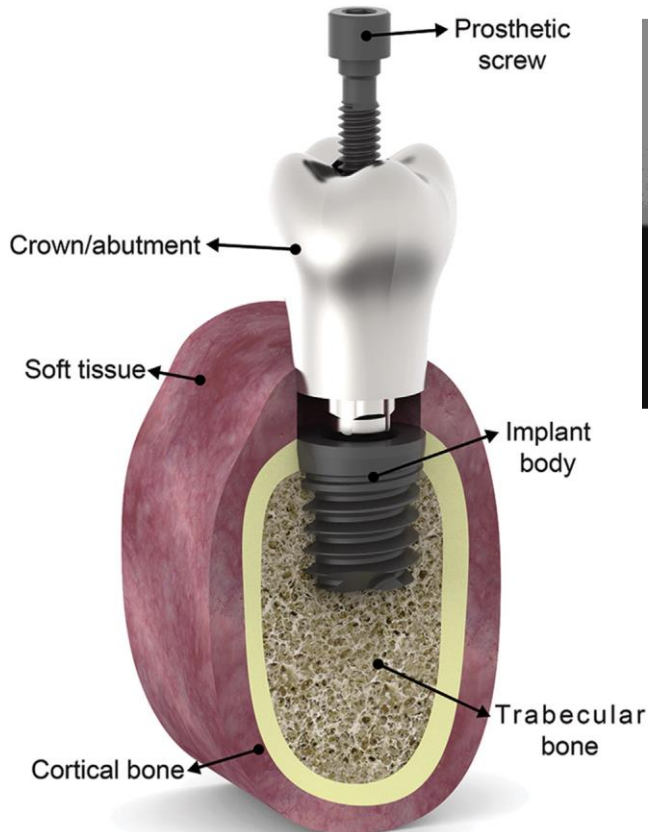
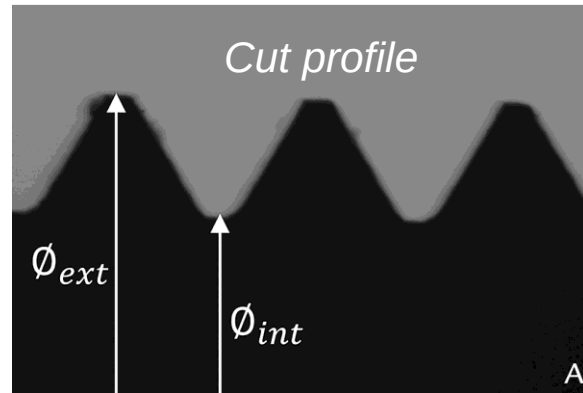
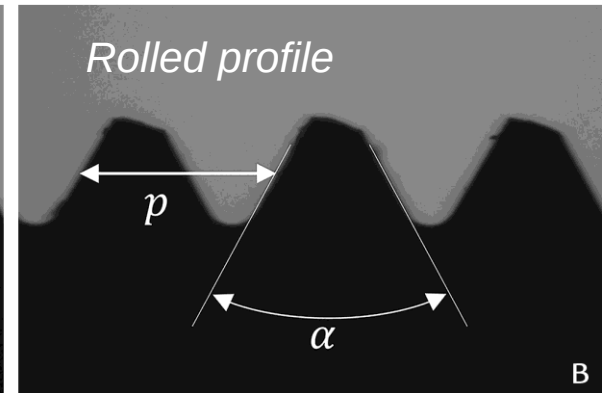
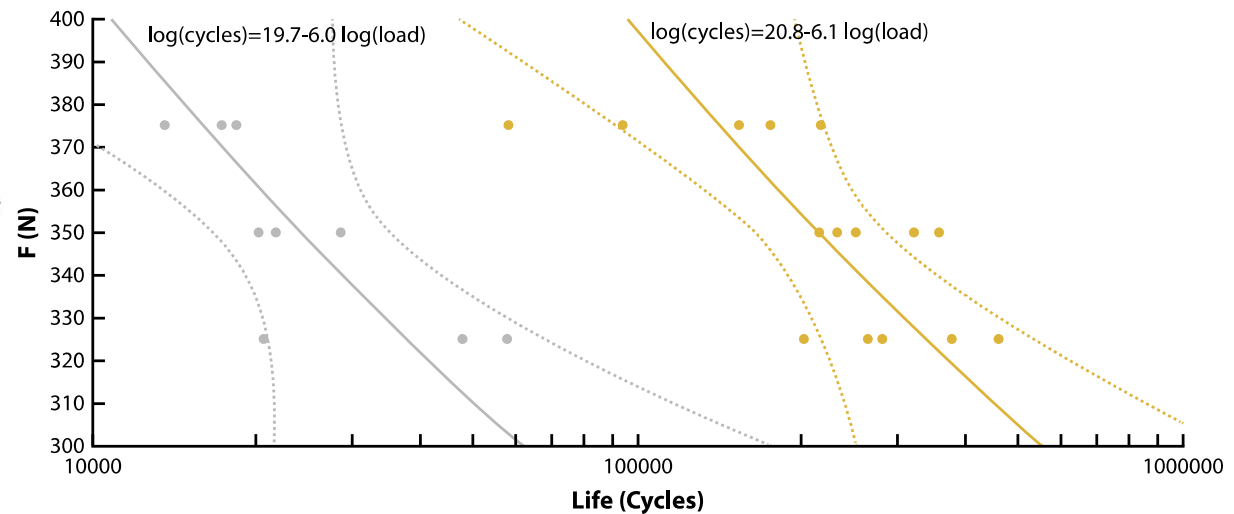
Thread-rolling processes: (a) and (b) reciprocating flat dies; (c) two-roller dies. Threaded fasteners, such as bolts, are made economically by these processes at high rates of production.

Rolled vs. machined threads



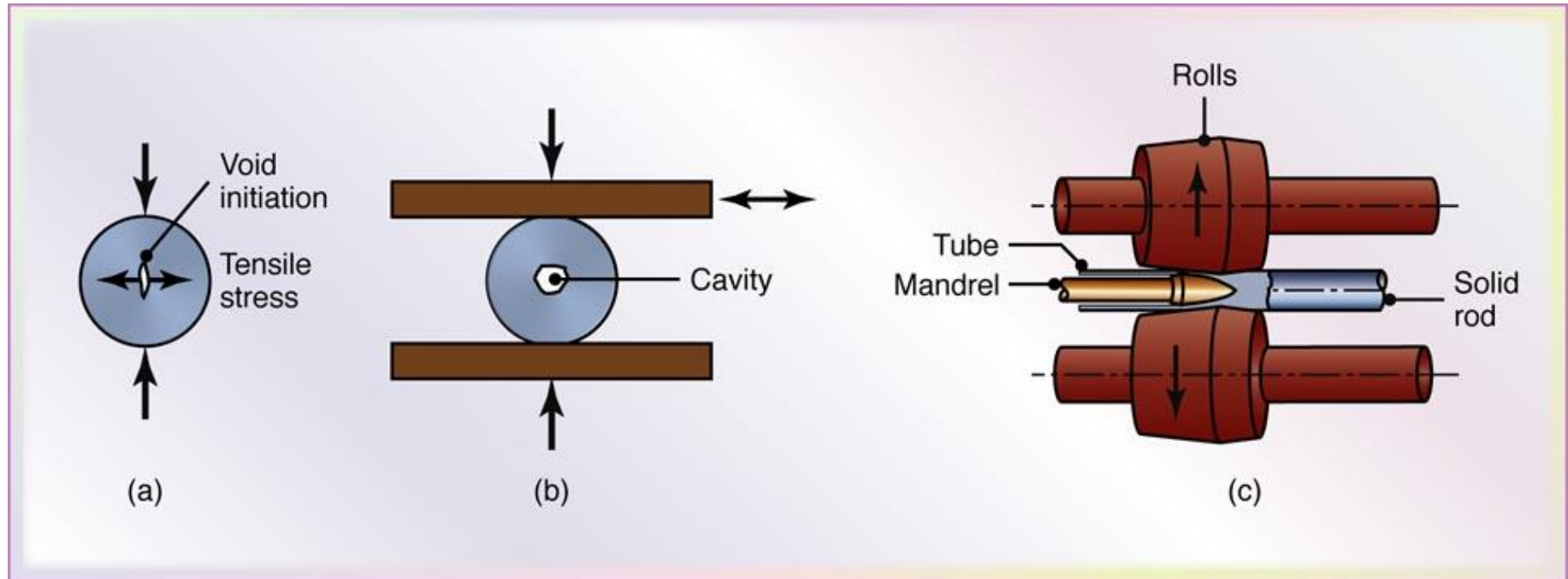
(a) Schematic illustration of machined or rolled threads. (b) Grain-flow lines in machined and rolled threads. Unlike machined threads, which are cut through the grains of the metal, rolled threads follow the grains and are stronger, because of the cold working involved.

Application case – prosthetic screw



- Roll threaded screws
- Roll threaded screws F-N
- 95% confidence bands
- Cut threaded screws
- Cut threaded screws F-N
- 95% confidence bands

Mannesmann process



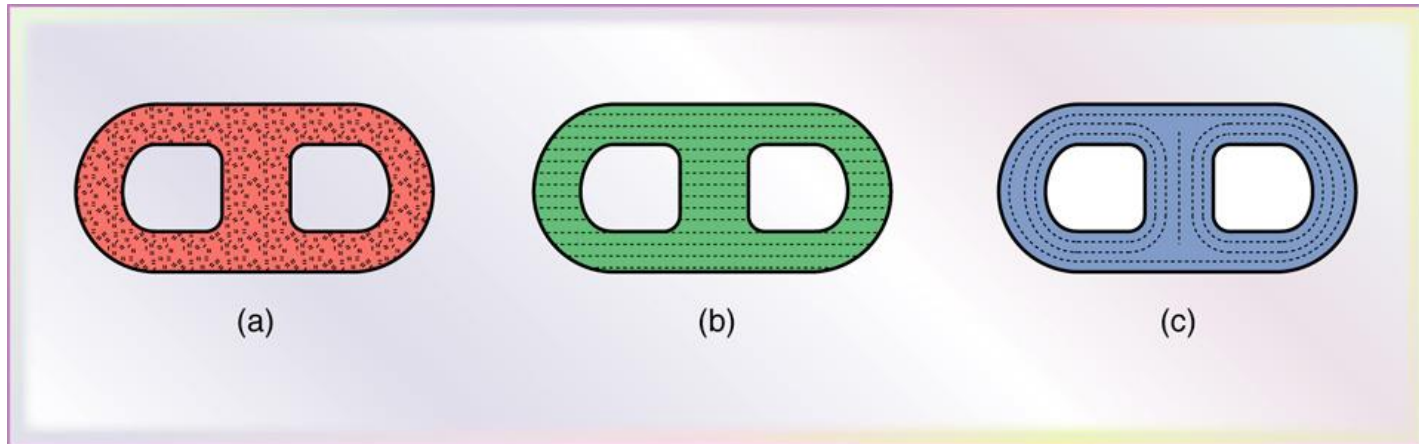
The rod is driven by a pair of cone-shape rolls that have skewed axis and rotate in the same direction. The frictional load between the rolls and the rod causes the rod to rotate and forces it to advance longitudinally over the piercer point, where the internal fracture starts. The round bar rotates and undergoes a cyclic progressive compression which results in high tensile stresses in the centre of the rod itself.

Forging procedure

- Prepare raw material including cleaning
- Heat workpiece (for hot forging)
- Descale if necessary
- Preheat and lubricate dies (for hot forging)
- *Forge in appropriate dies and in correct sequence*
- Remove excess material (for hot forging)
- Clean
- Check dimensions
- Straighten if necessary
- Machine to final dimensions
- Heat treat if necessary
- Inspect

Characteristics

- Tolerances of 0.5% to 1% can be achieved
- Material properties can be tailored by appropriate die design
 - **Directed material flow**



Schematic illustration of a part made by three different processes showing grain flow. (a) Casting, (b) machining from a blank, and (c) forging.

- **Advantages**

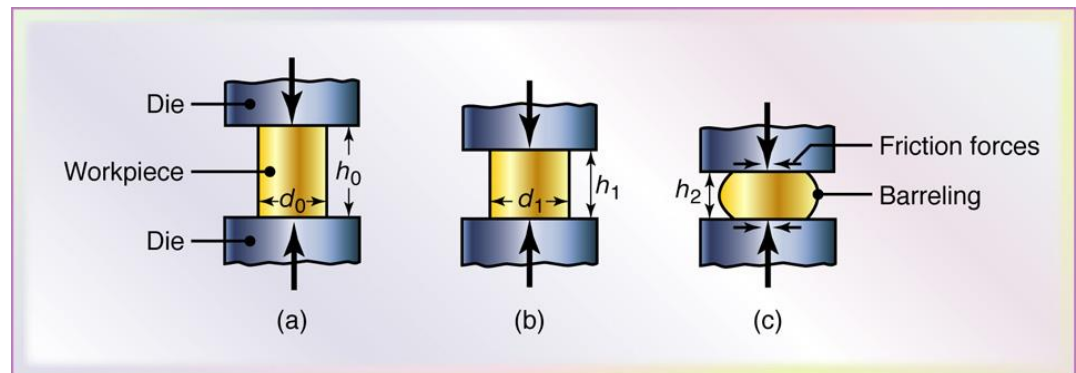
- Metal flow and grain structure can be controlled
- Results in good strength and toughness
- Near net shape (low buy to fly ratio)
- Parts of reasonable complexity can be created
 - Landing gear
 - Connecting rods
 - Complex shafts

- **Disadvantages**

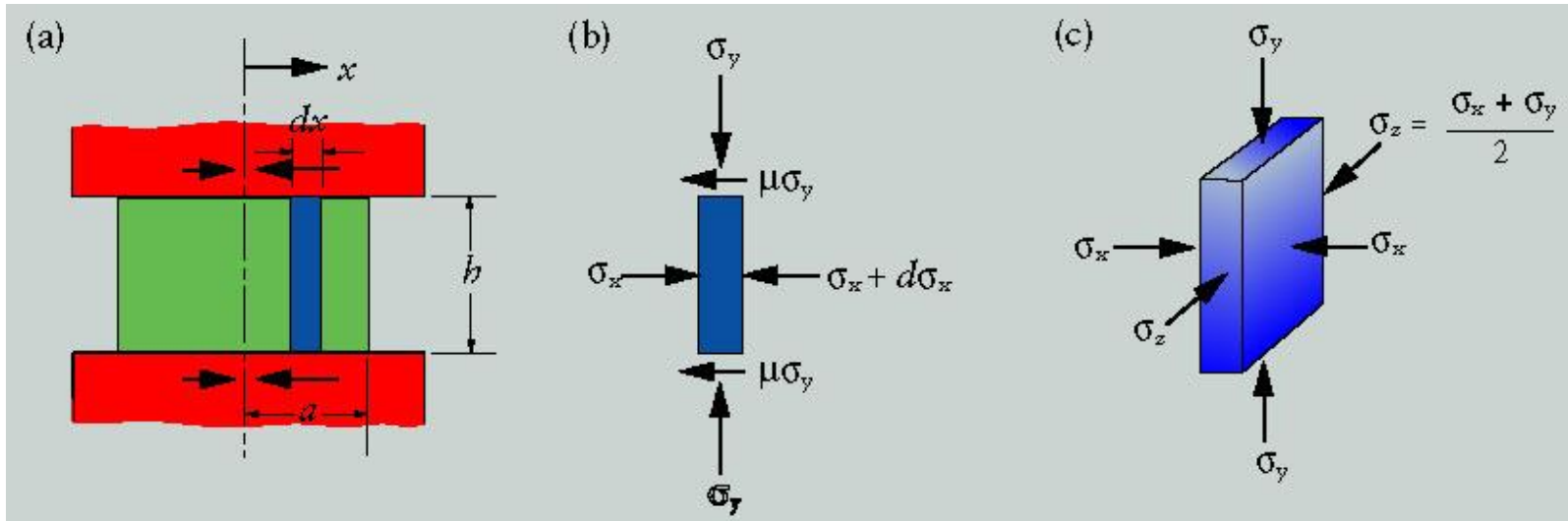
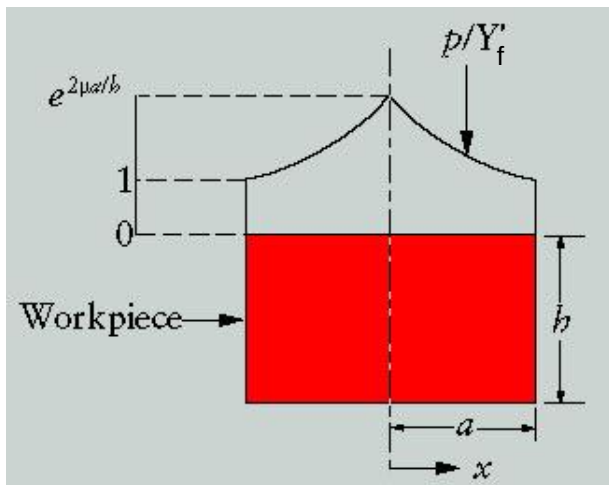
- Dies are expensive, particularly for hot forging
- Highly skilled labor required

Open die forging

- Simplest and cheapest
- Also called upsetting or flat-die forging
- Advantages
 - **Cheap**
 - **Can form a wide variety of simple shapes with the same dies**
 - **Squares, cylindrical**
 - **Useful for preparing material for other forms of forging or machining**
 - **Can handle large items (35 tons)**
- Disadvantages
 - **Barreling of shape due to high friction**



Plane strain open die forging

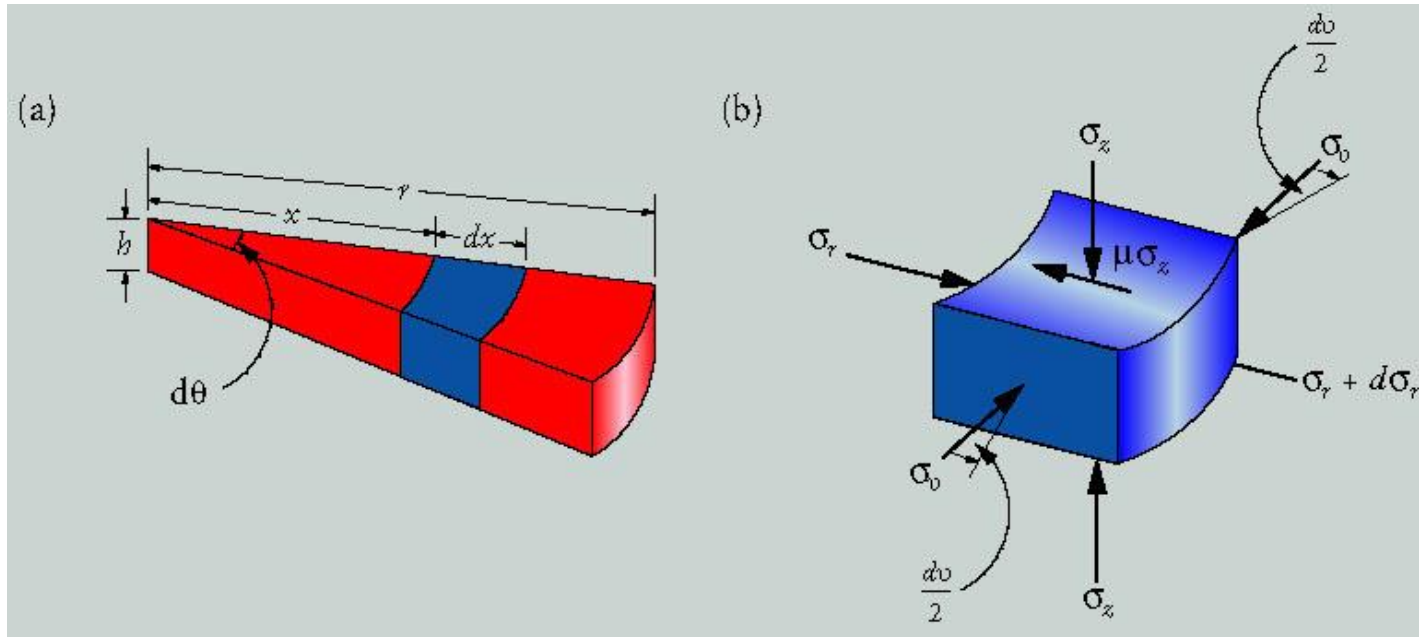


Distribution of die pressure, in terms of p/Y_f' , in plane-strain compression with sliding friction. Note that the pressure at the left and right boundaries is equal to the yield stress in plane strain, Y_f' . Sliding friction means that the frictional stress is directly proportional to the normal stress.

$$p_{av} @ Y_f' \left(1 + \frac{\mu a}{h} \right)$$

$$F = (p_{av})(2a)(width)$$

Axi-symmetric open die forging



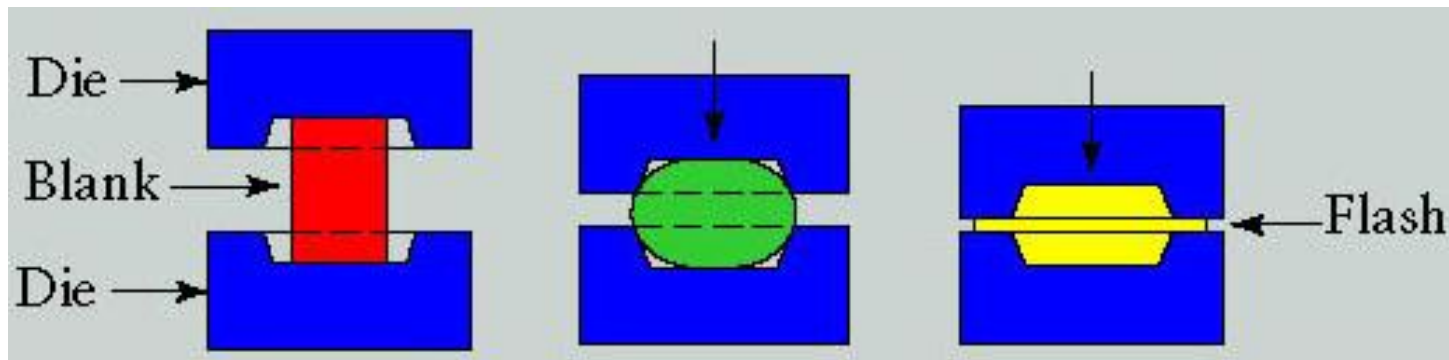
Stresses on an element in forging of a solid cylindrical workpiece between flat dies.

$$p_{av} @ Yf \left(1 + \frac{2mr}{3h} \right)$$

$$F = (p_{av})(\pi r^2)$$

Impression die forging

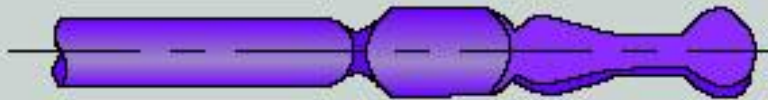
- Uses dies with the approximate end shape
 - Usually requires more than one die to complete the process
 - Fullering and Edging dies prepare material to take up die shape
 - **Fullering** moves material away from center
 - **Edging** moves material away from edges
 - Flashing produced from excess material in case of hot forging
-
- **Advantages**
 - Produces near-net-shape products
 - Material properties tailored to application
 - **Disadvantages**
 - High die costs
 - Highly skilled labor required



Connecting rod forging



Blank (bar stock)



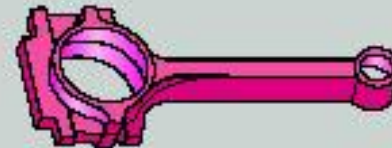
Edging



Blocking

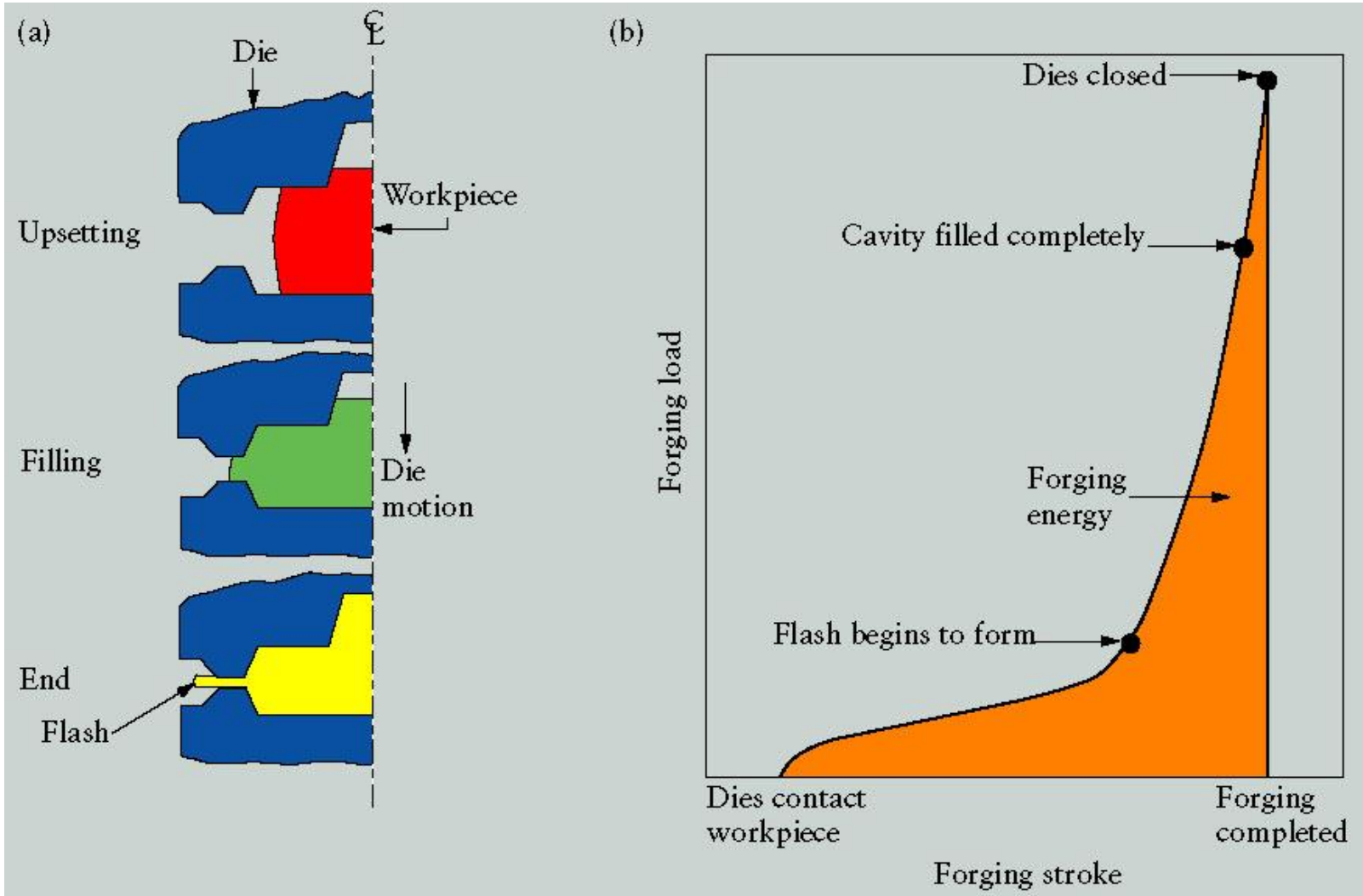


Finishing



Trimming

Forging load



Forging load

$$F = k Y_f A$$

where Y_f is the flow stress
 A is the area and
 k is a factor given below

Shapes	k
Simple, no flashing	3-5
simple, with flashing	5-8
Complex, with flashing	8-12

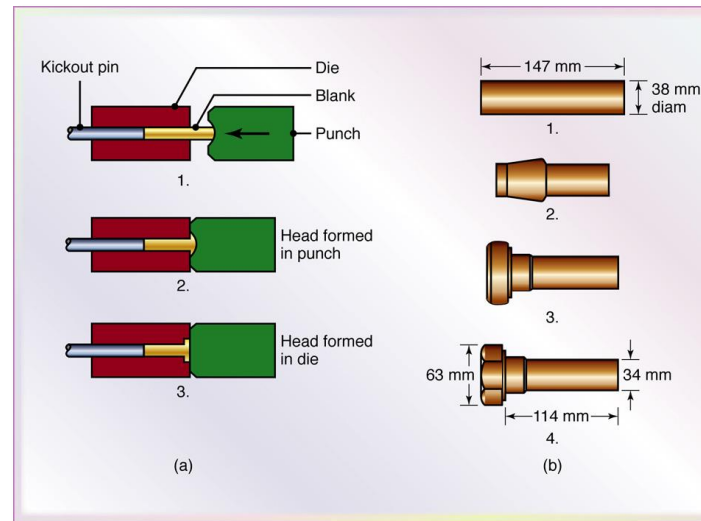
Forgeability

- Defined as the capability of a metal to undergo deformation without cracking
- Common test is the **upset test**
 - **Upset a cylindrical specimen to fixed, large deformation**
 - **Examine barrel surfaces for cracks**
- Another is the **hot torsion test**
 - **Twist long cylindrical specimen around its axis**
 - **Number of twists to failure is *material forgeability***
 - **Also used for rolling and extrusion deformation capabilities**

Further forging processes

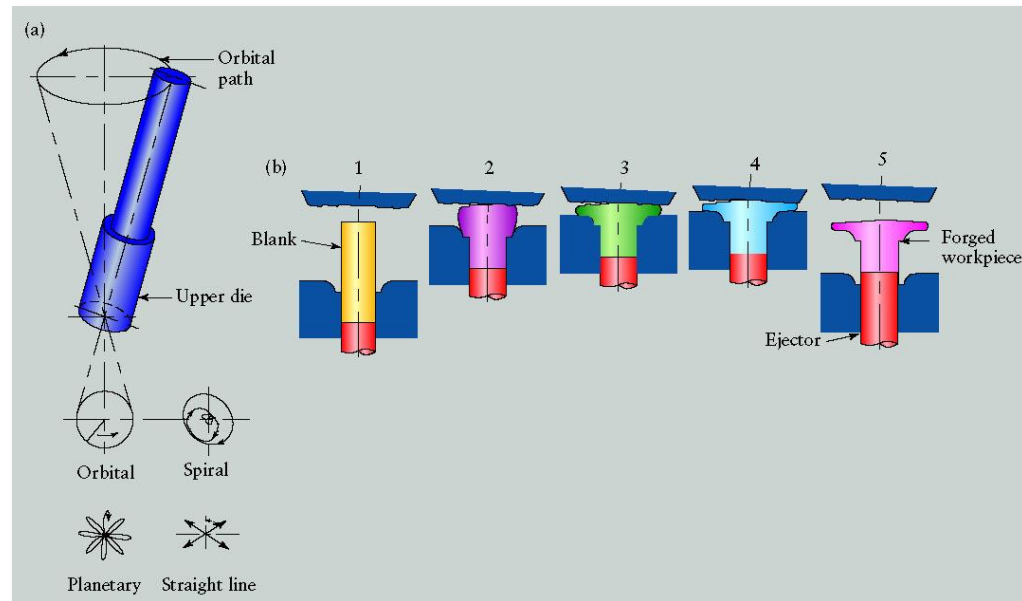
Heading

- Used mostly for bolts



Orbital forging

- Forms the part incrementally
- Small forging forces because the die contact is concentrated on a small part of the workpiece at time
- Applicable to mostly cylindrical shapes



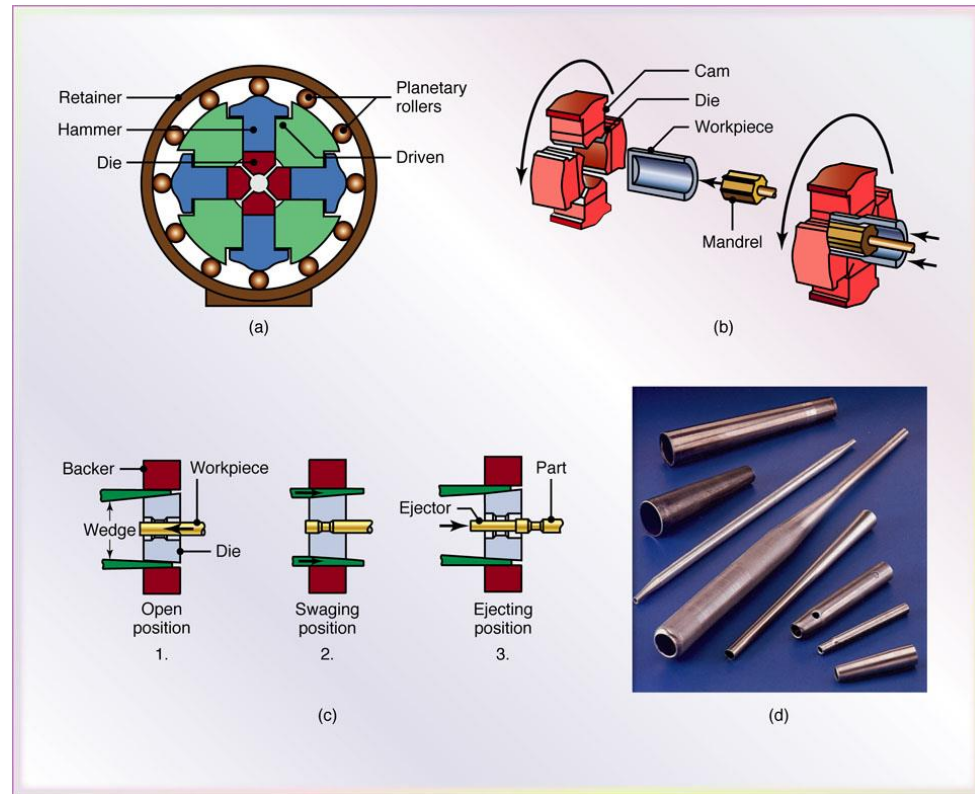
Further forging processes

Isothermal forging

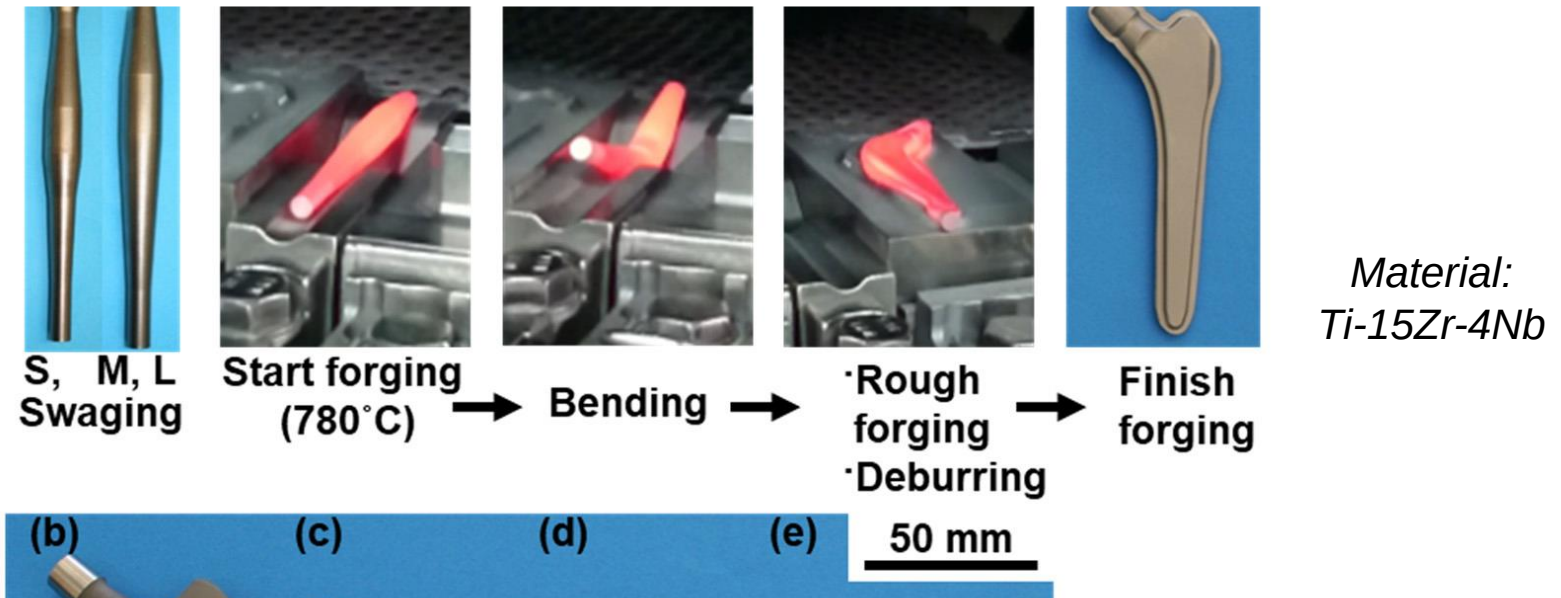
- Dies at same temperature of workpiece
- No workpiece cooling
- Low flow stresses
- Better material flow
- More close tolerances and finer details can be achieved

Cogging/swaging

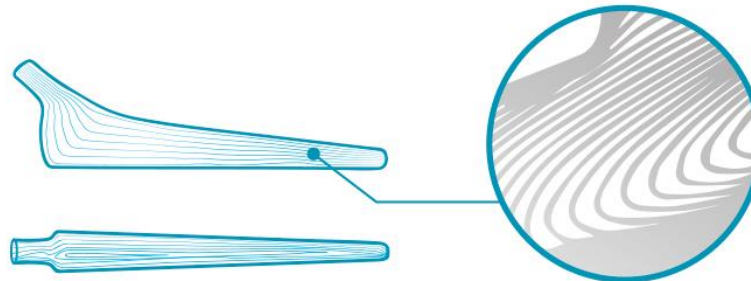
- Cylindrical parts subjected to radial impact forces by reciprocating dies
- Used to reduce tube diameter and introduce rifling into gun barrels



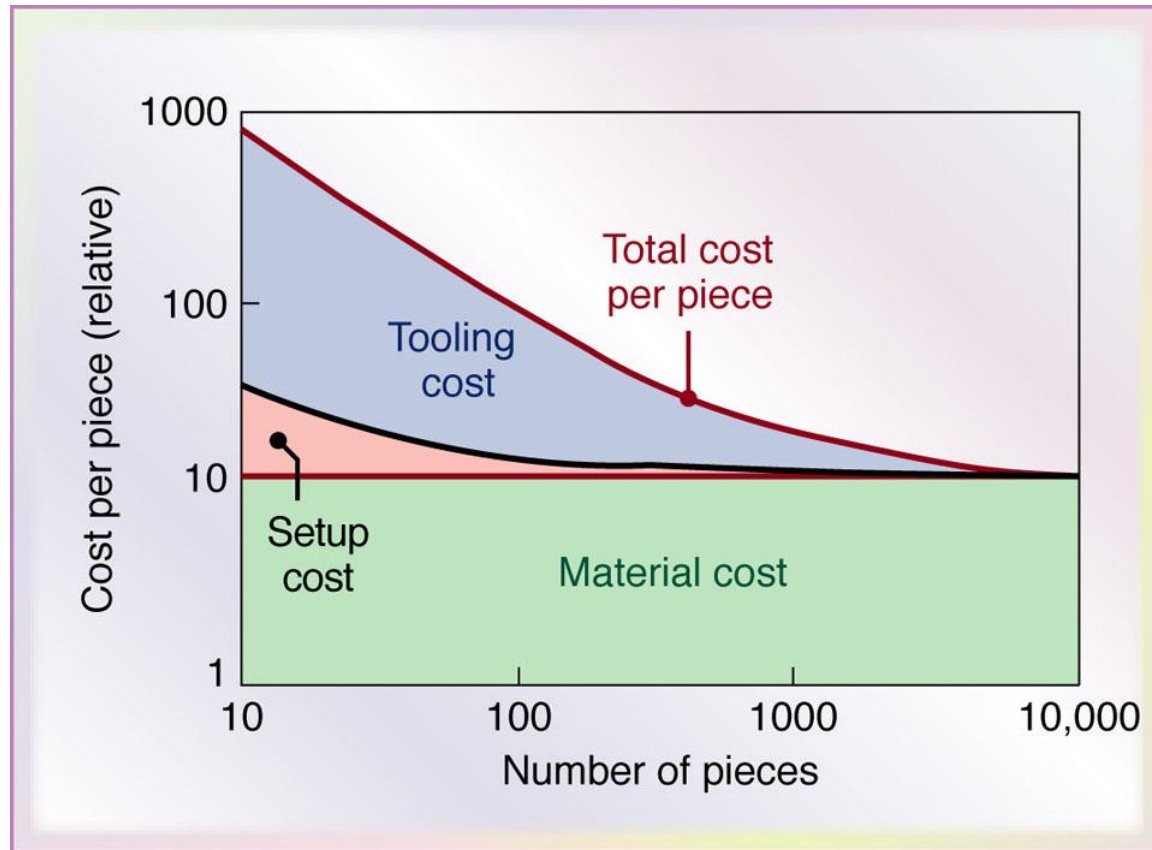
Application case – titanium alloy hip stem



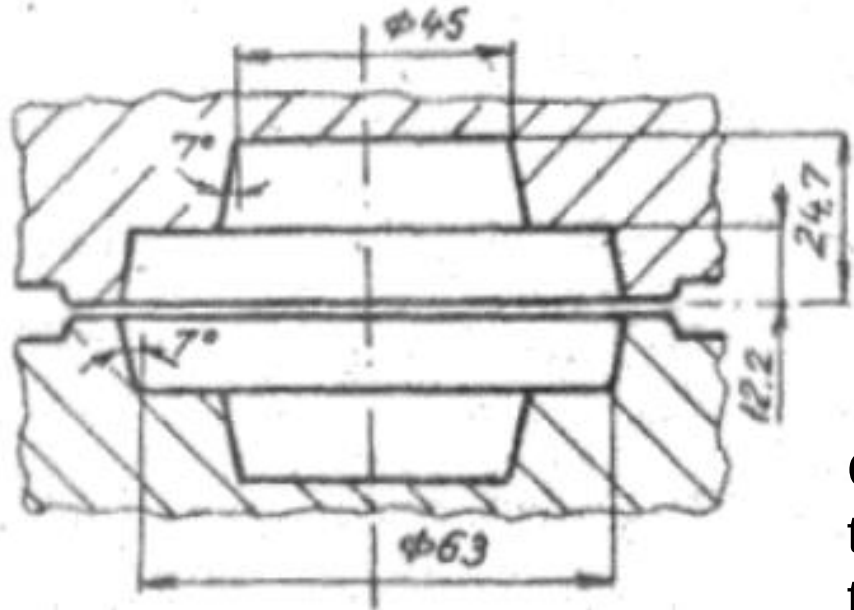
<https://www.youtube.com/watch?v=Ssdb9hkS8rU>



Forging costs



Application – Hot forging of a cylindrical billet /1



Data:

$T_{\text{forging}} = 1120^{\circ} \text{ C}$

$\rho = 7850 \text{ kg/m}^3$

Component diameter at the parting line = 66mm

Weight of the component after forging and flash trimming = 1.124kg

$Y_f = 120 \text{ MPa}$

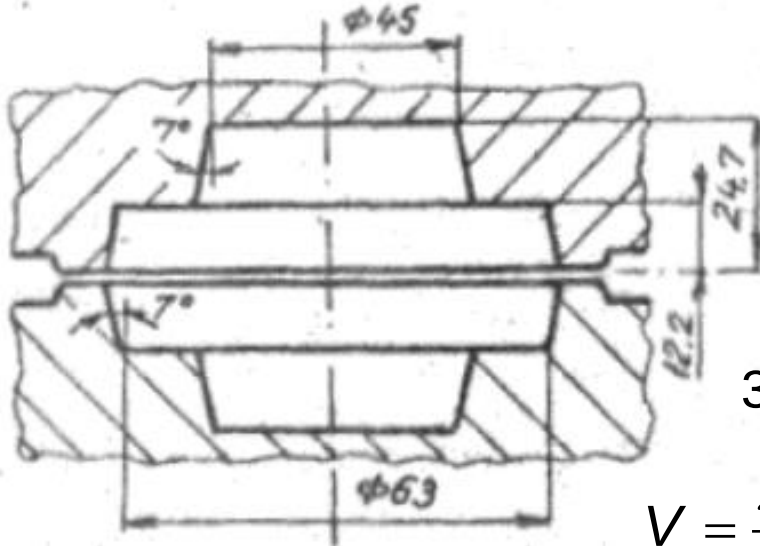
Calculate the dimensions of the billet before forging and the needed forging force

1) Weight of the initial billet:
$$M = (m_a + m_b)A$$

Flash weight = 5-15% forged component weight

Weight loss due to thermal oxidation = 3-5% initial billet weight

Application – Hot forging of a cylindrical billet /2



2) Volume of the initial billet

$$V = \frac{M}{\rho}$$

3) Dimensions of the initial billet

$$V = \frac{\pi}{4} D_b^2 H_b$$

- Upsetting design

- Extrusion design

4) Dimensions of the flash land

$$s = 0.017D + \frac{1}{\sqrt{D+5}}$$

$$\frac{b}{s} = \frac{62.5}{\sqrt{D}}$$

s = height of the flash land

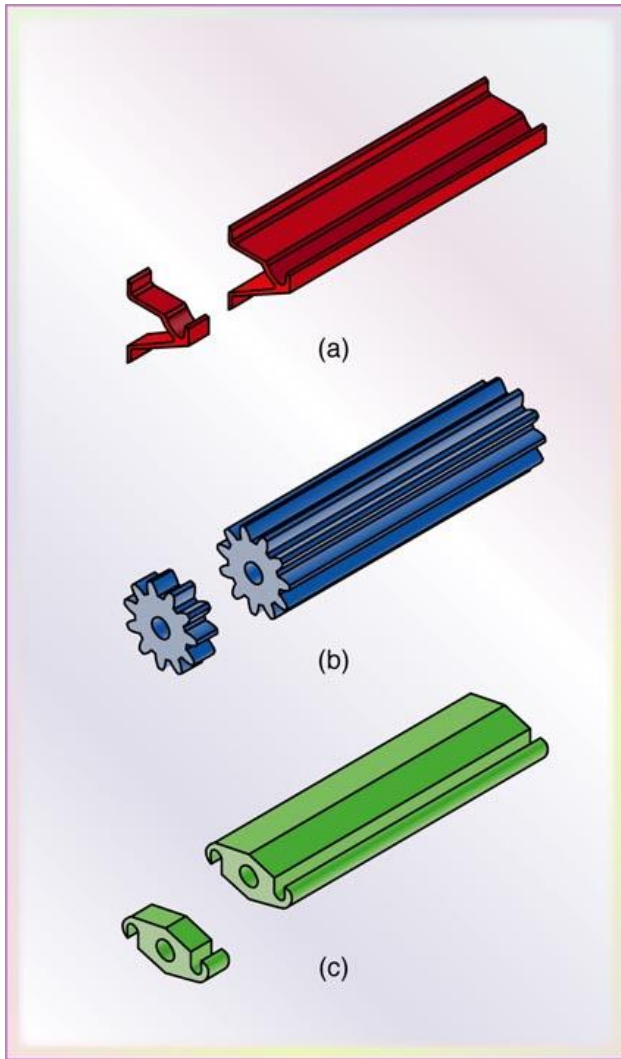
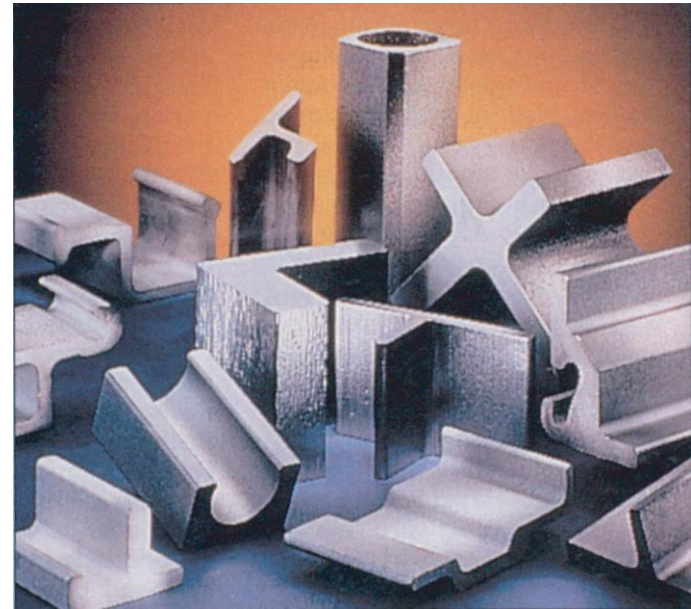
b = length of the flash land

D = component diameter at the parting line

5) Forging force

$$F = K_p Y_f A = K_p Y_f \frac{\pi(D + 2b)^2}{4}$$

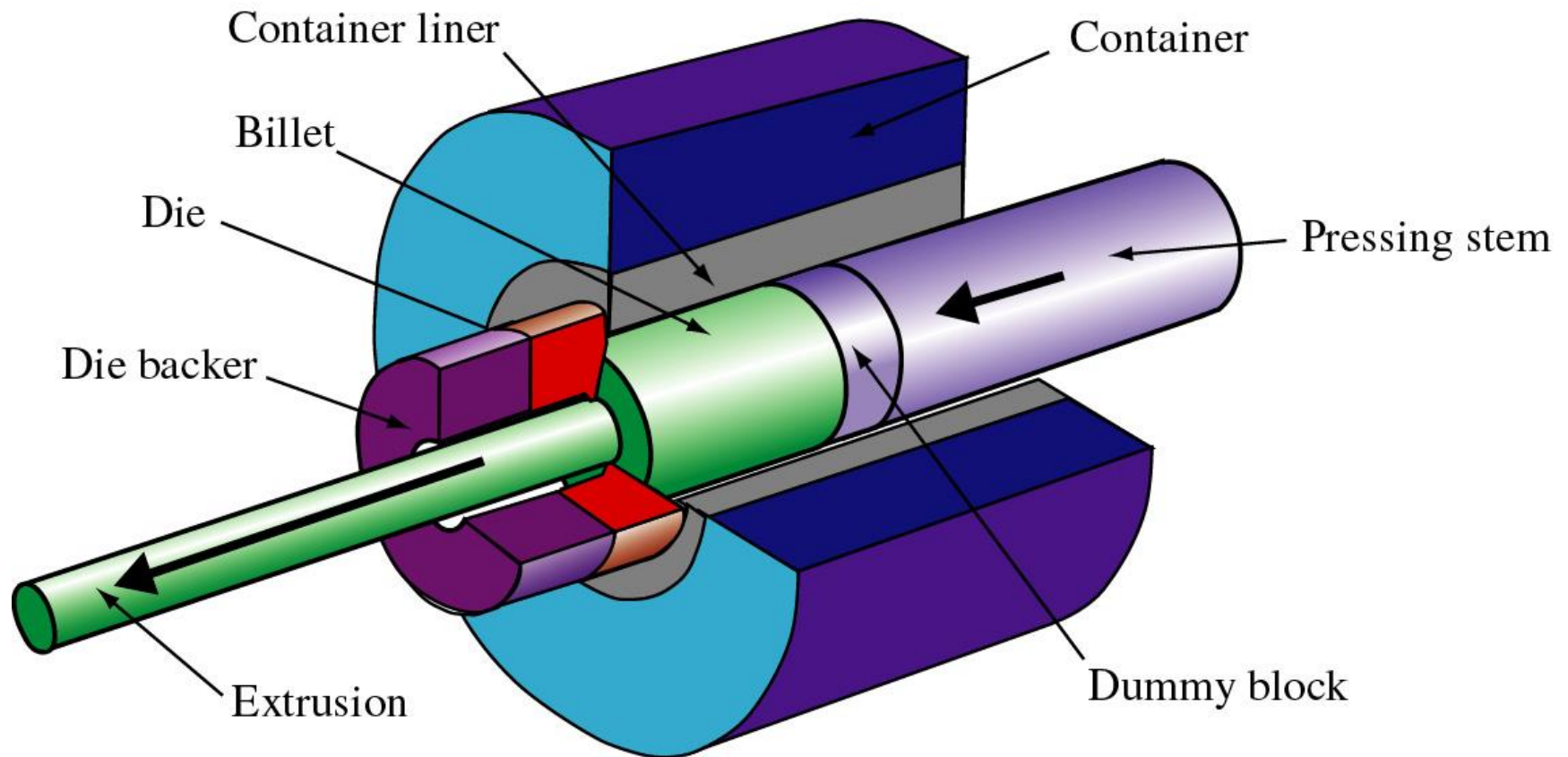
Extrusion process



- Push an ingot through an orifice with the desired shape
- Both *hot* and *cold* extrusion are possible
 - **Depends on the material**

Direct Extrusion

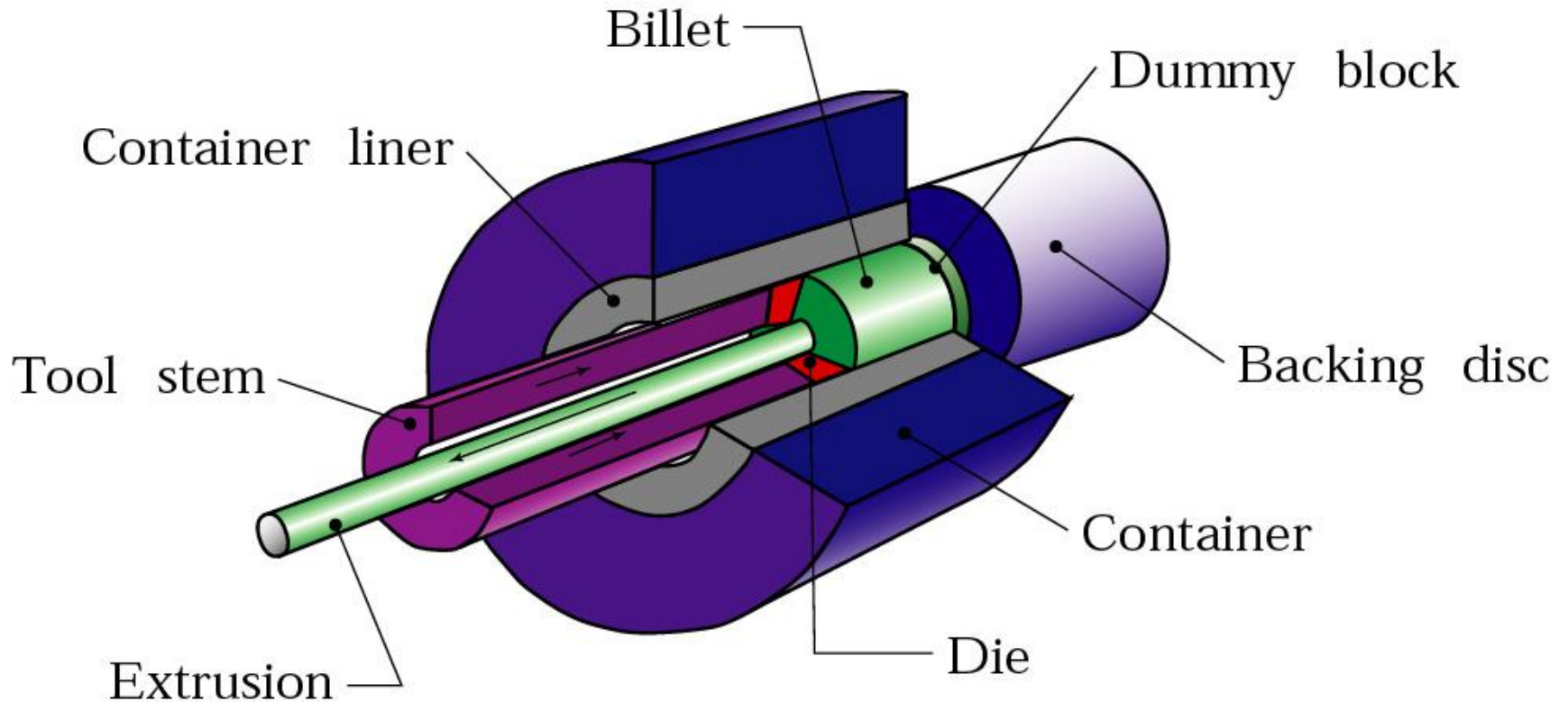
- Direct or forward extrusion
 - **Billet pushed through die from behind**



Indirect extrusion

- Die pushed into billet
- No relative motion at the billet-container interface

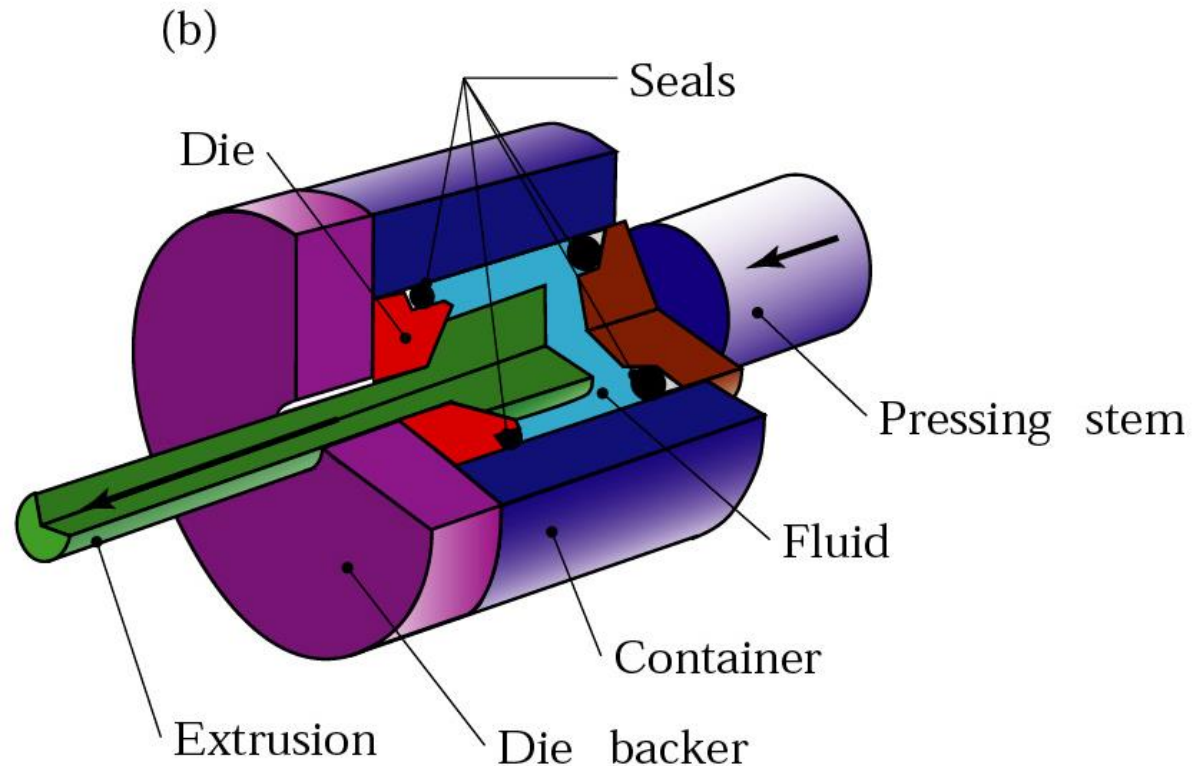
(a)



Hydrostatic extrusion

Ram compresses fluid surrounding billet which is pushed out through the die; the fluid transmits the pressure to the billet

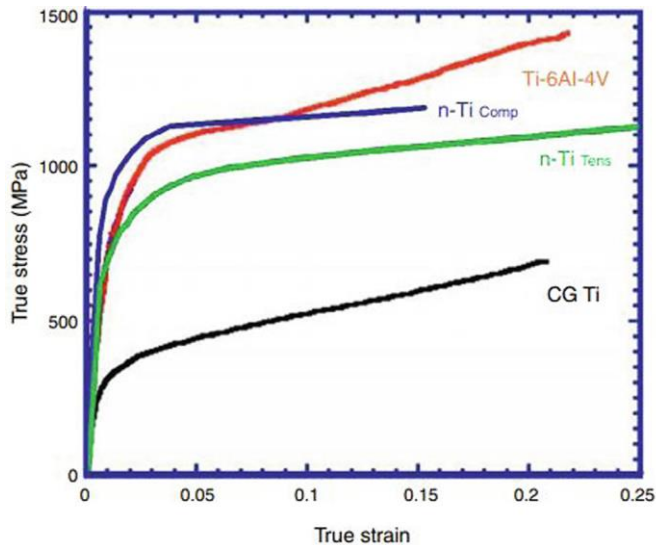
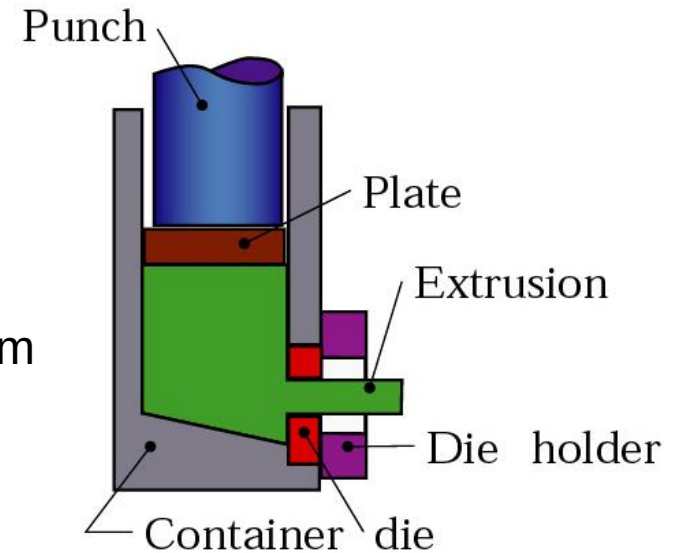
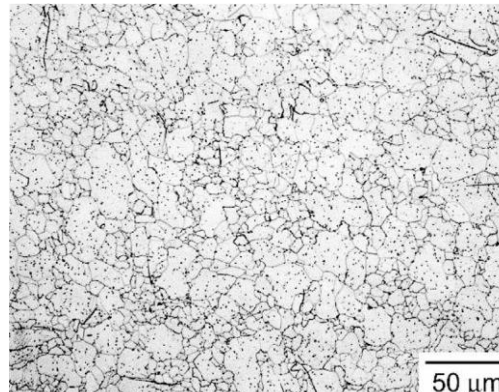
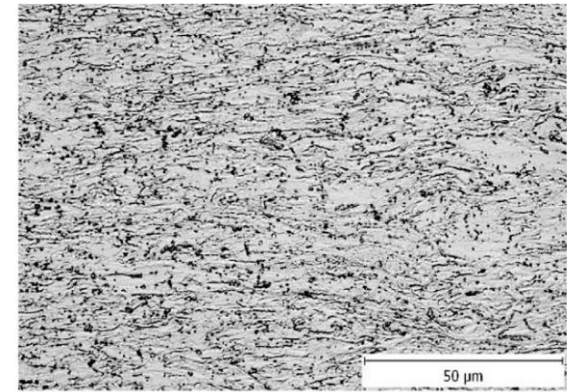
- Very recent development (1950's)
- *Advantages*
 - No friction at walls
 - Can successfully extrude brittle materials
 - Yield stress reduced by hydrostatic pressure
 - Room temperature operation
- *Disadvantages*
 - Limited industrial applications
 - Complex tooling
 - High pressure experience required



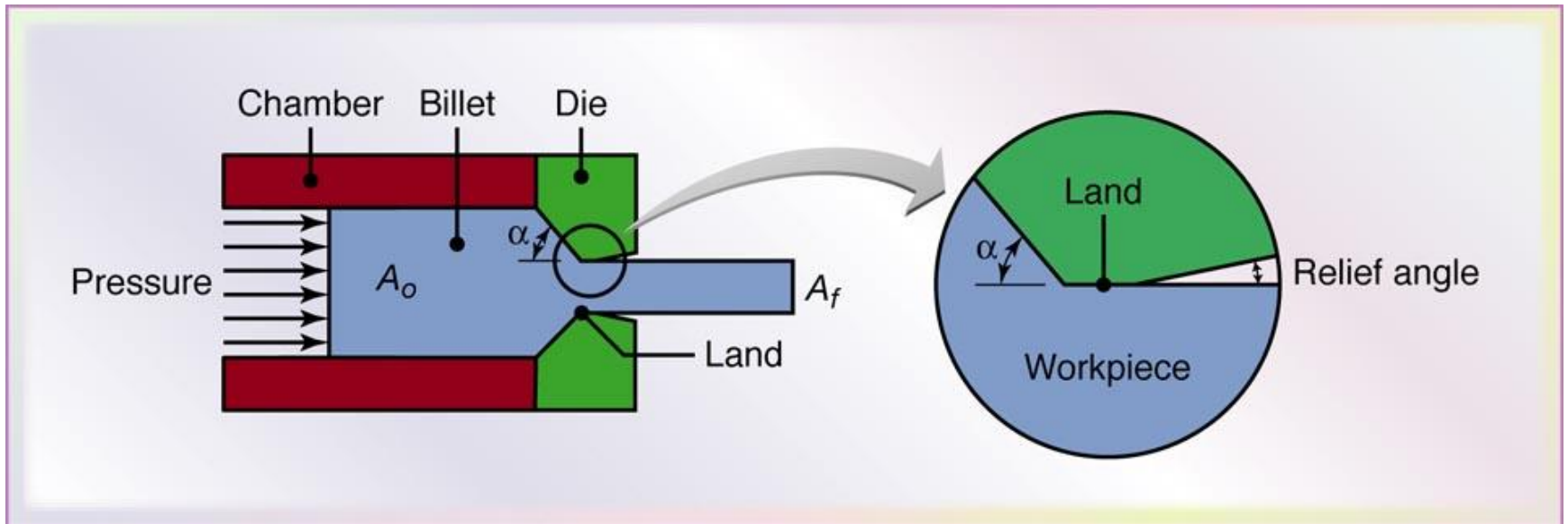
Lateral extrusion

Like direct, but material comes out of the die at right angles to the direction in which the billet is pushed

→ Chance to *nanostucture* metals, like pure titanium



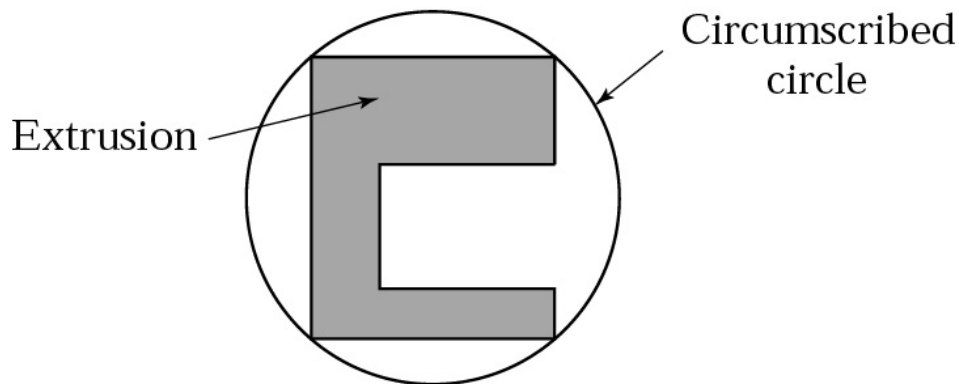
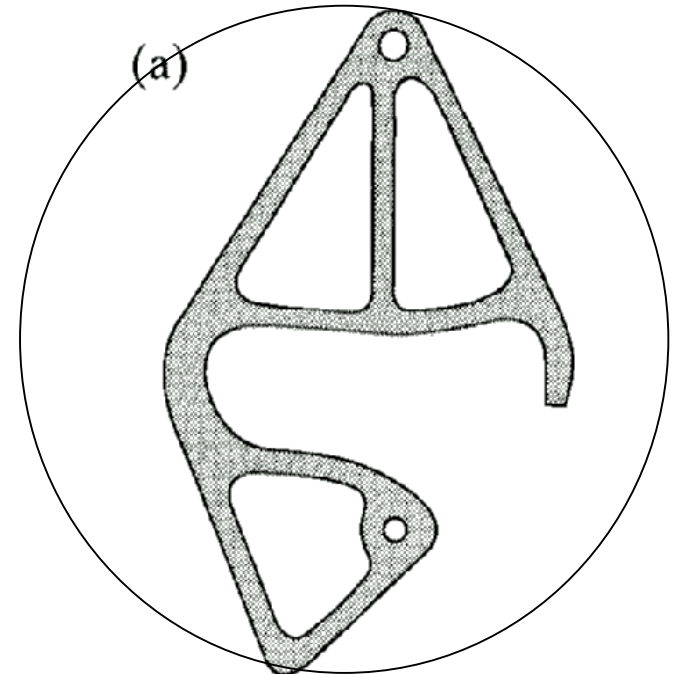
Process scheme



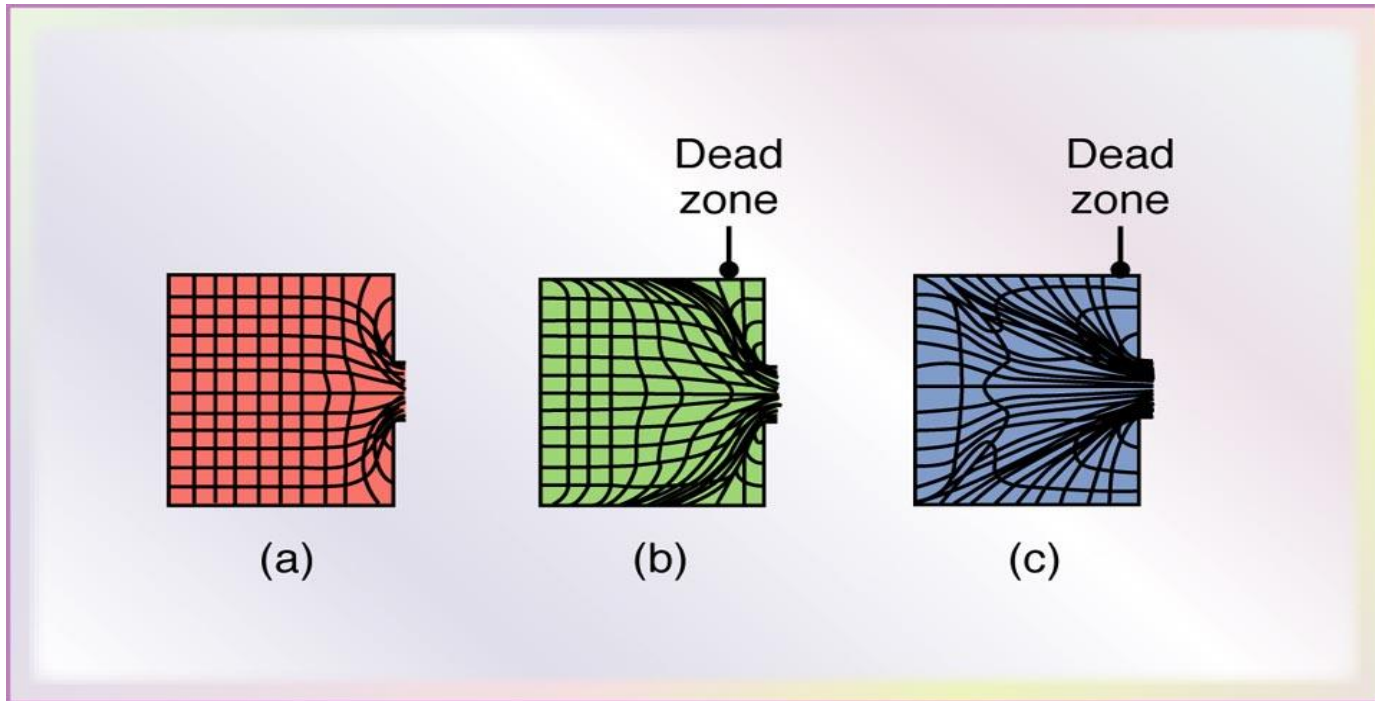
Process variables in direct extrusion. The die angle, reduction in cross-section, extrusion speed, billet temperature, and lubrication all affect the extrusion pressure.

Indipendent variables

- Die angle α
- Extrusion ratio (ratio of input to output cross-sectional areas) A_0/A_f
- Circumscribing circle diameter
- Shape factor
 - **Ratio of perimeter of shape to cross-sectional area**
 - **A circular shape has the minimum**
 - **A measure of the complexity of the extrusion**
- Billet temperature
- Ram speed
- Lubricant



Material flow



Types of metal flow in **extruding with square dies**. (a) Flow pattern obtained at low friction, or in indirect extrusion. (b) Pattern obtained with high friction at the billet-chamber interfaces. (c) Pattern obtained at high friction, or with cooling of the outer regions of the billet in the chamber. This type of pattern, observed in metals whose strength increases rapidly with decreasing temperature, leads to a defect known as pipe, or extrusion defect.



Frictional conditions at billet-container-die interfaces and thermal gradients in the billet

Process mechanics

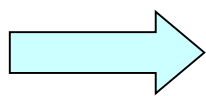
► Case of ideal deformation

Extrusion Ratio $R = \frac{A_0}{A_f}$

$$\varepsilon_1 = \ln\left(\frac{A_0}{A_f}\right) = \ln\left(\frac{L_f}{L_0}\right) = \ln R$$

$$Work = (A_0)(L_0)(u)$$

$$Work = FL_0 = pA_0L_0 \quad F: \text{ram force}$$



$$p = u = \int_0^{\varepsilon_1} \sigma d\varepsilon \quad \text{Extrusion Pressure at the Ram}$$

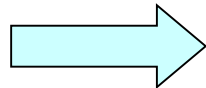
Process mechanics

► *Case of ideal deformation and friction (slab method)*

$$p = \bar{Y}_f \left(1 + \frac{\tan \alpha}{m} \right) \left[R^{m \cot \alpha} - 1 \right]$$

μ : friction at the die-billet interface

α : die angle


$$p = \bar{Y}_f \left(1.7 \ln R + \frac{2L}{D_0} \right)$$

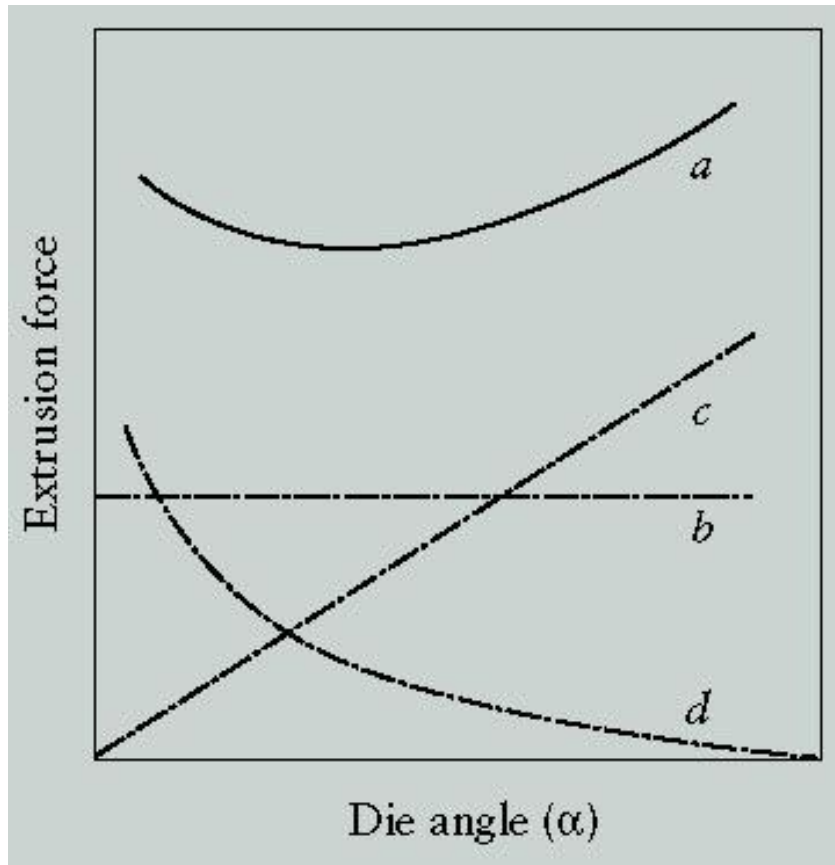
Hp: the frictional stress is equal to the shear yield stress; because of the dead metal zone, the material flows along a 45° “die angle”

► *Actual forces (also non-homogenous deformation)*

$$p = \bar{Y}_f (a + b \ln R)$$

where a and b are experimentally determined constants $a=0.8$; $b=1.2-1.5$

Optimal die angle



Schematic illustration of the **extrusion force as a function of the die angle**: (a) total force; (b) ideal force; (c) force required for redundant deformation (inhomogeneous deformation); (d) force required to overcome friction (the length of contact at the billet-die interface decreases).

Note that there is an optimum die angle where the total extrusion force is a minimum.

Cold extrusion

- More recent development (1940's)
- Includes some operations similar to forging

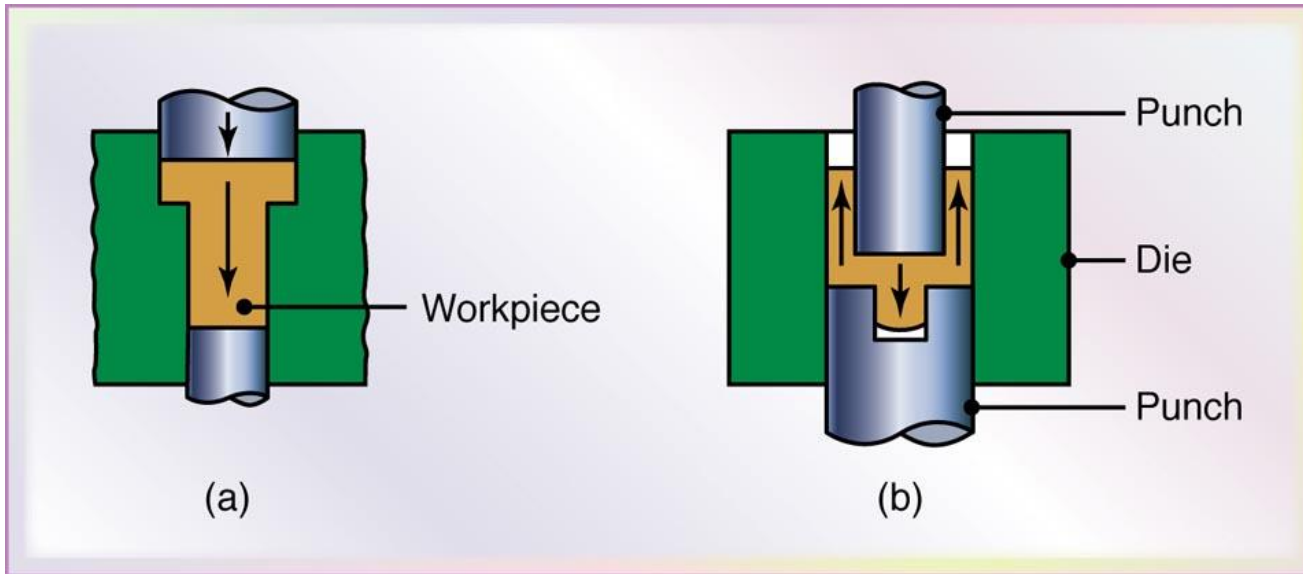
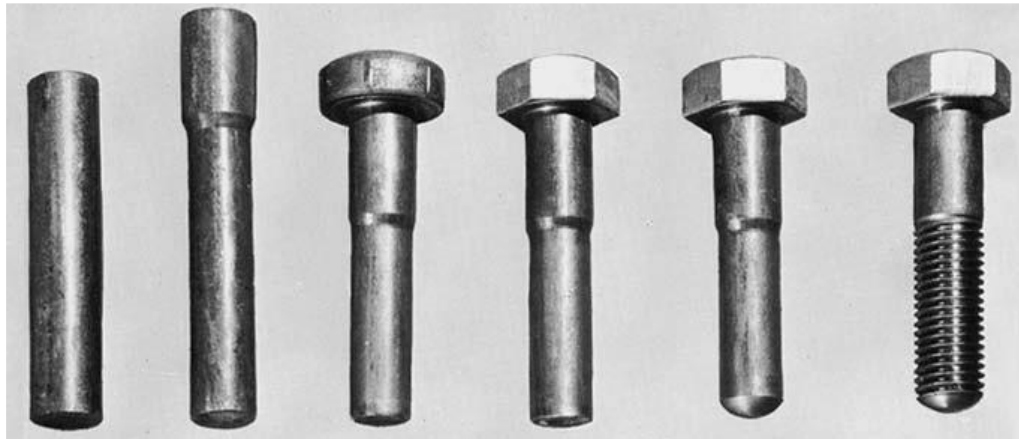
Advantages

- Improved mechanical properties
- Work hardening
- Good control of tolerances
- Improved surface finish
- Elimination of heating costs
- High production rates

Disadvantages

- Higher stresses require more expensive tooling and die material
- Difficult die design essential to success
- Lubrication is critical

Examples of cold extrusion



Hot extrusion

Advantages

- Lower stresses
- Sometimes the only way to extrude certain metals
 - e.g. titanium, refractory alloys, high strength alloys

Disadvantages

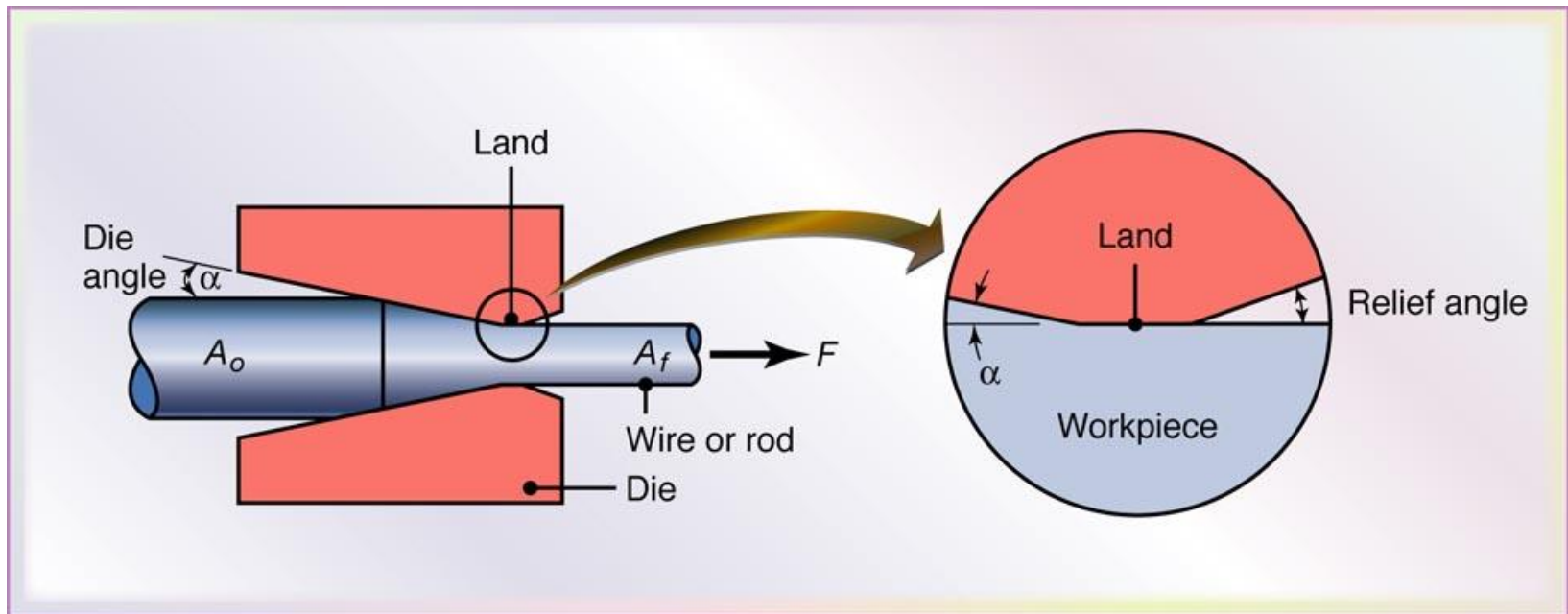
- Higher die wear
- Oxide film buildup results in non-uniform flow, inclusions and poor surface finish
- Cooling of the billet in the container results in non-uniform flow
- Distorted parts

Process temperature ranges

Material	Temp Range (°C)
Lead	200-250
Aluminum and alloys	375-475
Copper and alloys	650-975
Steels	875-1300
Refractory alloys	975-2200

Drawing process

- Like extrusion but the material is ***pulled*** out the orifice of the required shape instead of being pushed in.
- The resulting shape variety is more limited than in extrusion
 - **Rod** (larger cross sections)
 - **Wire** (smaller cross sections)



Advantages

- Very long product with non-flat cross-section than in extrusion - wire, rod (total length can exceed miles)
- Non circular cross sections can be produced, but uncommon

Disadvantages

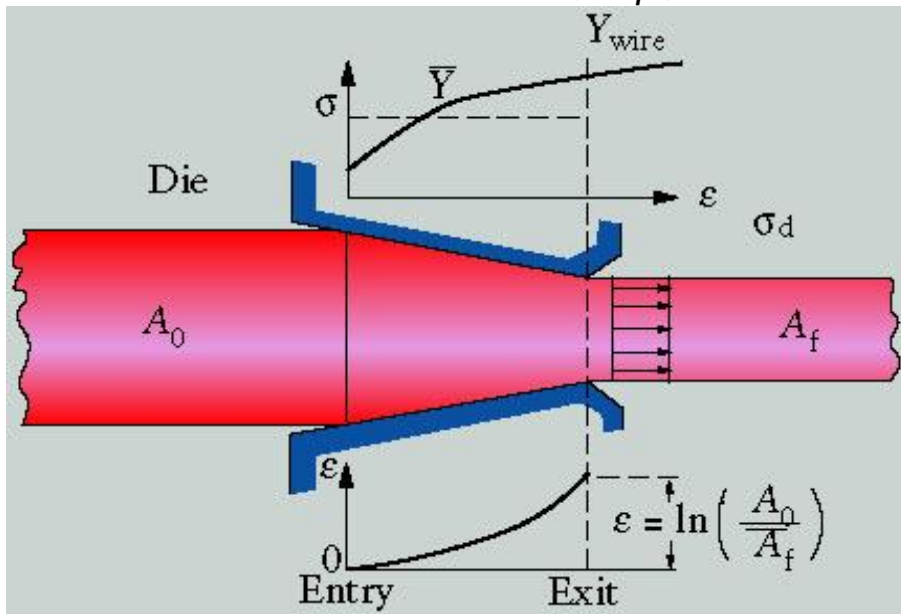
- Higher forces required
- If exceed tensile strength further deformation can be non-uniform
- Limited size reduction per pass (Maximum 63%)
- Need multiple dies and take up rolls

Mechanics of the drawing process

► Case of ideal deformation

$$s_d = u = \bar{Y}f \ln \left(\frac{A_0}{A_f} \right)$$

$$F = \bar{Y}f A_f \ln \left(\frac{A_0}{A_f} \right)$$



► Case of ideal deformation with friction

$$s_d = \bar{Y}f \left(1 + \frac{\tan a}{m} \right) \left[1 - \left(\frac{A_f}{A_0} \right)^{m \cot a} \right]$$

Variation in strain and flow stress in the deformation zone in drawing. Note that the strain increases rapidly toward the exit. The reason is that when the exit diameter is zero, the true strain reaches infinity. The point Y_{wire} represents the yield stress of the wire.

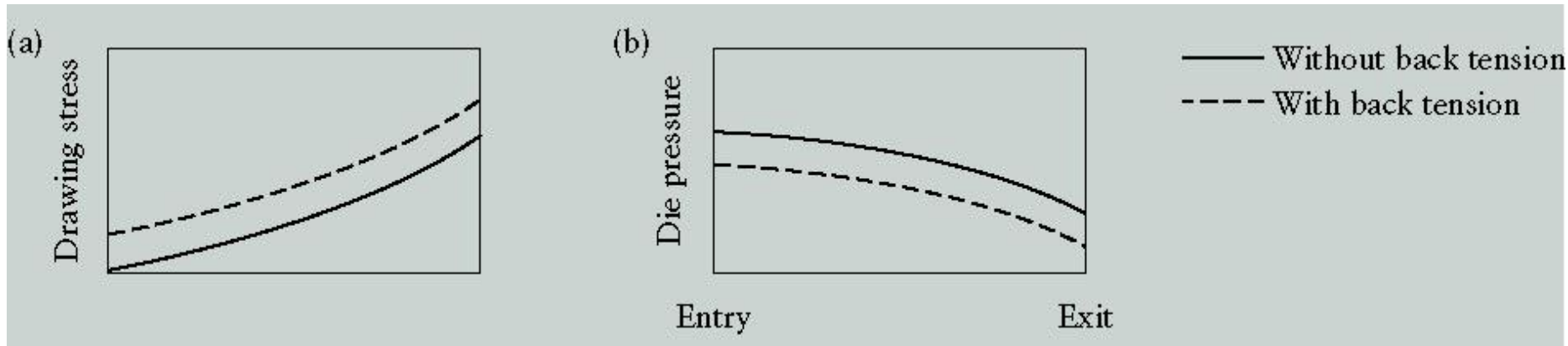
Die pressure

$$p = Y_f - S_d$$

σ_d : the tensile stress in the deformation zone at any diameter

Y_f : the material flow stress at any diameter

p : die pressure at any diameter along the die contact



Variation in the drawing stresses and die contact pressure along the deformation zone. Note that as the drawing stress increases, the die pressure decreases. Note the effect of back tension.

Maximum reduction per pass

Perfectly plastic material

Strain hardening material

Typical Wire Drawing Process Procedure

