Extrusion
- A cylindrical billet is forced through a die (‘push’)

Drawing
- The cross section of solid rod, wire, or tubing is reduced or changed in shape by pulling it through a die (‘pull’)
FIGURE 15.1 Schematic illustration of the direct-extrusion process.
Extrusion

- Large deformations can take place without fracture because material is under triaxial compression
- Produce products with constant cross section; cut to length
- A batch process; one length per billet
- Low tool costs; Economic for large & short production runs
- Perform cold or at elevated temperatures; depends on ductility of material
- Materials: Al, Cu, Steel, Mg, Pb, other
Extruded Products

- Railings for sliding doors
- Window frames
- Tubing (various, constant, cross sections)
- Aluminum ladder frames
- Structural & architectural shapes
- Brackets; Gears; Coat hangars
- Cold Extrusion (combine with forging)
  - Fasteners
  - Components for automobiles, bicycles, motorcycles, heavy machinery, transportation equipment
FIGURE 15.2 Extrusions and examples of products made by sectioning off extrusions. *Source:* Courtesy of Plymouth Extruded Shapes.
Extrusion Process

- **Direct (or Forward) Extrusion**
  - Billet in chamber is pushed through die by hydraulic ram

- **Indirect (or Reverse, Inverted, Backward) Extrusion**
  - The die moves toward the billet

- **Hydrostatic Extrusion**
  - Billet in chamber is surrounded by fluid

- **Lateral (or Side) Extrusion**

- **Impact Extrusion**
  - Punch descends rapidly on blank which is extruded backwards
FIGURE 15.3 Types of extrusion: (a) indirect; (b) hydrostatic; (c) lateral.
Figure 15.4  Process variables in direct extrusion. The die angle, reduction in cross section, extrusion speed, billet temperature, and lubrication all affect the extrusion pressure.
Extrusion Force

- Force, $F$, depends on:
  - Strength of billet material
  - Extrusion Ratio, $R$, $A_0/A_f$
  - Friction between billet and chamber & die surfaces
  - Process variables: temperature, velocity

$$F = A_0 k \ln(A_0/A_f) \quad \text{Eq. 15.1}$$

- The Extrusion constant, $k$, is determined experimentally, see Figure 15.5
FIGURE 15.5 Extrusion constant $k$ for various metals at different temperatures. *Source:* After P. Loewenstein.
Metal Flow in Extrusion

- Influences quality & mechanical properties of extruded product
- Material flows longitudinally
- Elongated grain structure
**FIGURE 15.6** 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.
Hot Extrusion

- Use higher temperatures to improve ductility & metal flow
- Can cause excessive die wear, result of abrasion from surface oxides
- Can have nonuniform deformation caused by cooling surfaces of billet and die
  - Improve by preheating die
- Surface oxides on product may be undesirable when good surface finish is important
- Can prevent extrusion of surface oxides by making the diameter of the dummy block a little smaller than the container; this keeps a thin shell ("skull") of oxides in the container
Figure 15.1

- Container liner
- Container
- Billet
- Die
- Die backer
- Extrusion
- Dummy block
- Pressing stem
<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>200–250</td>
</tr>
<tr>
<td>Aluminum and its alloys</td>
<td>375–475</td>
</tr>
<tr>
<td>Copper and its alloys</td>
<td>650–975</td>
</tr>
<tr>
<td>Steels</td>
<td>875–1300</td>
</tr>
<tr>
<td>Refractory alloys</td>
<td>975–2200</td>
</tr>
</tbody>
</table>
FIGURE 15.7 Typical extrusion–die configurations:
(a) die for nonferrous metals;
(b) die for ferrous metals;
(c) die for a T-shaped extrusion made of hot-work die steel and used with molten glass as a lubricant.

Source: (c) Courtesy of LTV Steel Company.
Die Design

- **Square dies (shear dies)**
  - Are used for nonferrous metals (Aluminum)
  - Develop dead-metal zones, causing a ‘die angle’ of metal flow
  - Have burnishing at the interface between the dead-metal zone and die angle; result is a bright surface finish
**FIGURE 15.8** Extrusion of a seamless tube
(a) using an internal mandrel that moves independently of the ram. (An alternative arrangement has the mandrel integral with the ram.)
(b) using a spider die (see Fig. 15.9) to produce seamless tubing.
FIGURE 15.9 (a) An extruded 6063-T6 aluminum-ladder lock for aluminum extension ladders. This part is 8 mm (5/16 in.) thick and is sawed from the extrusion (see Fig. 15.2). (b) through (d) Components of various dies for extruding intricate hollow shapes. 

Source: (b) through (d) after K. Laue and H. Stenger.
FIGURE 15.10
Poor and good examples of cross sections to be extruded. Note the importance of eliminating sharp corners and of keeping section thicknesses uniform.

Die Materials

- For hot extrusion:
  - Hot worked die steels
  - For simple shapes without severe stress gradients, may apply coatings (e.g. partially stabilized zirconia) to extend die life
Lubrication

- Useful in hot extrusion:
  - Material flow during extrusion
  - Surface finish & integrity
  - Product quality
  - Extrusion forces
- Glass is excellent lubricant for:
  - Steels
  - Stainless steels
  - High-temperature metals & alloys
- Glass applied as powder to billet surface, or
- Insert glass pad at die entrance; when heated, melted glass lubricates die surface
FIGURE 15.11
(a) Aluminum extrusion used as a heat sink for a printed circuit board, (b) Extrusion die and extruded heat sinks.
Source: Courtesy of Aluminum Extruders Council.
Cold Extrusion

- Uses slugs cut from cold finished or hot rolled bars, wire, or plates
- Smaller slugs (≤ 40 mm or 1.5”) are sheared; ends squared if necessary
- Larger slugs are machined to specific lengths
- Stresses on tool dies are very high
- Lubrication is critical, especially with steels
  - Apply phosphate-conversion coating on workpiece, followed by soap or wax (Sec. 34.10)
FIGURE 15.12
Two examples of cold extrusion. Thin arrows indicate the direction of metal flow during extrusion.
Cold Extrusion

- Force = $F = 1.7A_o Y_{avg} \dot{\varepsilon}$  
  Eq. 15.2

- $A_o$ is cross sectional area of blank
- $Y_{avg}$ is average flow stress of metal
- $\dot{\varepsilon}$ is true strain that piece undergoes
  
  $= \ln(A_o/A_f)$
Advantages Cold vs. Hot Extrusion

- Improved mechanical properties due to work hardening
- Good control of dimensional tolerances
- Improved surface finish
- Competitive production rates & costs
FIGURE 15.13  Production steps for a cold-extruded spark plug.

*Source:* Courtesy of National Machinery Company.
FIGURE 15.14
A cross section of the metal part in Fig. 15.13, showing the grain-flow pattern.

*Source:* Courtesy of National Machinery Company.
FIGURE 15.15
Schematic illustration of the impact-extrusion process. The extruded parts are stripped by the use of a stripper plate, because they tend to stick to the punch.
FIGURE 15.16
(a) Impact extrusion of a collapsible tube by the Hooker process.
(b) and (c) Two examples of products made by impact extrusion. These parts also may be made by casting, forging, or machining. The choice of process depends on the materials involved, part dimensions and wall thickness, and the properties desired. Economic considerations also are important in final process selection.
Hydrostatic Extrusion

- The pressure required in the chamber is supplied via a piston through an incompressible fluid medium surrounding the billet.
- The fluid in contact with die surfaces reduces friction.
- A cold process:
  - The viscosity of the fluids used (vegetable oils such as castor oil) does not change with heat.
- Can use to extrude brittle materials:
  - Ductility is increased.

Limited applications:
- Complex tooling; specialized equipment; uneconomic.
Extrusion Defects

- **Surface cracking**
  - High extrusion temperature, friction, speed cause high surface temperatures
  - Cracks are intergranular (along grain boundaries)
  - Caused by *hot shorting*: local cooling of constituents or impurities at grain boundaries
  - May also occur at lower temperatures
    - Caused by sticking of extrusion along die land
    - Sticking raises pressure
    - Cyclic action produces circumferential cracks, "bamboo effect"
Pipe (aka *pipe defect, tailpipe, fishtailing*)

- Metal-flow pattern in (c) tends to draw surface oxides and impurities toward the centre of the billet
- Can be minimized
  - By modifying flow pattern to be more uniform
    - Control friction
    - Minimize temperature gradients
  - Improve billet surface by machining or etching to remove scale & surface impurities prior to extrusion
Extrusion Defects (continued)

Internal Cracking

- Aka *centre cracking, centre-burst, arrowhead fracture, chevron cracking*
- These cracks in the centre of the extrusion are attributed to a state of hydrostatic tensile stress at the centreline in the deformation zone
- Increases with increasing die angle
- Increases with increasing amount of impurities
- Decreases with increasing extrusion ratio & friction
FIGURE 15.17  (a) Chevron cracking (central burst) in extruded round steel bars. Unless the products are inspected, such internal defects may remain undetected and later cause failure of the part in service. This defect can also develop in the drawing of rod, of wire, and of tubes. (b) Schematic illustration of rigid and plastic zones in extrusion. The tendency toward chevron cracking increases if the two plastic zones do not meet. Note that the plastic zone can be made larger either by decreasing the die angle, by increasing the reduction in cross section, or both. Source: After B. Avitzur.
Extrusion Equipment

- Horizontal Hydraulic Press
  - Can control stroke & speed
  - Can apply constant force over long stroke

- Vertical Hydraulic Press
  - Used for cold extrusion
  - Lower capacity, smaller footprint
Figure 15.18  General view of a 9-MN (1000-ton) hydraulic-extrusion press. Source: Courtesy of Jones & Laughlin Steel Corporation.
Drawing

- Drawn rods used for:
  - Shafts, spindles, small pistons
  - Raw material for
    - Rivets, Bolts, Screws, Nails
- Round and shaped cross sections
- ‘Rod’ is larger diameter than ‘wire’
- ‘Wire’ is reduced at least once from ‘rod’
- The cross section of a long rod or wire is reduced by pulling (or ‘drawing’) through a "draw die"
FIGURE 15.19 Process variables in wire drawing. The die angle, the reduction in crosssectional area per pass, the speed of drawing, the temperature, and the lubrication all affect the drawing force, $F$. 
Drawing Force

Frictionless

\[ F = Y_{avg} A_f \ln(A_o/A_f) \]  \hspace{1cm} \text{Eq. 15.3}

Friction & Redundant Work

\[ F = Y_{avg} A_f [(1+\mu/\alpha)\ln(A_o/A_f)+2\alpha/3] \]  \hspace{1cm} \text{Eq. 15.4}

\( \alpha \) is die angle, in radians
Drawing Force

- Drawing force increases as reduction increases.
- Maximum ideal (no friction) theoretical reduction in cross-sectional area per pass is 63%.
- There is an optimum die angle for minimum force for a certain reduction in diameter.
FIGURE 15.20  Examples of tube-drawing operations, with and without an internal mandrel. Note that a variety of diameters and wall thicknesses can be produced from the same initial tube stock (which has been made by other processes).
Drawing Practice

- Usually, the smaller the initial cross section, the smaller the reduction per pass
  - Fine wires: 15 – 25% reduction
  - Larger wires: 20 – 45% reduction
- Usually a ‘cold’ process (room temperature)
- *Sizing Pass*
  - A small reduction on rods to improve finish & dimensional accuracy
  - Results in non-uniform deformation across section
Drawing Practice

- **Pointing** – A ‘push’ operation to create a feathered tip at start to be threaded through dies

- **Drawing speeds:**
  - Depend on material & % reduction
  - High speeds may raise temperatures, affecting properties

- **Temper:**
  - A designation for hardness (1/4 hard, ½ hard) due to work hardening
  - May need to anneal (soften) metal between passes to maintain ductility
Bundle Drawing

- Draw many (100s) wires together
- To increase productivity, esp. fine wires
- Keep wires separated by suitable metallic material, lower chemical resistance; later leached
- Produces polygonal x-section

- Can alternatively produce fine wires of different size & shape
FIGURE 15.21  Terminology pertaining to a typical die used for drawing a round rod or wire.
Die Design

- Die angles usually 6° to 15°
- Two angles: entering & approach
- Land
  - Sets final diameter of drawn wire
  - Maintains diameter with wear

Profile Drawing (non-round)

- Requires a set of dies,
- Involves stages of deformation
- May be one die or several in a retaining ring
- Use computer-aided-design techniques
FIGURE 15.22 Tungsten-carbide die insert in a steel casing. Diamond dies used in drawing thin wire are encased in a similar manner.
Lubrication

- To improve die life
- To improve product surface finish
- To reduce drawing forces
- To reduce temperature
- Especially critical at mandrel/tube interface for tube drawing
- Commonly use phosphate coatings
Methods of Lubrication

Wet drawing
- Dies & rod are immersed in lubricant

Dry drawing
- Surface of rod is coated with lubricant in a stuffing box prior to drawing through die

Metal coating
- Coat rod/wire with soft metal (Cu, Sn) that acts as solid lubricant

Ultrasonic Vibration
- Vibrate dies & mandrels; Vibrations reduce forces, improve surface finish & die life; allow greater reductions
Drawing Defects

- **Seams**
  - Longitudinal scratches or folds
  - May open up in later forming operations
  - Cause serious quality-control problems

- **Surface defects (scratches, die marks)**
  - Improper selection of process parameters
  - Poor lubrication
  - Poor die condition (e.g. scratches)
Residual Stress

- Caused by non-uniform deformation during cold drawing
- Light reductions
  - Longitudinal-surface residual stresses are compressive; bulk is in tension
  - Improve fatigue life
- Heavier reductions
  - Surface stresses in tension; bulk in compression
- Can be significant cause of stress-corrosion cracking over time
- May cause part to *warp* if a layer is removed (as part of a forming operation such as slitting, machining, grinding)
FIGURE 15.23
Cold drawing of an extruded channel on a draw bench to reduce its cross section. Individual lengths of straight rods or of cross sections are drawn by this method.
FIGURE 15.24 An illustration of multistage wire drawing typically used to produce copper wire for electrical wiring. 

*Source:* After H. Auerswald.
Summary

- **Extrusion**: Push billet through die to reduce x-sect; Hot for lower force, better ductility
- **Extrusion Factors**: Die design; extrusion ratio; billet temperature; lubrication; speed. Cold improves some mechanical properties
- **Drawing (rod, wire, tube)**: pulling through die(s); usually round; mandrels for tubes
- **Drawing Factors**: Die design, % reduction/pass, die materials, lubricants
- External/internal defects minimized by die angle, % reduction, material quality