Metal Extrusion and Drawing Processes and Equipment

Ch 15
Extrusion and drawing involve, respectively, pushing or pulling a material through a die basically for the purpose of reducing or changing its cross-sectional area.

Extrusion and drawing have numerous applications in the manufacture of continuous as well as discrete products from a wide variety of metals and alloys.

In extrusion, a cylindrical billet is forced through a die in a manner similar to squeezing toothpaste from a tube or extruding Play-Doh, in various cross sections in a toy press.
Metal Extrusion

Typical products made by extrusion are railings for sliding doors, window frames, tubing having various cross sections, aluminum ladder frames, and numerous structural and architectural shapes. Extrusions can be cut into desired lengths, which then become discrete parts, such as brackets, gears, and coat hangers.

Commonly extruded materials are aluminum, copper, steel, magnesium, and lead; other metals.

Depending on the ductility of the material, extrusion is carried out at room or elevated temperatures. Extrusion at room temperature often is combined with forging operations, in which case it generally is known as cold extrusion.

Extrusions and examples of products made by sectioning off extrusions.
Drawing

In drawing, the cross section of solid rod, wire, or tubing is reduced or changed in shape by pulling it through a die. Drawn rods are used for shafts, spindles, and small pistons and as the raw material for fasteners (such as rivets, bolts, and screws). In addition to round rods, various profiles can be drawn.

The distinction between the terms rod and wire is somewhat arbitrary, with rod taken to be larger in cross section than wire. In industry, wire generally is defined as a rod that has been drawn through a die at least once, or its diameter is small enough so that it can be coiled.

Wire drawing involves smaller diameters than rod drawing, with sizes down to 0.01 mm for magnet wire and even smaller for use in very low current fuses.
The Extrusion Process

There are three basic types of extrusion. In the most common process (called direct or forward extrusion), a billet is placed in a chamber (container) and forced through a die opening by a hydraulically driven ram (pressing stem or punch),

The die opening may be round, or it may have various shapes, depending on the desired profile.

The function of the dummy block shown in the figure is to protect the tip of the pressing stem (punch), particularly in hot extrusion.

Other Types of extrusion: (a) indirect; (b) hydrostatic; (c) lateral.
Types of extrusion

**Indirect extrusion** has the advantage of having no billet-container friction, since there is no relative motion. Thus, indirect extrusion is used on materials with very high friction, such as high strength steels.

In **hydrostatic extrusion** the billet is smaller in diameter than the chamber (which is filled with a fluid), and the pressure is transmitted to the fluid by a ram. The fluid pressure results in triaxial compressive stresses acting on the workpiece and thus improved formability; also, there is much less workpiece-container friction than in direct extrusion.

A less common type of extrusion is **lateral (or side) extrusion**
Extrusion Force

the geometric variables in extrusion are the die angle, $\alpha$, and the ratio of the cross-sectional area of the billet to that of the extruded product, $A_0/A_f$, called the extrusion ratio, $R$. Other variables are the temperature of the billet, the speed at which the ram travels, and the type of lubricant used.

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

The force required for extrusion depends on (a) the strength of the billet material, (b) the extrusion ratio, (c) the friction between the billet and the chamber and die surfaces, and (d) process variables, such as the temperature of the billet and the speed of extrusion.

The extrusion force, $F$, can be estimated from the formula

$$F = A_o k \ln\left(\frac{A_o}{A_f}\right),$$

where $k$ is the extrusion constant (which is determined experimentally) and $A_o$ and $A_f$ are the billet and extruded product areas, respectively.

Extrusion constant $k$ for various metals at different temperatures.
EXAMPLE 15.1 Calculation of Force in Hot Extrusion

A round billet made of 70–30 brass is extruded at a temperature of 675°C. The billet diameter is 125 mm, and the diameter of the extrusion is 50 mm. Calculate the extrusion force required.
Metal Flow in Extrusion.

The metal flow pattern in extrusion, as in other forming processes, is important because of its influence on the quality and the mechanical properties of the extruded product.

**typical flow patterns for the case of direct extrusion with square dies (a 90° die angle)**

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.
**Process Parameters**

Because they have high ductility, wrought aluminum, capper; and magnesium and their alloys, as well as steels and stainless steels, are extruded with relative ease into numerous shapes.

In practice, extrusion ratios, $R$, usually range from about 10 to 100. They may be higher for special applications (400 for softer nonferrous metals) or lower for less ductile materials, although the ratio usually has to be at least 4 to deform the material plastically through the bulk of the workpiece.

Extruded products usually are less than 7.5 m long because of the difficulty in handling greater lengths, but they can be as long as 30 m. Ram speeds range up to 0.5 m/s. Generally, lower speeds are preferred for aluminum, magnesium, and copper, higher speeds for steels, titanium, and refractory alloys. Dimensional tolerances in extrusion are usually in the range from $\pm 0.25$ to 2.5 mm, and they increase with increasing cross section.
The presence of a die angle causes a small portion of the end of the billet to remain in the chamber after the operation has been completed. This portion (called scrap or the butt end) subsequently is removed by cutting off the extrusion at the die exit and removing the scrap from the chamber. Alternatively, another billet or a graphite block may be placed in the chamber to extrude the piece remaining from the previous extrusion.

In coaxial extrusion, or cladding, coaxial billets are extruded together provided that the strength and ductility of the two metals are compatible.

An example is copper clad with silver. Stepped extrusions are produced by extruding the billet partially in one die and then in one or more larger dies.
Hot Extrusion

For metals and alloys that do not have sufficient ductility at room temperature, or in order to reduce the forces required, extrusion is carried out at elevated temperatures.

<table>
<thead>
<tr>
<th>Typical Extrusion Temperature Ranges for Various Metals and Alloys</th>
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<tbody>
<tr>
<td>°C</td>
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<tr>
<td>Lead</td>
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<tr>
<td>Aluminum and its alloys</td>
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<tr>
<td>Copper and its alloys</td>
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<tr>
<td>Steels</td>
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<tr>
<td>Refractory alloys</td>
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As in all other hot-working operations, hot extrusion has special requirements because of the high operating temperatures. For example, die wear can be excessive, and cooling of the surfaces of the hot billet (in the cooler chamber) and the die can result in highly nonuniform deformation.
Hot Extrusion

To reduce cooling of the billet and to prolong die life, extrusion dies may be preheated, as is done in hot-forging operations. Because the billet is hot, it develops an oxide film, unless it is heated in an inert-atmosphere furnace. Oxide films can be abrasive and can affect the flow pattern of the material. Their presence also results in an extruded product that may be unacceptable when good surface finish is important. In order to avoid the formation of oxide films on the hot extruded product, the dummy block placed ahead of the ram is made a little smaller in diameter than the container. As a result, a thin shell (skull) consisting mainly of the outer oxidized layer of the billet is left in the container. The skull is removed later from the chamber.

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.
Die Design

Die design requires considerable experience.

Tubing is extruded from a solid or hollow billet. Wall thickness is usually limited to 1 mm for aluminum, 3 mm for carbon steels, and 5 mm for stainless steels.

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 to produce seamless tubing.
Hollow cross sections can be extruded by welding-chamber methods and using various dies known as a porthole die, spider die, and bridge die.

(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 (b) through (d). Components of various dies for extruding intricate hollow shapes.
Die Design

Some guidelines for proper die design in extrusion are illustrated. Note the (a) importance of symmetry of cross section, (b) avoidance of sharp corners, and (c) avoidance of extreme changes in die dimensions within the cross section.

![Diagram showing poor and good examples of cross sections to be extruded. Note the importance of eliminating sharp corners and of keeping section thicknesses uniform.](image)

**Poor**
- Sharp outside corner
- Sharp inside corner
- Inadequate section thickness

**Knife edge**
- Unbalanced die tongue
- Unbalanced section wall
- Unbalanced voids

**Good**
- More balanced die tongue; no sharp corners
- Adequate, balanced wall thickness
- Balanced voids

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

Die materials for hot extrusion usually are hot-worked die steels. Coatings (such as partially stabilized zirconia) may be applied to the dies to extend their life. Partially stabilized zirconia dies also are used for hot extrusion of tubes and rods.

However, they are not suitable for making dies for extruding complex shapes, because of the severe stress gradients developed in the die, which may lead to their premature failure.

Lubrication.

Lubrication is important in hot extrusion because of its effects on (a) material flow during extrusion, (b) surface finish and integrity, (c) product quality, and (d) extrusion forces.

For metals that have a tendency to stick to the container and the die, the billet can be enclosed in a thin-walled container, or jacket, made of a softer and lower strength metal, such as copper or mild steel. This procedure is called jacketing or canning. In addition to acting as a low-friction interface, the jacket prevents contamination of the billet by the environment. Also, if the billet material is toxic or radioactive, the jacket prevents it from contaminating the environment.
Example of hot extrusion Manufacture of Aluminum Heat Sinks

Aluminum is used widely to transfer heat for both cooling and heating applications because of its very high thermal conductivity. In fact, on a weight-to-cost basis, no other material conducts heat as economically as does aluminum.

(a) Aluminum extrusion used as a heat sink for a printed circuit board, (b) Extrusion die and extruded heat sinks.
Cold Extrusion

Cold extrusion is a general term that often denotes a combination of operations, such as direct and indirect extrusion and forging.

The cold-extrusion process uses slugs cut from cold-finished or hot-rolled bars, wire, or plates. Slugs that are less than about 40 mm in diameter are sheared (cropped), and if necessary, their ends are squared off by processes such as upsetting, machining, or grinding.

Two examples of cold extrusion. Thin arrows indicate the direction of metal flow during extrusion.
The force, $F$, in cold extrusion may be estimated from the formula

$$F = 1100A_o Y_{avg} \epsilon,$$

where $A_o$ is the cross-sectional area of the blank, $Y_{avg}$ is the average flow stress of the metal, and $\epsilon$ is the true strain that the piece undergoes based on its original and final cross-sectional area; i.e., $\ln(A_o/A_f)$. For example, assume that a round slug 10 mm in diameter and made of a metal with $Y_{avg} = 350$ MPa is reduced to a final diameter of 7 mm by cold extrusion. Then the force would be

$$F = 1100(\pi)(10^2/4)(350)[\ln(10/7)^2] = 21.6 \text{ MN}.$$
Cold extrusion has the following advantages over hot extrusion:

Improved mechanical properties resulting from work hardening, provided that the heat generated by plastic deformation and friction does not recrystallize the extruded metal.

Good control of dimensional tolerances, reducing the need for subsequent machining or finishing operations.

Improved surface finish, due partly to the absence of an oxide film and provided that lubrication is effective.

Production rates and costs that are competitive with those of other methods of producing the same part, such as machining. Some machines are capable of producing more than 2000 parts per hour.

The magnitude of the stresses on the tooling in cold extrusion, however, is very high (especially with steel and specialty-alloy work pieces), being on the order of the hardness of the work piece material. The punch hardness usually ranges between 60 and 65 HRC and the die hardness between 58 and 62 HRC. Punches are a critical component, as they must possess not only sufficient strength, but also sufficient toughness and resistance to wear and fatigue failure.
Production steps for a cold-extruded spark plug.

A cross section of the metal part showing the grain-flow pattern.
Impact Extrusion

Impact extrusion is similar to indirect extrusion, and the process often is included in the cold-extrusion category. The punch descends rapidly on the blank (slug), which is extruded backwards.

Most nonferrous metals can be impact extruded in vertical presses and at production rates as high as two parts per second.

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.
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.
Extrusion Defects

Depending on workpiece material condition and process variables, extruded products can develop several types of defects that can affect significantly their strength and product quality.

There are three principal extrusion defects: surface cracking, pipe, and internal cracking.

Surface Cracking. If extrusion temperature, friction, or speed is too high, surface temperatures can rise significantly, which may cause surface cracking and tearing (fir tree cracking or speed cracking). These cracks are intergranular (i.e., along the grain boundaries; and usually are caused by hot shortness).

This situation can be avoided by lowering the billet temperature and the extrusion speed.

Surface cracking also may occur at lower temperatures, where it has been attributed to periodic sticking of the extruded product along the die land. Because of the similarity in appearance to the surface of a bamboo stem, it is known as a bamboo defect.
Pipe. The type of metal-flow pattern in extrusion tends to draw surface oxides and impurities toward the center of the billet—much like a funnel. This defect is known as pipe defect, tailpipe, or fishtailing. As much as one-third of the length of the extruded product may contain this type of defect and thus has to be cut off as scrap.

Piping can be minimized by modifying the flow pattern to be more uniform, such as by controlling friction and minimizing temperature gradients. Another method is to machine the billet's surface prior to extrusion, so that scale and surface impurities are removed. These impurities also can be removed by the chemical etching of the surface oxides prior to extrusion.
Extrusion Defects

**Internal Cracking.** The center of the extruded product can develop cracks, called center cracking, center-burst, arrowhead fracture, or chevron cracking.

(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. 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.
Extrusion Equipment

The basic equipment for extrusion is a horizontal hydraulic press. These presses are suitable for extrusion because the stroke and speed of the operation can be controlled, depending on the particular application. They are capable of applying a constant force over a long stroke.

Hydraulic presses with a ram-force capacity as high as 120 MN have been built, particularly for hot extrusion of large-diameter billets.
The Drawing Process

In drawing, the cross section of a long rod or wire is reduced or changed by pulling (hence the term drawing) it through a die called a draw die.

Thus, the difference between drawing and extrusion is that in extrusion the material is pushed through a die, whereas in drawing it is pulled through it.

Process variables in wire drawing. The die angle, the reduction in cross sectional area per pass, the speed of drawing, the temperature, and the lubrication all affect the drawing force, $F$. 
Drawing Force

Drawing Force. The expression for the drawing force, \( F \), under ideal and frictionless conditions is similar to that for extrusion and is given by the equation

\[
F = Y_{\text{avg}} A_f \ln \left( \frac{A_o}{A_f} \right),
\]

where \( Y_{\text{avg}} \) is the average true stress of the material in the die gap. Because more work has to be done to overcome friction, the force increases with increasing friction. Furthermore, because of the nonuniform deformation that occurs within the die zone, additional energy (known as the redundant work of deformation) is required. Although various equations have been developed to estimate the force (described in greater detail in advanced texts), a useful formula that includes friction and the redundant work is

\[
F = Y_{\text{avg}} A_f \left[ \left( 1 + \frac{\mu}{\alpha} \right) \ln \left( \frac{A_o}{A_f} \right) + \frac{2}{3} \alpha \right],
\]

where \( \alpha \) is the die angle in radians.
As can be seen from these equations, the drawing force increases as reduction increases. However, there has to be a limit to the magnitude of the force, because when the tensile stress reaches the yield stress of the metal being drawn, the workpiece will simply yield and, eventually, break. It can be shown that, ideally and without friction, the maximum reduction in cross-sectional area per pass is 63%. Thus, a 10-mm-diameter rod can be reduced (at most) to a diameter of 6.1 mm in one pass without failure.

It can be shown that, for a certain reduction in diameter and a certain frictional condition, there is an optimum die angle at which the drawing force is a minimum. Often, however, the die force is not the major product quality concern, and the actual die angle may deviate from this value.
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

As in all metalworking processes, successful drawing requires careful selection of process parameters. In drawing, reductions in the cross-sectional area per pass range up to about 45%.

Usually, the smaller the initial cross section, the smaller the reduction per pass. Fine wires usually are drawn at 15 to 25\% reduction per pass and larger sizes at 20 to 45\%.

Reductions of higher than 45\% may result in lubricant breakdown, leading to surface-finish deterioration. Although most drawing is done at room temperature, drawing large solid or hollow sections can be done at elevated temperatures in order to reduce forces.

A light reduction (sizing pass) also may be taken on rods to improve their surface finish and dimensional accuracy. However, because they basically deform only the surface layers, light reductions usually produce highly nonuniform deformation of the material and its microstructure. Consequently, the properties of the material will vary with location within the cross section.
Drawing Practice

A rod or wire has to have its tip reduced in cross section in order to be fed through the die opening and be pulled. This typically is done by swaging the tip of the rod or wire; this operation is called pointing.

Drawing speeds depend on the material and on the reduction in cross-sectional area. They may range from 1 to 2.5 m/s for heavy sections to as much as 50 m/s for very fine wire, such as that used for electromagnets. Because the product does not have sufficient time to dissipate the heat generated, temperatures can rise substantially at high drawing speeds and can have detrimental effects on product quality.

Bundle Drawing

Although very fine wire can be produced by drawing, the cost can be high. One method employed to increase productivity is to draw many wires (a hundred or more) simultaneously as a bundle. The wires are separated from one another by a suitable metallic material with similar properties, but lower chemical resistance (so that it subsequently can be leached out from the drawn-wire surfaces). These wires are then used in applications such as electrically conductive plastics, heat-resistant and electrically conductive textiles, filter media, radar camouflage, and medical implants. The wires produced can be as small as 4 /i-m in diameter and can be made from such materials as stainless steels, titanium, and high-temperature alloys.
Die Design

Die angles usually range from 6° to 15°. Note, however, that there are two angles (entering and approach) in a typical die. The purpose of the bearing surface (land) is to set the final diameter of the product (sizing) and to maintain this diameter even with wear on the die-workpiece interface.

A set of dies is required for profile drawing, which involves various stages of deformation to produce the final profile. The dies may be made in one piece or (depending on the complexity of the cross-sectional profile) with several segments held together in a retaining ring.

Terminology pertaining to a typical die used for drawing a round rod or wire.
Die Materials

Die materials for drawing typically are tool steels and carbides. For hot drawing, cast-steel dies are used because of their high resistance to wear at elevated temperatures.

**Diamond** dies are used for drawing fine wire with diameters ranging from 2 µm to 1.5 mm. They may be made from a single-crystal diamond or in polycrystalline form with diamond particles in a metal matrix (compacts). Because of their very low tensile strength and toughness, carbide and diamond dies typically are used as inserts or nibs, which are supported in a steel casing.
Lubrication

Proper lubrication is essential in drawing in order to improve die life and product surface finish and to reduce drawing forces and temperature. Lubrication is critical, particularly in tube drawing, because of the difficulty of maintaining a sufficiently thick lubricant film at the mandrel-tube interface. In the drawing of rods, a common method of lubrication uses phosphate coatings.

The following are the basic methods of lubrication used in wire drawing:
• Wet drawing, in which the dies and the rod are immersed completely in the lubricant
• Dry drawing, in which the surface of the rod to be drawn is coated with a lubricant by passing it through a box filled with the lubricant (stuffing box)
• Metal coating, in which the rod or wire is coated with a soft metal, such as copper or tin, that acts as a solid lubricant
• Ultrasonic vibration of the dies and mandrels; in this process, vibrations reduce forces, improve surface finish and die life, and allow larger reductions per pass without failure.
Drawing Defects and Residual Stresses

Typical defects in a drawn rod or wire are similar to those observed in extrusion, especially center cracking.

Another major type of defect in drawing is seams, which are longitudinal scratches or folds in the material. Seams may open up during subsequent forming operations (such as upsetting, heading, thread rolling, or bending of the rod or wire), and they can cause serious quality-control problems. Various other surface defects (such as scratches and die marks) also can result from improper selection of the process parameters, poor lubrication, or poor die condition.

Because they undergo nonuniform deformation during drawing, cold-drawn products usually have residual stresses.

For light reductions, such as only a few percent, the longitudinal-surface residual stresses are compressive (while the bulk is in tension) and fatigue life is thus improved. Conversely, heavier reductions induce tensile surface stresses (while the bulk is in compression). Residual stresses can be significant in causing stress-corrosion cracking of the part over time. Moreover, they cause the component to warp if a layer of material subsequently is removed.
Drawing Equipment

Although it is available in several designs, the equipment for drawing is basically of two types: the draw bench and the bull block.

A draw bench contains a single die, and its design is similar to that of a long, horizontal tension-testing machine.

The pulling force is supplied by a chain drive or is activated hydraulically. Draw benches are used for a single-length drawing of straight rods and tubes with diameters larger than 20 mm and lengths up to 30 m. Machine capacities reach 1.3 MN of pulling force with a speed range of 6 to 60 m/min.
Drawing Equipment

Very long rods and wire (many kilometers) and wire of smaller cross sections, usually less than 13 mm, are drawn by a rotating drum (bull block or capstan).

The tension in this setup provides the force required for drawing the wire, usually through multiple dies (tandem drawing).

An illustration of multistage wire drawing typically used to produce copper wire for electrical wiring.