University of Basrah
College of Engineering
Mechanical Engineering Department
Lecture Notes of MANUFACTURING PROCESSES (ME337), 3rd Year (2015-2016)
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Chapter Eight: Metal Forming - Extrusion

8.1. Introduction

Extrusion is a compression process in which the work metal is forced to flow through a die opening to produce a desired cross-sectional shape. The process can be likened to squeezing toothpaste out of a toothpaste tube. Extrusion dates from around 1800 (Historical Note 19.3). There are several advantages of the modern process: (1) a variety of shapes are possible, especially with hot extrusion; (2) grain structure and strength properties are enhanced in cold and warm extrusion; (3) fairly close tolerances are possible, especially in cold extrusion; and (4) in some extrusion operations, little or no wasted material is created. However, a limitation is that the cross section of the extruded part must be uniform throughout its length.

8.1. Historical Note

Extrusion as an industrial process was invented around 1800 in England, during the Industrial Revolution when that country was leading the world in technological innovations. The invention consisted of the first hydraulic press for extruding lead pipes. An important step forward was made in Germany around 1890, when the first horizontal extrusion press was built for extruding metals with higher melting points than lead. The feature that made this possible was the use of a dummy block that separated the ram from the work billet.

8.3. Types of Extrusion

Extrusion is carried out in various ways. One important distinction is between direct extrusion and indirect extrusion. Another classification is by working temperature: cold, warm, or hot extrusion. Finally, extrusion is performed as either a continuous process or a discrete process.

- **Direct Versus Indirect Extrusion** Direct extrusion (also called ***forward extrusion***) is illustrated in Figure 8.1.A metal billet is loaded into a container, and a ram compresses the material, forcing it to flow through one or more openings in a die at the opposite end of the container. As the ram approaches the die, a small portion of the billet remains that cannot be forced through the die opening. This extra portion, called the ***butt***, is separated from the product by cutting it just beyond the exit of the die.

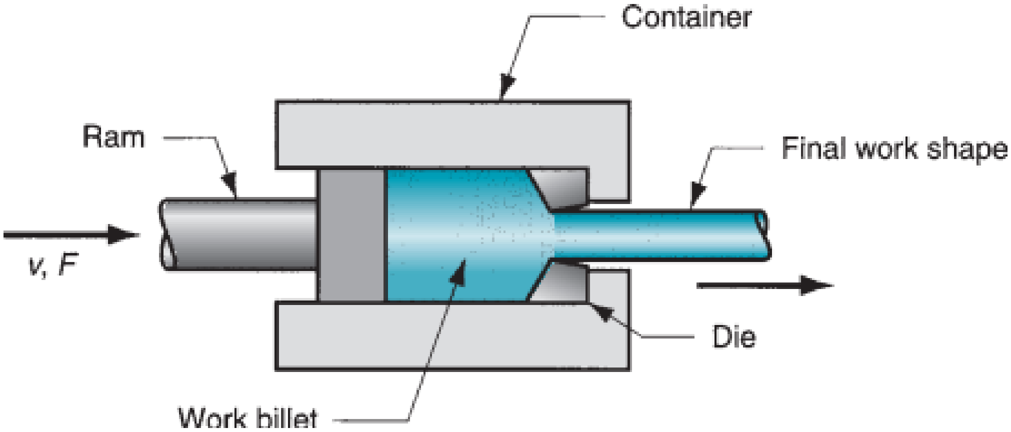

Figure 8.1 Direct Extrusion

One of the problems in direct extrusion is the significant friction that exists between the work surface and the walls of the container as the billet is forced to slide toward the die opening. This friction causes a substantial increase in the ram force required in direct extrusion. In hot extrusion, the friction problem is aggravated by the presence of an oxide layer on the surface of the billet. This oxide layer can cause defects in the extruded product. To address these problems, a dummy block is often used between the ram and the work billet. The diameter of the dummy block is slightly smaller than the billet diameter, so that a narrow ring of work metal (mostly the oxide layer) is left in the container, leaving the final product free of oxides.

Hollow sections (e.g., tubes) are possible in direct extrusion by the process setup in Figure 8.2. The starting billet is prepared with a hole parallel to its axis. This allows passage of a mandrel that is attached to the dummy block. As the billet is compressed, the material is forced to flow through the clearance between the mandrel and the die opening. The resulting cross section is tubular. Semi-hollow cross-sectional shapes are usually extruded in the same way.

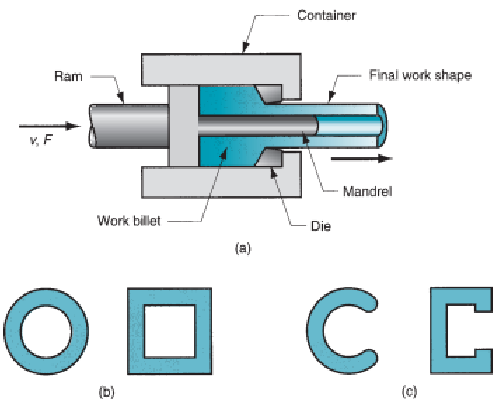

Figure 8.2 (a) Direct Extrusion to Produce a Hollow or Semi-hollow Cross Section (b) Hollow and (c) Semi-hollow Cross Sections.

The starting billet in direct extrusion is usually round in cross section, but the final shape is determined by the shape of the die opening. Obviously, the largest dimension of the die opening must be smaller than the diameter of the billet.

In ***indirect extrusion***, also called ***backward extrusion*** and ***reverse extrusion***, Figure 8.3 (a), the die is mounted to the ram rather than at the opposite end of the container. As the ram penetrates into the work, the metal is forced to flow through the clearance in a direction opposite to the motion of the ram. Since the billet is not forced to move relative to the container, there is no friction at the container walls, and the ram force is therefore lower than in direct extrusion. Limitations of indirect extrusion are imposed by the lower rigidity of the hollow ram and the difficulty in supporting the extruded product as it exits the die.

In direct extrusion can produce hollow (tubular) cross sections, as in Figure 8.3(b). In this method, the ram is pressed into the billet, forcing the material to flow around the ram and take a cup shape. There are practical limitations on the length of the extruded part that can be made by this method. Support of the ram becomes a problem as work length increases.

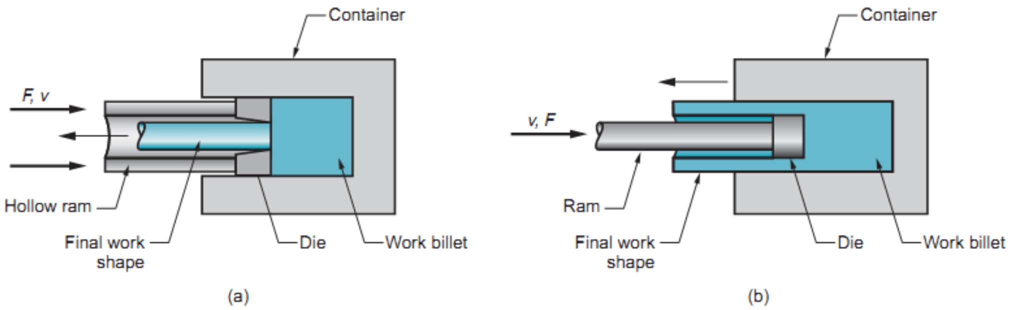

Figure 8.3 Indirect extrusion to produce (a) a solid cross section and (b) a hollow cross section.

- **Hot Versus Cold Extrusion** Extrusion can be performed either hot or cold, depending on work metal and amount of strain to which it is subjected during deformation. Metals that are typically extruded hot include aluminum, copper, magnesium, zinc, tin, and their alloys. These same metals are sometimes extruded cold. Steel alloys are usually extruded hot, although the softer, more ductile grades are sometimes cold extruded (e.g., low carbon steels and stainless steel). Aluminum is probably the most ideal metal for extrusion (hot and cold), and many commercial aluminum products are made by this process (structural shapes, door and window frames, etc.).

Hot extrusion involves prior heating of the billet to a temperature above its recrystallization temperature. This reduces strength and increases ductility of the metal, permitting more extreme size reductions and more complex shapes to be achieved in the process. Additional advantages include reduction of ram force, increased ram speed, and reduction of grain flow characteristics in the final product. Cooling of the billet as it contacts the container walls is a problem, and isothermal extrusion is sometimes used to overcome this problem. Lubrication is critical in hot extrusion for certain metals (e.g., steels), and special lubricants have been developed that are effective under the harsh conditions in hot extrusion. Glass is sometimes used as a lubricant in hot extrusion; in addition to reducing friction, it also provides effective thermal insulation between the billet and the extrusion container.

Cold extrusion and warm extrusion are generally used to produce discrete parts, often in finished (or near finished) form. The term impact extrusion is used to indicate high-speed cold extrusion, and this method is described in more detail in Section 19.5.4. Some important advantages of cold extrusion include increased strength due to strain hardening, close tolerances, improved surface finish, absence of oxide layers, and high production rates. Cold extrusion at room temperature also eliminates the need for heating the starting billet.

- **Continuous Versus Discrete Processing** A true continuous process operates in steady state mode for an indefinite period of time. Some extrusion operations approach this ideal by producing very long sections in one cycle, but these operations are ultimately limited by the size of the starting billet that can be loaded into the extrusion container. These processes are more accurately described as semi-continuous operations. In nearly all cases, the long section is cut into smaller lengths in a subsequent sawing or shearing operation.

  In a discrete extrusion operation, a single part is produced in each extrusion cycle. Impact extrusion is an example of the discrete processing case.

8.4. Analysis of Extrusion

Let us use Figure 8.4 as a reference in discussing some of the parameters in extrusion. The diagram assumes that both billet and extrudate are round in cross section. One important parameter is the ***extrusion ratio***, also called the ***reduction ratio***. The ratio is defined:

$$r_x = \frac{A_o}{A_f} \tag{8.1}$$

where r_x= extrusion ratio; A_o = cross-sectional area of the starting billet, mm^2 (in^2); and A_f = final cross-sectional area of the extruded section , mm^2 (in^2) . The ratio applies for both direct and indirect extrusion. The value of r_x can be used to determine true strain in extrusion, given that ideal deformation occurs with no friction and no redundant work:

$$\epsilon = \ln r_x = \ln \frac{A_o}{A_f} \tag{8.2}$$

Under the assumption of ideal deformation (no friction and no redundant work), the pressure applied by the ram to compress the billet through the die opening depicted in our figure can be computed as follows:

$$p = \overline{Y}_f \ln r_x \tag{8.3}$$

Where $\overline{Y}_f$ average flow stress during deformation, MPa (lb/in^2). For convenience, we restate Eq. ($\overline{Y}_f = \frac{K\,\epsilon^n}{1+n}$) from the previous chapter Six:

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

In fact, extrusion is not a frictionless process, and the previous equations grossly underestimate the strain and pressure in an extrusion operation. Friction exists between the die and the work as the billet squeezes down and passes through the die opening. In direct extrusion, friction also exists between the container wall and the billet surface. The effect of friction is to increase the strain experienced by the metal. Thus, the actual pressure is greater than that given by Eq. (8.3), which assumes no friction.

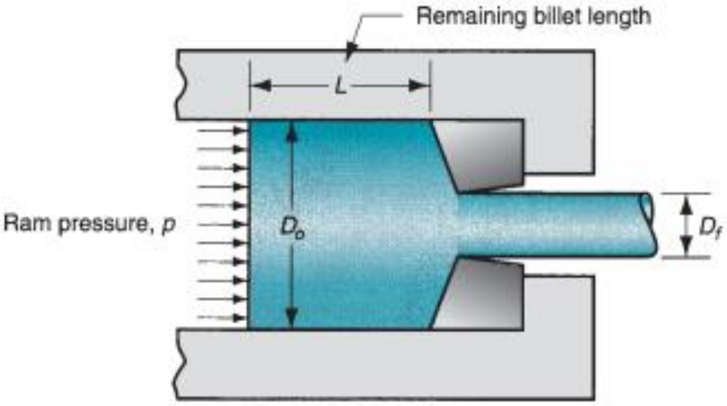

Figure 8.4 Pressure and Other Variable Direct Extrusion.

. Various methods have been suggested to calculate the actual true strain and associated ram pressure in extrusion. The following empirical equation proposed by **Johnson** for estimating extrusion strain has gained considerable recognition:

$$\epsilon_x = a + b \ln r_x \qquad (8.4)$$

where ϵ_x=extrusion strain; and *a* and *b* are empirical constants for a given die angle. Typical values of these constants are: a = 0.8 and b = 1.2 to 1.5. Values of *a* and *b* tend to increase with increasing die angle.

The ram pressure to perform ***indirect extrusion*** can be estimated based on Johnson's extrusion strain formula as follows:

$$p = \overline{Y}_f \epsilon_x \tag{8.5a}$$

where $\overline{Y}_f$ is calculated based on ideal strain from Eq. (8.2), rather than extrusion strain in Eq. (8.4).

In direct extrusion, the effect of friction between the container walls and the billet causes the ram pressure to be greater than for indirect extrusion. We can write the following expression which isolates the friction force in the direct extrusion container:

$$\frac{p_f \pi D_o^2}{4} = \mu p_c \pi D_o L$$

where p_f = additional pressure required to overcome friction, MPa (lb/in^2); $\pi D_0^2/4$= billet cross-sectional area, mm^2 (in^2); μ= coefficient of friction at the container wall; p_c = pressure of the billet against the container wall, MPa (lb/in^2); and $\pi D_o L$ = area of the interface between billet and container wall, mm^2 (in^2). The right-hand side of this equation indicates the billet-container friction force, and the left-hand side gives the additional ram force to overcome that friction. In the worst case, sticking occurs at the container wall so that friction stress equals shear yield strength of the work metal:

$$\mu p_s \pi D_o L = Y_s \pi D_o L$$

where Y_s = shear yield strength, MPa (lb/in^2). If we assume that $Y_s = \bar{Y}_f/2$, then p_f reduces to the following:

$$p_f = \bar{Y}_f \frac{2L}{D_o}$$

Based on this reasoning, the following formula can be used to compute ram pressure in direct extrusion:

$$p = \bar{Y}_f \left(\epsilon_x + \frac{2L}{D_o} \right) \tag{8.5b}$$

where the term $2L/D_o$ accounts for the additional pressure due to friction at the container – billet interface. L is the portion of the billet length remaining to be extruded, and D_o is the original diameter of the billet. Note that p is reduced as the remaining billet length decreases during the process. Typical plots of ram pressure as a function of ram stroke for direct and indirect extrusion are presented in Figure 8.5. Eq. (8.5 b) probably overestimates ram pressure. With good lubrication, ram pressures would be lower than values calculated by this equation.

Ram force in indirect or direct extrusion is simply pressure p from Eqs. (8.5a) or (8.5b), respectively, multiplied by billet area A_o:

$$F = pA_o \tag{8.6}$$

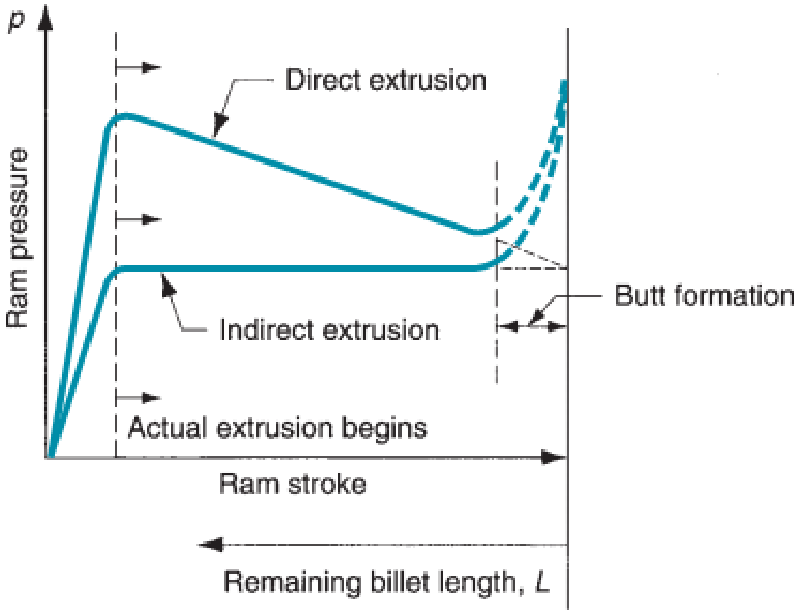

Figure 8.5 Typical plots of ram pressure versus ram stroke (and remaining billet length) for direct and indirect extrusion. The higher values in direct extrusion result from friction at the container wall. The shape of the initial pressure buildup at the beginning of the plot depends on die angle (higher die angles cause steeper pressure buildups). The pressure increase at the end of the stroke is related to formation of the butt.

where F = ram force in extrusion, N (lb). Power required to carry out the extrusion operation is simply

$$P = Fv \tag{8.7}$$

where P = power, J/s (in-lb/min); F = ram for ce, N (lb); a nd v ¼ ram velocity, m/s (in/min).

Example: A billet 75 mm long and 25 mm in diameter is to be extruded in a direct extrusion operation with extrusion ratio $r_x = 4.0$. The extrudate has a round cross section. The die angle (half-angle) = 90°. The work metal has a strength coefficient = 415 MPa, and strain-hardening exponent = 0.18. Use the Johnson formula with a = 0.8 and b = 1.5 to estimate extrusion strain. Determine the pressure applied to the end of the billet as the ram moves forward.

Solution: Let us examine the ram pressure at billet lengths of L = 75 mm (starting value), L = 50 mm, L = 25 mm, and L = 0. We compute the ideal true strain, extrusion strain using Johnson's formula, and average flow stress:

$$\epsilon = \ln r_x = \ln 4.0 = 1.3863$$

$$\epsilon_x = 0.8 + 1.5(1.3863) = 2.8795$$

$$\overline{Y}_f = \frac{415(1.3863)^{0.18}}{1.18} = 373 \text{ MPa}$$

L = 75 mm: With a die angle of 90° , the billet metal is assumed to be forced through the die opening almost immediately; thus, our calculation assumes that maximum pressure is reached at the billet length of 75 mm. For die angles less than 90°, the pressure would build to a maximum as in Figure 19.34 as the starting billet is squeezed into the cone-shaped portion of the extrusion die. Using Eq. (8.5b),

$$p = 373\left(2.8795 + 2\frac{75}{25}\right) = 3312\ \text{MPa}$$

$$L = 50\ \text{mm}: p = 373\left(2.8795 + 2\frac{50}{25}\right) = 2566\ \text{MPa}$$

$$L = 25\ \text{mm}: p = 373\left(2.8795 + 2\frac{25}{25}\right) = 1820\ \text{MPa}$$

L = 0: Zero length is a hypothetical value in direct extrusion. In reality, it is impossible to squeeze all of the metal through the die opening. Instead, a portion of the billet (the ‘‘butt ’’) remains unextruded and the pressure begins to increase rapidly as L approaches zero. This increase in pressure at the end of the stroke is seen in the plot of ram pressure versus ram stroke in Figure 8.5. Calculated below is the hypothetical minimum value of ram pressure that would result at L= 0.

$$p = 373\left(2.8795 + 2\frac{0}{25}\right) = 1074\ \text{MPa}$$

This is also the value of ram pressure that would be associated with indirect extrusion throughout the length of the billet.

8.5. Extrusion Dies and Presses

Important factors in an extrusion die are die angle and orifice shape. Die angle, more precisely die half-angle, is shown as a in Figure 8.6(a). For low angles, surface area of the die is large, leading to increased friction at the die–billet interface. Higher friction results in larger ram force. On the other hand, a large die angle causes more turbulence in the metal flow during reduction, increasing the ram force required. Thus, the effect of die angle on ram force is a U-shaped function, as in Figure 8.6(b). An optimum die angle exists, as suggested by our hypothetical plot. The optimum angle depends on various factors (e.g., work material, billet temperature, and lubrication) and is therefore difficult to determine for a given extrusion job. Die designers rely on rules of thumb and judgment to decide the appropriate angle.

Our previous equations for ram pressure, Eqs. (8.5a), apply to a circular die orifice. The shape of the die orifice affects the ram pressure required to perform an extrusion operation. A complex cross section, such as the one shown in Figure 8.7, requires a higher pressure and greater force than a circular shape. The effect of the die orifice shape can be assessed by the die shape factor, defined as the ratio of the pressure required to extrude a cross section of a given shape relative to the extrusion pressure for a round cross section of the same area. We can express the shape factor as follows:

$$K_x = 0.98 + 0.02\left(\frac{C_x}{C_c}\right)^{2.25} \tag{8.8}$$

where K_x = die shape factor in extrusion; C_x = perimeter of the extruded cross section, mm (in); and C_c = perimeter of a circle of the same area as the extruded shape, mm (in). Eq. (8.8) is based on empirical data in Altan et al. [1] over a range of C_x/C_c values from 1.0 to about 6.0. The equation may be invalid much beyond the upper limit of this range.

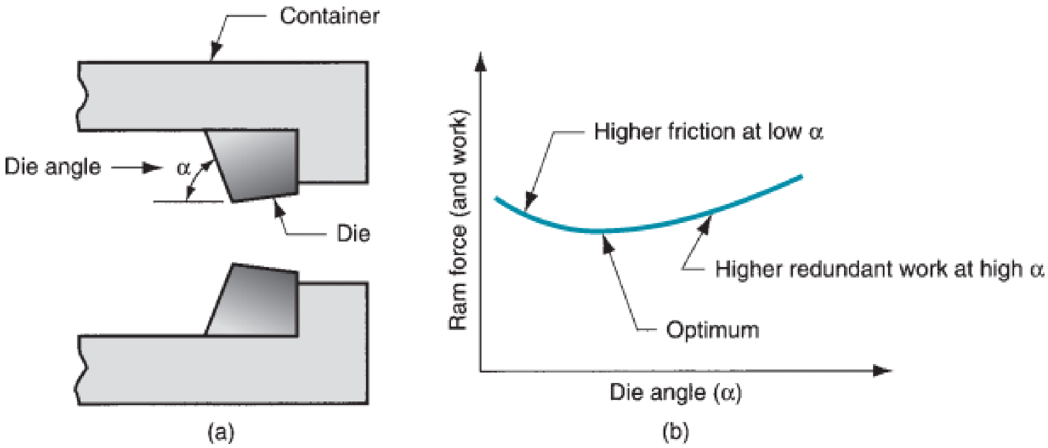

Figure 8.6 (a) Definition of die angle in direct extrusion;

(b) effect of die angle on ram force.

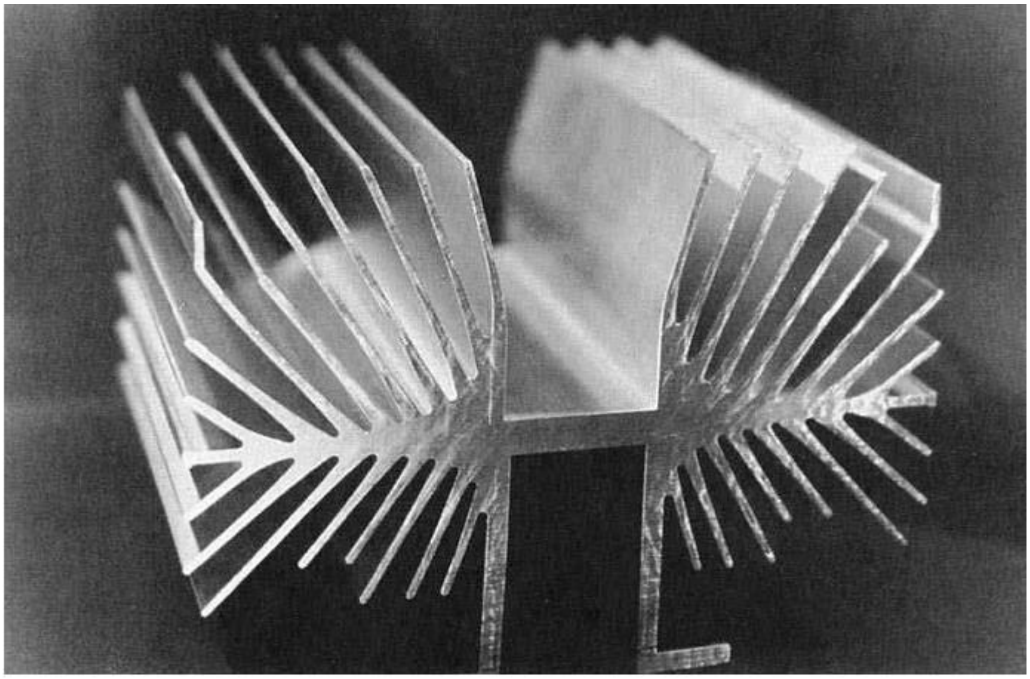

Figure 8.7 A complex extruded cross section for a heat sink. (Photo courtesy of Aluminum Company of America, Pittsburg, Pennsylvania.)

As indicated by Eq. (8.8), the shape factor is a function of the perimeter of the extruded cross section divided by the perimeter of a circular cross section of equal area. A circular shape is the simplest shape, with a value of $K_x = 1.0$. Hollow, thin-walled sections have higher shape factors and are more difficult to extrude. The increase in pressure is not included in our previous pressure equations, Eqs. (8.5a and 8.5b), which apply only to round cross sections. For shapes other than round, the corresponding expression for indirect extrusion is

$$p = K_x \overline{Y}_f \epsilon_x \tag{8.9}$$

and the direct extrusion

$$p = K_x \overline{Y}_f \left(\epsilon_x + \frac{2L}{D_o} \right) \tag{8.10}$$

where p = extrusion pressure, MPa (lb/in^2); K_x = shape factor; and the other terms have the same interpretation as before. Values of pressure given by these equations can be used in Eq. (8.6) to determine ram force.

Die materials used for hot extrusion include tool and alloy steels. Important properties of these die materials include high wear resistance, high hot hardness, and high thermal conductivity to remove heat from the process. Die materials for cold extrusion include tool steels and cemented carbides. Wear resistance and ability to retain shape under high stress are desirable properties. Carbides are used when high production rates, long die life, and good dimensional control are required.

Extrusion presses are either horizontal or vertical, depending on orientation of the work axis. Horizontal types are more common. Extrusion presses are usually hydraulically driven. This drive is especially suited to semi-continuous production of long sections, as in direct extrusion. Mechanical drives are often used for cold extrusion of individual parts, such as in impact extrusion.

8.6. Other Extrusion Presses

Direct and indirect extrusion are the principal methods of extrusion. Various names are given to operations that are special cases of the direct and indirect methods described here. Other extrusion operations are unique. In this section we examine some of these special forms of extrusion and related processes.

- **Impact Extrusion** Impact extrusion is performed at higher speeds and shorter strokes than conventional extrusion. It is used to make individual components. As the name suggests, the punch impacts the workpart rather than simply applying pressure to it. Impacting can be carried out as forward extrusion, backward extrusion, or combinations of these. Some representative examples are shown in Figure 8 .8.

  Impact extrusion is usually done cold on a variety of metals. Backward impact extrusion is most common. Products made by this process include toothpaste tubes and battery cases. As indicated by these examples, very thin walls are possible on impact extruded parts. The high-speed characteristics of impacting permit large reductions and high production rates, making this an important commercial process.

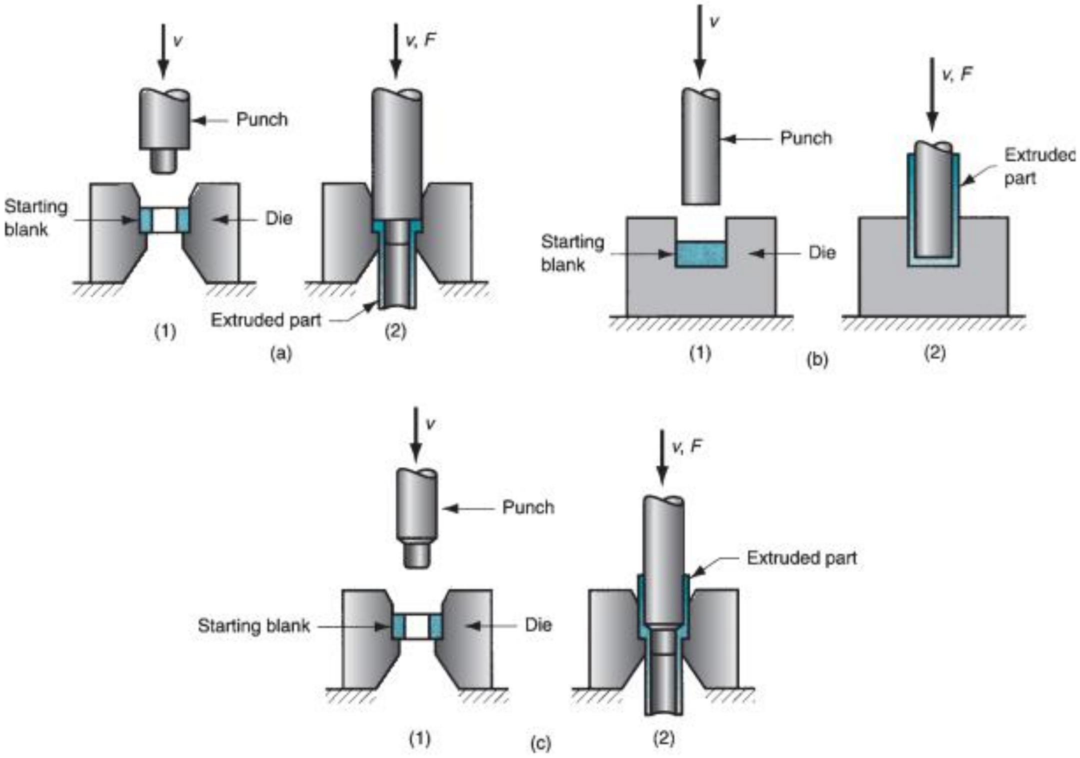

Figure 8.8 Several examples of impact extrusion: (a) forward, (b) backward, and (c) combination of forward and backward.

- **Hydrostatic Extrusion** One of the problems in direct extrusion is friction along the billet container interface. This problem can be addressed by surrounding the billet with fluid inside the container and pressurizing the fluid by the forward motion of the ram, as in Figure 8.9. This way, there is no friction inside the container, and friction at the die opening is reduced. Consequently, ram force is significantly lower than in direct extrusion. The fluid pressure acting on all surfaces of the billet gives the process its name. It can be carried out at room temperature or at elevated temperatures. Special fluids and procedures must be used at elevated temperatures. Hydrostatic extrusion is an adaptation of direct extrusion.

Hydrostatic pressure on the work increases the material’s ductility. Accordingly, this process can be used on metals that would be too brittle for convention al extrusion operations. Ductile metals can also be hydrostatically extruded, and high reduction ratios are possible on these materials. One of the disadvantages of the process is the required preparation of the starting work billet. The billet must be formed with a taper at one end to fit snugly into the die entry angle. This establishes a seal to prevent fluid from squirting out the die hole when the container is initially pressurized.

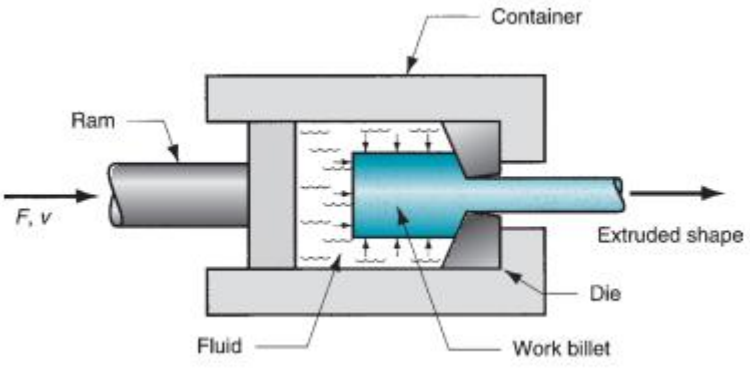

Figure 8.9 Hydrostatic extrusion

8.7. Defect in Extruded product

Owing to the considerable deformation associated with extrusion operations, a number of defects can occur in extruded products. The defects can be classified into the following categories, illustrated in Figure 8.10:

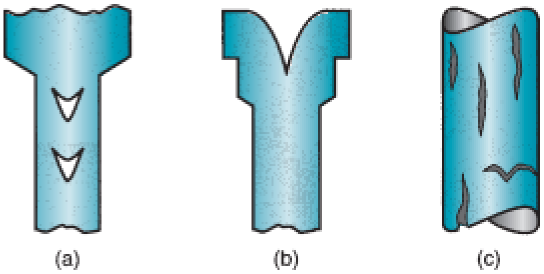

Figure 8.10 Some common defects in extrusion: (a) centerburst, (b) piping, and (c) surface cracking.

a) ***Centerburst:*** This defect is an internal crack that develops as a result of tensile stresses along the centerline of the workpart during extrusion. Although tensile stresses may seem unlikely in a compression process such as extrusion, they tend to occur under conditions that cause large deformation in the regions of the work away from the central axis. The significant material movement in these outer regions stretches the material along the center of the work. If stresses are great enough, bursting occurs. Conditions that promote centerburst are high die angles, low extrusion ratios, and impurities in the work metal that serve as starting points for crack defects. The difficult aspect of centerburst is its detection. It is an internal defect that is usually not noticeable by visual observation. Other names sometimes used for this defect include ***arrowhead fracture, center cracking, and chevron cracking***.

b) Piping: Piping is a defect associated with direct extrusion. As in Figure 8.10(b), it is the formation of a sink hole in the end of the billet. The use of a dummy block whose diameter is slightly less than that of the billet helps to avoid piping. Other names given to this defect include tailpipe and ***fishtailing***.

c) Surface cracking: This defect results from high workpart temperatures that cause cracks to develop at the surface. They often occur when extrusion speed is too high, leading to high strain rates and associated heat generation. Other factors contributing to surface cracking are high friction and surface chilling of high temperature billets in hot extrusion.